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Response Assessment of Nonstructural Building Elements

Shahram Taghavi
Stanford University

and

Eduardo Miranda
Stanford University

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Shahram Taghavi
Graduate Student Researcher
Department of Civil and Environmental Engineering
Stanford University

Eduardo Miranda
Assistant Professor

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College of Engineering
University of California Berkeley

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ABSTRACT

A database is developed in this study for the adequate organization, storage, and easy retrieval of information related to the seismic performance of nonstructural components and contents of commercial buildings. The database addresses several problems and aspects of nonstructural components including damage and cost information. The performance of nonstructural components including damage descriptions and information about ground motions and structures are investigated and collected in the database. Also included are numerous photos of damaged components with a detailed damage description for each. The data are accessible through a search engine designed for the database using several graphical user interfaces. Fragility curves are explained as well as issues regarding data collection and development of these components. Part of the database is dedicated to the cost information about nonstructural components. A cost breakdown of several typical commercial buildings in the database is presented along with some comparisons. Cost functions that represent the cost of repair of components are explained, and an example for the development of these functions is presented. A new classification of nonstructural components is proposed. The proposed classification is designed to match with what is needed in performance-based design. The nonstructural components are classified according to their functionality in the building and to the sensitive structural response parameter. Damage states are defined for the components and their respective damage states. Several repercussions of the damage states from a performance perspective are listed.

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1 Introduction

The nonstructural components and contents of buildings play a crucial role in performance-based earthquake engineering for several reasons. First, with few exceptions, the nonstructural components in most types of commercial buildings represent a major portion of the total cost of the building and, as such, will represent a large portion of the potential losses to owners, occupants, and insurance companies. Second, damage to most types of nonstructural components in buildings is usually triggered at levels of deformation much smaller than those required to initiate structural damage. For example, damage to brittle partitions often begins at drift levels smaller than those required to induce damage to the structure. Similarly, high accelerations associated with small drifts can damage ceilings, piping, and other nonstructural components with little or no damage to the structural members. Third, if nonstructural damage is substantial, important economic losses can be produced from a temporary loss of function in the building. Hence, implementation of performance-based earthquake engineering where loss control is of primary concern requires significantly expanding our knowledge about the design, construction, maintenance, and performance of nonstructural components.

In recent years significant progress has been made in modeling and predicting the performance of structures during earthquakes, as well as in knowledge about the design of structures. However, despite the enormous contribution of nonstructural components to total economic losses, nonstructural components have received much less attention, with most of the documentation on performance typically anecdotal and lacking in detail.

The objective of this research is to collect, organize, and summarize existing information about the performance of building nonstructural components and contents in previous earthquakes. For this purpose a computer database was developed. The database includes a taxonomy to organize nonstructural components depending on their function, as well as other information required in performance-based earthquake engineering, such as the structural response parameter to which the nonstructural component is primarily sensitive, or the consequences of the failure of the component. Typical costs associated with the installation of these components are included. Information about the performance of nonstructural components in previous earthquakes is obtained from damage reports and includes an abundance of digital images that illustrate typical damage to nonstructural components in these earthquakes. The information gathered in the database allows engineers, owners, insurers, and contractors to learn more about nonstructural components and their contribution to the total costs of buildings, as well as about the performance of nonstructural components in previous earthquakes.

This report has been organized as follows: Chapter 2 presents a new method to classify nonstructural components. The proposed classification addresses the needs for performance-based design and classifies the components according to functionality and damage-related issues. Chapter 3 describes the general structure of the database and summarizes the information available there. Chapter 4 presents issues regarding damage to nonstructural components. The issues regarding fragility curves are explained. Also presented are the types of information in the database about damaged components, including text and image reports. A summary of the failure modes of different components with photos is shown at the end of the chapter. Cost information about nonstructural components is presented in Chapter 5 where the development of loss functions, cost of typical nonstructural components, and cost breakdown of commercial buildings are explained. Appendix 1 describes the efforts done to collect the information about the 2001 Nisqually, Washington, earthquake. Appendix 2 presents a summary of the formulation to estimate earthquake losses in buildings.

2 Nonstructural Components in Commercial Buildings

As previously stated, nonstructural components are important to considering the overall performance of buildings in earthquakes, and therefore a better understanding of these components from different aspects is crucial. Nonstructural components can be studied from different perspectives such as their functionality in buildings, their effects on the building performance, how the components get damaged, what structural responses they are most sensitive to, and repercussions resulting from damaged nonstructural components. In this chapter, two research projects classifying nonstructural components are reviewed, different issues about nonstructural components are addressed, and a new method is presented to classify nonstructural components. The new proposed classification of the components intends to satisfy the needs of the performance-based design of buildings and is focused on how damage to different components may affect the performance of the building from various aspects.

2.1 PREVIOUS WORK REGARDING CLASSIFICATION OF NONSTRUCTURAL COMPONENTS

The classification of nonstructural components according to the repercussions of damage has been done before in different ways in several studies. For example, in FEMA-274 (1997), the components are classified for three levels of earthquake, and for each case, divided into two categories that the components should be designed for:

- Immediate Occupancy
- Life Safety

In a separate work by Roger Scholl et al. (1984), nonstructural components have been classified according to their hazard to life, loss of function, and economic loss.

2.2 NEW CLASSIFICATION OF NONSTRUCTURAL COMPONENTS

In this report a new and more comprehensive method is proposed for classifying the component based on its functionality, sensitive response parameter, damage state, and the repercussions of each damage state.

A tree-shape classification of nonstructural components is proposed which covers most aspects from functionality in buildings, to sensitivity to different structural response parameters, to the repercussions of different damage states. A graphic outline of the taxonomy is shown in Figure 2.1. In the following, each level of the taxonomy is explained:

a. *System:* A nonstructural component is classified according to its system. A nonstructural system can be “Interior Construction,” “Mechanical Systems,” and the like.

b. *Level-1 Components:* Each system of nonstructural components contains some components. These components have certain functions and the components are defined at this level according to their function. A more detailed classification is left for the next step. For example, “Interior Construction” is divided into “Partitions,” “Ceilings,” and the like.

c. *Level-2 Components:* Each component in “Level-1 Components” is divided into several components. At this level, all the components that are a subset of a component have the same functionality but differ in detail. “Ceilings,” for example, is divided into “Suspended Acoustical Ceiling,” “Plaster Ceiling,” and the like.

d. *Damage States:* The damage state for each component is defined at this level and is used for determining the fragility curve and also cost function.

e. *Sensitive Response Parameter:* Each component shows sensitivity to one or more structural response parameters.

f. *Repercussions:* For each damage state, repercussions are defined and explained.

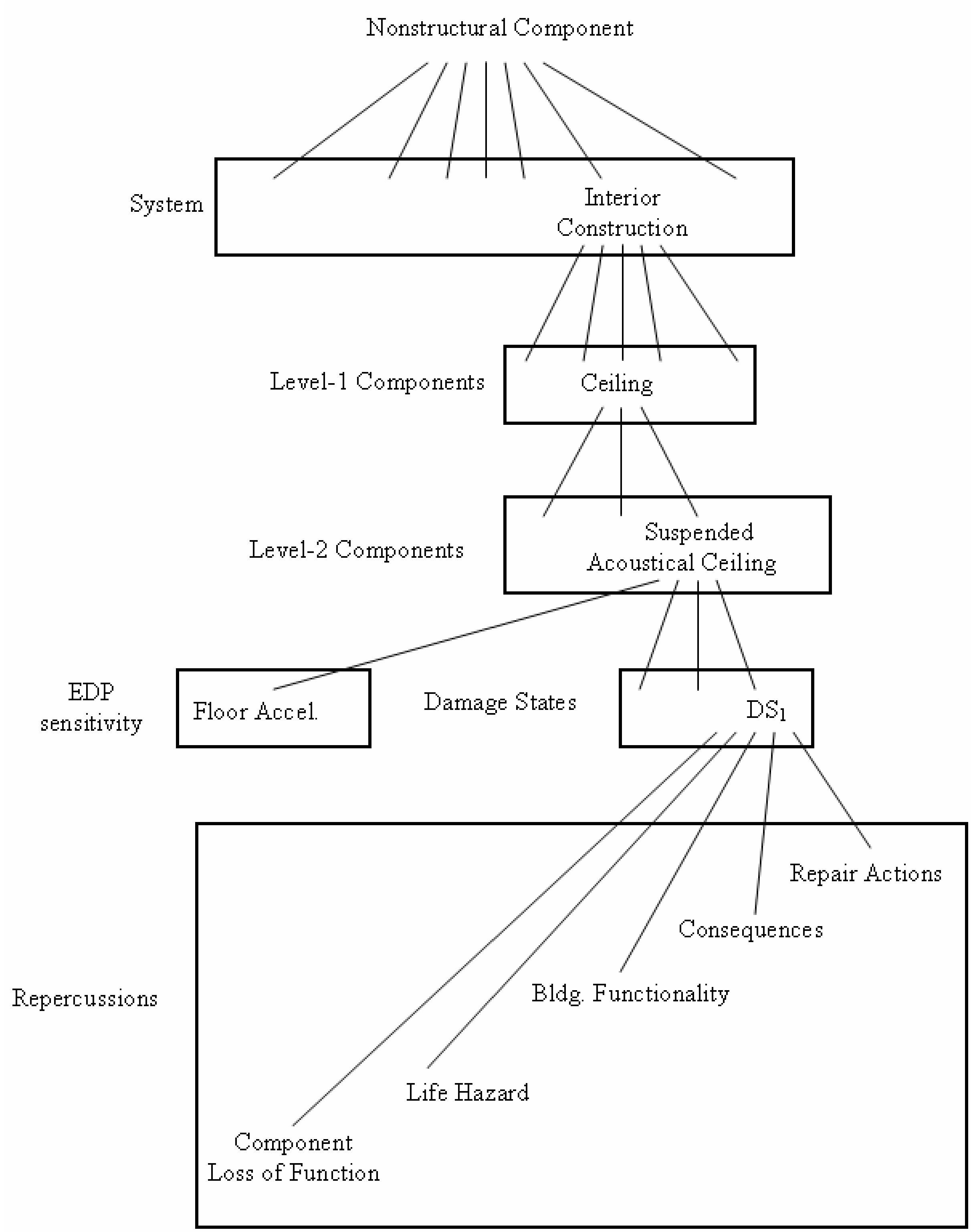

Figure 2.1 Taxonomy of nonstructural components

In the following, more information is presented on each part of the classification shown in Figure 2.1. Since the intention of this study is to show how the information can be classified, the information listed in the following sections are just some examples and does not include all nonstructural components.

2.2.1 Systems

The nonstructural components may be divided into the systems shown in Table 2.1.

Table 2.1 Nonstructural components systems

	Systems
Nonstructural Components	1 – Exterior Construction
	2 – Roofing
	3 – Interior Construction
	4 – Conveying Systems
	5 – Mechanical Systems
	6 – Electrical Systems

2.2.2 Classification According to the System

Systems of nonstructural components are divided into Level-1 Components (Table 2.2). As explained earlier, in Level-1 Components we do not show the different types of one component with the same functionality. For example, “Exterior Construction” is divided into four components such as walls, doors, windows, and parapets, but different types of walls or doors are not included at this level.

Table 2.2 Classification of nonstructural component based on the system

System	Level-1 Components
1 – Exterior Construction	1.1 – Walls
	1.2 – Doors
	1.3 – Windows and glazed walls
	1.4 – Parapets
2 – Roofing	2.1 – Roof covers
	2.2 – Openings
3 – Interior Construction	3.1 – Partitions
	3.2 – Doors
	3.3 – Wall finishes
	3.4 – Ceilings
	3.5 – Floor finishes
4 – Conveying systems	4.1 – Elevators
	4.2 – Escalators
5 – Mechanical Systems	5.1 – Piping
	5.2 – Fire Protection
	5.3 – Heating systems
	5.4 – Cooling systems
	5.5 – Ducts
6 – Electrical Systems	6.1 – Lighting and power
	6.2 – Power generator
	6.3 – Wiring

2.2.3 Classification of Level-1 Components

Tables 2.3 to 2.8 show a few examples of each Level-1 Component. "Level-2 Components" related to a Level-1 Component have the same function in the building but are different in details.

Table 2.3 Classification of exterior construction

Exterior Construction	Level-2 Components
1.1 – Walls	1.1.1 – Cast in place concrete
	1.1.2 – Precast concrete
	1.1.3 – Concrete block wall
	1.1.4 – Solid brick wall
	1.1.5 – Stone veneer
	1.1.6 – Openings
1.2 – Doors	1.2.1 – Single leaf door
	1.2.2 – Sliding entrance
	1.2.3 – rolling overhead
1.3 – Windows and glazed walls	1.3.1 – Wood windows
	1.3.2 – Steel windows
	1.3.3 – Curtain wall panels
1.4 – Parapets	1.4.1 – Cast in place concrete
	1.4.2 – Concrete block parapets
	1.4.3 – Solid brick parapets

Table 2.4 Classification of roofing systems

Roofing	Level-2 Components
2.1 – Roof covers	2.1.1 – Single-ply member
	2.1.2 – Shingle and tile
	2.1.3 – Roof insulation
2.2 – Openings	2.2.1 – Roof hatches
	2.2.1 – Roof skylights

Table 2.5 Classification of interior construction

Interior Construction	Level-2 Components
3.1 – Partitions	3.1.1 – Drywall wood stud partitions
	3.1.2 – Drywall steel stud partitions
	3.1.3 – Concrete block partitions
3.2 – Doors	3.2.1 – Wood doors
	3.2.2 – Aluminum doors
3.3 – Wall finishes	3.3.1 – Ceramic tile
	3.3.2 – Wallpaper
	3.3.3 – Plaster
3.4 – Ceilings	3.4.1 – Suspended acoustical
	3.4.2 – Suspended plaster
	3.4.3 – Plaster
3.5 – Floor finishes	3.5.1 – Carpet tile
	3.5.2 – Ceramic tile

Table 2.6 Classification of conveying systems

Conveying systems	Level-2 Components
4.1 – Elevators	4.1.1 – Hydraulic elevators
	4.1.2 – Traction gear elevators

Table 2.7 Classification of mechanical systems

Mechanical Systems	Level-2 Components
5.1 – Piping	5.1.1 – Hot and clod water pipes
	5.1.2 – Waste water pipes
	5.1.3 – Gas pipes
5.2 – Fire protection	5.2.1 – Wet pipe sprinkler system
	5.2.2 – Dry pipe sprinkler system
	5.2.3 – Fire cycle sprinkler system
5.3 – Heating systems	5.3.1 – Boiler
	5.3.2 – Unit heater
	5.3.3 – Radiator
5.4 – Cooling systems	5.4.1 – Packaged chiller
	5.4.2 – Rooftop air conditioner
5.5 – Ducts	5.5.1 – Aluminum ducts
	5.5.2 – Galvanized ducts
	5.5.3 – PVC ducts

Table 2.8 Classification of electrical systems

Electrical Systems	Level-2 Components
6.1 – Lighting and power	6.1.1 – Fluorescent fixture
	6.1.2 – Incandescent fixture
	6.1.3 – Wall switches
	6.1.4 – Receptacles
6.2 – Power generator	6.2.2 – Generator
	6.2.3 – Transformer
6.3 – Wiring	6.3.1 – Wiring within the partitions
	6.3.2 – Wiring within cable tray

2.2.4 Classification According to Sensitive Response Parameter

Each component shows sensitivity to one or more response parameters of the structure, and the damage of the component is correlated to these response parameters. The components have been divided into three categories:

1. Interstory-drift-sensitive components
2. Acceleration-sensitive components
3. Interstory-drift- and acceleration-sensitive components

Table 2.9 shows some nonstructural components classified according to sensitive response parameter.

Table 2.9 Classification of nonstructural component based on the sensitive response parameter

Sensitivity	Component
Drift-sensitive	Masonry walls
	Windows
	Interior doors
	Partitions
	Floor finishes (tile or wood)
	Plaster ceiling
	Electrical system within partitions (data, electrical, telephone, etc.)
	Floor finishes (tile or wood)
	Doors
	Plaster ceiling
	Elevator cabin

Table 2.9 *(continued)* Classification of nonstructural component based on the sensitive response parameter

Sensitivity	Component
Acceleration-sensitive	Parapets
	Suspended ceilings
	Ducts
	Boilers
	Chillers
	Tanks
	Elevators (machine room)
	Light fixtures
	Electrical systems in horizontal pipes or cable trays (data, electrical, telephone, etc)
Drift and Acceleration-sensitive	Precast elements
	Fire sprinklers
	Cold and Hot water pipes
	Gas pipes
	Elevators (counterweight and guide rails)
	Waste water pipes

2.2.5 Damage States and Their Repercussions

For each Level-2 Component, damage states based on observations of its performance in previous earthquakes or experiments are defined. Then, for each damage state, several repercussions are listed according to the following framework:

1. *Repair Actions:* The actions needed to be done to repair the damaged component.

2. *Consequences:* Each damage state of a component has some impact on other components that are listed in this part of the taxonomy.
3. *Functionality of the building:* The functionality of the building falls into one of the following states: Fully functional, partially functional, not functional.
4. *Life Hazard:* The life hazard that may occur due to the damage of the component can be one of the following cases: None, small, moderate, high.
5. *Component Loss of Function:* A component may lose its total functionality as a result of the damage. The following modes for the loss of functionality defined in this taxonomy are none, small, moderate, high.

Tables 2.10 to 2.14 show the damage states and their repercussions for a few components. The intention here is to show how the taxonomy can provide better understanding of the behavior of the nonstructural component, but more studies are required to complete the taxonomy.

Table 2.10 Damage states and their repercussions for solid brick walls

COMPONENT	DAMAGE STATE	TYPE OF CONSEQUENCE	INFORMATION
Solid Brick Wall	Damage state 1: Hairline cracks in mortar and wall finishes	Repair actions	The wall needs some minor repair of exterior finishes
		Damage consequences	It has no effect on the performance of other components and the building can be used immediately
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	None
	Damage state 2: Severe crack in wall and spalling of wall finishes	Repair actions	Depending on the extent of damage, some parts of the wall may need demolition and reconstruction. Also the damaged area needs the repair of exterior finish
		Damage consequences	The functionality of the rooms adjacent to the damaged wall may be interrupted until the wall gets repaired. If there are some small sensitive electrical and mechanical devices on the wall, they may stop functioning and need repair.
		Functionality of Bldg.	Partially functional
		Life hazard	Small
		Component loss of function	Moderate
	Damage state 3: Total failure of the wall	Repair actions	The damaged area must be demolished completely and new wall must be reconstructed
		Damage consequences	The damaged wall must be demolished and reconstructed before the adjacent rooms can function regularly. Electrical systems, such as plugs and wiring, and mechanical systems, such as piping, may break or not work
		Functionality of Bldg.	Partially functional
		Life hazard	High
		Component loss of function	High

Table 2.11 Damage states and their repercussions for drywall wood stud partitions

COMPONENT	DAMAGE STATE	TYPE OF CONSEQUENCE	INFORMATION
Drywall Wood Stud Partitions	Damage state 1: Crack in the painting or the drywall	Repair actions	The partition needs taping, pasting, and painting
		Damage consequences	It has no effect on the performance of other components, and the building will be functional
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	None
	Damage state 2: Broken drywall panel	Repair actions	The damaged panels have to be replaced. After the damaged panels are replaced, the partition will also need taping, pasting, and painting
		Damage consequences	The use of areas in the building with damaged partitions may be interrupted for short periods of time during the repair of the partitions. The mechanical and electrical devices, such as plugs, wiring, and piping, placed inside the partitions may break. Depending on the usage of the room, it may cause the interruption of the functionality until these devices and systems are repaired completely (e.g., the hospitals)
		Functionality of Bldg.	Partially functional
		Life hazard	None
		Component loss of function	Moderate
	Damage state 3: Damage to panels and frames	Repair actions	Both panel and wood frame must be removed and replaced and then painted
		Damage consequences	The damaged area is not usable because of extensive damage to the wall. Mechanical and electrical systems face similar damage mentioned above in damage state 2 but more extensive
		Functionality of Bldg.	Partially functional
		Life hazard	Small
		Component loss of function	High

Table 2.12 Damage states and their repercussions for suspended acoustical ceilings

COMPONENT	DAMAGE STATE	TYPE OF CONSEQUENCE	INFORMATION
Suspended Acoustical Ceiling	Damage state 1: Some of the panels get damaged	Repair actions	The extent of damage is very limited and only some panels are cracked or damaged at the corners. The damaged panels must be replaced
		Damage consequences	Building is operational and the components attached to the ceiling are not damaged
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	Small
	Damage state 2: Panels fall and minor damage to T-bar frame	Repair actions	Damaged panel must be replaced but the frame can be fixed with minor repairs
		Damage consequences	Fire sprinklers attached to the ceiling panels may break resulting in water leakage causing damage to both the ceiling and the building contents. The light fixtures may fall or dislocate. The usage of the area will be interrupted as a result of damage.
		Functionality of Bldg.	Partially functional
		Life hazard	None
		Component loss of function	Moderate
	Damage state 3: Severe distortion of frame	Repair actions	Some parts of the frame deform and a substantial portion of the panels fall or break. Damaged panels must be replaced with new ones and damaged parts of frame must be replaced.
		Damage consequences	Similar to damage state 2 but more extensive. In particular removal and installation of new ceilings will take substantially more down time than just replacing of ceiling panels. Typically area will not be usable before major repair/replacement takes place.
		Functionality of Bldg.	Not functional
		Life hazard	Small
		Component loss of function	High

Table 2.13 Damage states and their repercussions for light fixtures

COMPONENT	DAMAGE STATE	TYPE OF CONSEQUENCE	INFORMATION
Light Fixture	Damage state 1: Damage to components such as lamps and light covers	Repair actions	The components may fall or come loose. The components may need repair or replacement.
		Damage consequences	This level of damage does not have an effect on the functionality of the building. The damage is repaired rapidly. Also it does not cause damage to other components.
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	Small
	Damage state 2: Light fixture supports partially fail	Repair actions	The support fails partly but the whole system is still attached to the ceiling. The support must be repaired. Also the damaged components must be replaced.
		Damage consequences	The building is still functional. Due to failure of the support, the light fixture may have large movement in the ceiling. In case of suspended ceiling, it may cause damage to adjacent ceiling panels.
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	Moderate
	Damage state 3: Total failure of support	Repair actions	Due to total failure of support, the fixture falls down, which probably causes complete damage to and replacement of the light fixture.
		Damage consequences	Falling light fixtures may cause damage to other contents in the room and injuries to people. The light fixtures must be repaired rapidly in order to bring the building back to normal functionality
		Functionality of Bldg.	Partially functional
		Life hazard	Moderate
		Component loss of function	Moderate to High

Table 2.14 Damage states and their repercussions for wet pipe sprinkler systems

COMPONENT	DAMAGE STATE	TYPE OF CONSEQUENCE	INFORMATION
Wet Pipe Sprinkler System	Damage state 1: Breaking the hangers	Repair actions	Hangers must be replaced
		Damage consequences	If the only damage is breaking the hangers due to contact with some other components or shearing off because of intensive force, no important consequence. The hangers must be replaced in order to prohibit further damage.
		Functionality of Bldg.	Fully functional
		Life hazard	None
		Component loss of function	Small
	Damage state 2: Damage to piping	Repair actions	Damage usually occurs at connections or at floor levels. The pipe and possibly the connections must be replaced
		Damage consequences	At this damage state, there are some breakages in piping that lead to almost severe damage to some components as a result of water leakage. Ceilings are more vulnerable, since they are the first component facing the water. Also floor finishes, furniture, and electrical devices in the room may be entirely ruined..
		Functionality of Bldg.	Partially functional
		Life hazard	None
		Component loss of function	Moderate to High
	Damage state 3: Damage to sprinkler heads	Repair actions	Due to movement of ceiling and impact with sprinkler heads, the sprinkler head may break, which necessitates replacement of sprinkler head
		Damage consequences	Damage is similar to previous case but more extensive. The damage due to water may be more severe than damage caused by fire.
		Functionality of Bldg.	Not functional
		Life hazard	None
		Component loss of function	High

3 General Description of the Nonstructural Components Database

3.1 MOTIVATION

Engineers’ unfamiliarity with nonstructural components has been a major reason that the importance of these components to the performance of buildings in earthquakes has been underestimated. The nonstructural components database is a tool for engineers to gain better insight into these components. The objective of this database is to present major issues related to nonstructural components, such as cost information, performance in previous earthquakes, repair costs, fragility functions, and experiments.

The database was developed based on a database produced by Soong et al. (1999). The focus of the original database has been on the performance of nonstructural components and contents in previous earthquakes. The types of data available in this database have been extracted from damage reports of past earthquakes, along with information about the earthquake and the structure. In some cases, the response of the structure is available. About 3000 records of information are included in this database.

Although valuable information was collected in this database on the performance of nonstructural components in previous earthquakes, many issues were not addressed. Also, the lack of a query system integrated with the tables of the database makes the user unable to extract the data in an effective way.

Our database improves on the Soong et al. database by:

- Expanding the database to a much wider range of information about nonstructural components and
- Developing queries and forms such that the retrieval of information from the database is possible in an easy and informative way

3.2 DATA MANAGEMENT

Although our database has been developed in Microsoft Access 2000, the user does not need the MS Access package, since the database is provided in an executable version. The database is constructed based on tables, forms, and queries. The tables are used to keep the data. Forms are used to show the data or for use as a search engine. Queries connect the user to tables for selecting the desired set of information and to output. The following explains these three concepts in more detail.

3.2.1 Tables

The collected data have been placed in a series of tables. The tables are interconnected according to their dependency. For example, many records may have the same information in some fields or many tables share the same fields, such as an earthquake or building type; therefore these kinds of information are placed in a separate table and connected to that field of the main table. This has several advantages:

- The data become more condensed and therefore the database uses less space
- Because the same kinds of information are not repeated in different parts, if needed changes can be easily done by changing one instead of many tables
- Development of the database is much easier
- Access to the data is faster by using the interconnected tables

3.2.2 Forms

Forms are the layers of the database for transferring information between the user and the tables or for sending and receiving queries. The forms are used in the following ways:

- *As informative windows about the database*: in this case, there is no connection between the form and the tables and the form just shows static data.
- *As a search engine interface*: the user can select the options in the form and the option becomes a query.

- *As a window showing the output*: The outputs of tables are transferred to the forms through queries.

3.2.3 Queries

Queries are a layer between the forms and tables such that they obtain the conditions from the forms and deliver it to the tables. Then, the records that are compatible with the conditions are selected and shown in output form. The queries are an essential part of our database that allow users to select between hundreds of records of information. In the following sections, how queries are formulated will be explained in more detail, but in general the user is shown a set of pop-up menus in each step, based on what kind of information the user is looking for and the information actually available in the database. This method seems to be the optimum method to extract the desired data.

3.3 GENERAL OVERVIEW OF THE INFORMATION IN DATABASE

This database contains the following types of information:

- Nonstructural components commonly used in commercial buildings:
    - *Taxonomy of nonstructural components: the classification of nonstructural components according to their functionality, representing modes of failure, sensitive response parameter, and repercussions of damage to the components*
- Damageability of nonstructural components:
    - *Fragility curves of nonstructural components*
    - *About 4000 documented reports of performance of nonstructural components in previous earthquakes*
    - *More than 1000 images of damaged nonstructural components in previous earthquakes*
- Costs and losses of nonstructural components:
    - *Information of about 200 nonstructural components commonly used in buildings, along with costs and photos for some selected components*

- *Cost breakdown of 23 different types of buildings*
- *Cost functions of nonstructural components for different damage states*

3.4 DATABASE MAIN PAGE

The PEER Nonstructural Component Database starts with the following page. The user accesses the database by pushing the “Start” button, or “About” to read information about the database.

Figure 3.1 Main page of the database

4 Damageability of Nonstructural Components

The estimation of damage of structural and nonstructural components and the contents of buildings during earthquakes is an essential part of the loss estimation and performance assessment of buildings. Damage estimation requires a study of the performance of the components in previous earthquakes or laboratory experiments. The output of these studies transform into fragility curves that are used in probabilistic structural analysis to assess the performance of the building in a specific earthquake or to derive the economic loss due to damage to the components.

In this chapter, the concept of a fragility curve is explained. The methods to collect information for fragility curves are presented first, and a sample fragility curve is shown. Next, the information collected in the database from previous earthquakes is explained. What the available data are and how the database can be accessed to retrieve the information are shown.

4.1 FRAGILITY CURVES

In loss estimation, one of the important steps toward the evaluation of the total loss in buildings during an earthquake is the "fragility curve," the relation between the structural response and the damage state of the component. In this section, a brief explanation of fragility curves will be presented. Then, the different sources of information for the development of fragility curves are explained, ending with the development of a sample fragility curve.

4.1.1 Definition of Fragility Curve

A fragility curve is a relation between a structural response parameter, or *Engineering Demand Parameter* (EDP), and the probability of exceeding a specific state of damage. Figure 4.1 shows a typical fragility curve. The horizontal axis is the *EDP* and the vertical axis is the probability that the damage exceeds the damage state.

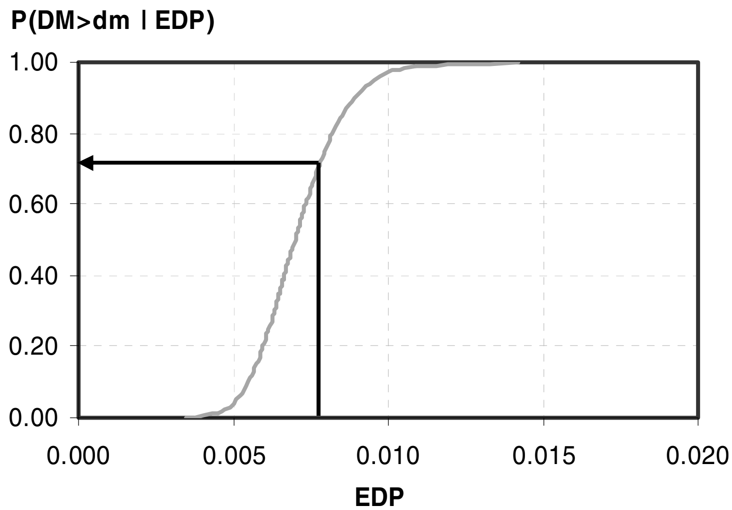

Figure 4.1 A typical fragility curve

There are two *EDPs* that are well correlated to damage in a building, and hence are particularly useful in performance-based earthquake engineering:

- Maximum interstory drift ratio (IDR)
- Peak floor acceleration (PFA)

Almost all structural components are damaged as a result of structural deformation resulting from lateral deformations; thus the IDR provides a good measure of possible damage to the structural elements. A large portion of nonstructural components are sensitive to IDR, but other nonstructural components are vulnerable primarily as the result of inertial forces. Elements that are hung from the floor slabs and beams, such as many mechanical and electrical components, ceilings and contents, are examples of acceleration-sensitive components. Some components are sensitive to both IDR and PFA. Elevators have rails, doors, and other components that are damaged primarily by interstory drift ratios, while other elevator components, such as the motor and counterweights, are damaged as a result of floor accelerations.

Several performance levels should be defined for the performance-based design of structures and for nonstructural components. By defining intermediate damage states for components, we are able to represent the behavior of components more precisely, and as a result, loss estimation will be more accurate. Damage states are dependent on the modes of failure of each component and therefore vary from one component to another.

The primary type of information required to develop fragility functions is a description of the damage, together with information about the intensity of the structural motion (*EDP)* at which the damage occurred. This allows the establishment of Damage-Motion, or Damage-Measure, (*DM-EDP)* pairs.

4.1.2 Source of Data for Development of Fragility Curves

The information for developing fragility curves has been obtained primarily from the performance of components in previous earthquakes or from experimental data. In the following sections, each of these sources of information is explained in more detail.

(a) Experimental results

Experiments are one of the most reliable sources of data to study the progress of damage in components as a result of applied loads, since everything in an experiment is monitored closely. While practically all experimental research reports the mode of failure and the level of loading or deformation at which the failure is produced, a detailed description of the different levels of damage is not always reported.

(b) Data from instrumented buildings

Despite considerable reports in existence about damage and performance of nonstructural components in previous earthquakes, many have not been carefully documented.. There are a number of instrumented buildings around the world that would have provided good information for the development of fragility curves if the damage to components had been well documented. By having a detailed description of damage and the response of the instrumented structure, damage-motion pairs can easily be developed. Since only a relatively small number of the total number of buildings are instrumented, and detailed damage inspections have been conducted only in a small portion of them, in most cases the amount of information for the development of fragility functions from this potentially excellent source has been rather limited.

(c) Data from non-instrumented buildings

A less reliable but more readily available source of information is non-instrumented buildings for which ground motion records were obtained at a nearby site and for which detailed damage inspections were conducted after the earthquake. In these cases, it is possible to estimate the level of motion in the structure by structural analyses, hence providing a way to establish damage-motion pairs at all levels in the structure and for different types of nonstructural components.

In many cases there will not be enough information to develop detailed structural models. In other cases, even if this information is available, these models can only be developed for a relatively small number of buildings. Hence the use of simplified analysis tools is particularly useful in these cases. There are some approximate methods to estimate the response of the structure including IDR (interstory drift ratio) and PFA (peak floor acceleration) without performing exact finite element dynamic analysis. Miranda (1999) has presented an approximate method to estimate the maximum roof displacement and IDR based on a simple model which uses some basic information of the structure which can be estimated easily. Also Miranda and Taghavi (2003) have a method to estimate peak floor acceleration based on the same model.

4.1.3 Sample Fragility Function

In the following, an example for developing a fragility curve is shown. The data are based on an experiment done by Rihal (1982) on drywall partitions. The specimen under study is an 8' x 8' drywall partition on 3-5/8″ metal studs. The load pattern and test setup is not important and the reader is referred to the paper for more details. Two damage states have been identified during the test, "visible damage" "and significant damage." Visible damage occurs first. At this stage, the partition needs taping and painting for repair. As the load increases, the damage state changes from visible damage to significant damage. At this stage, the partitions have to be demolished and replaced. The construction of fragility curves explained before are based on the test results, and the fragility curve of drywall partitions for two damage states can be derived, as shown in Figure 4.2.

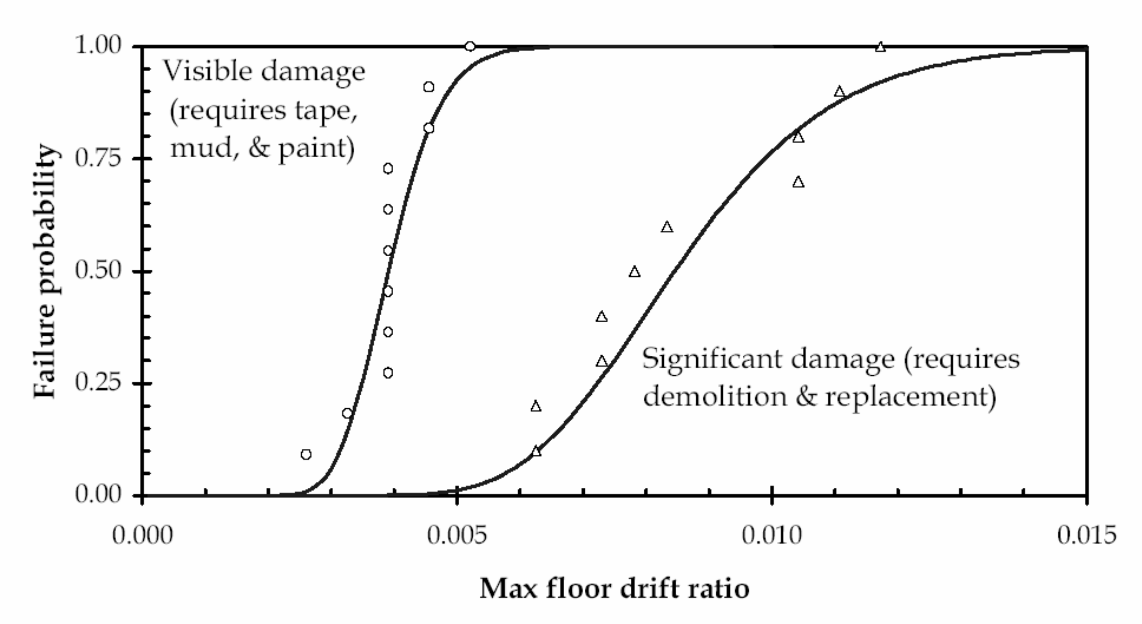

Figure 4.2 Fragility curve of a drywall partition on 3-5/8″ metal stud (Porter et al., 2001)

4.2 DIGITAL IMAGES OF DAMAGED COMPONENTS

4.2.1 Data Structure of Digital Images

Actual photos of damaged components give significant insight to the performance of nonstructural components. The common states of damage can be observed only by looking at what has happened to components in real earthquakes. Around 1100 photos taken in previous earthquakes from damaged components have been gathered in the database. Thus the user can figure out the most common types of damage to components and use this information in their future design. The photos have mainly been collected from the NISEE Image Database (**http://nisee.berkeley.edu/eqiis.html**), the EERI slide collection (1997), and images taken by the authors.

In this part of the database, for each record, there are six fields of information:

- Photo
- System (e.g., Electrical)
- Component (e.g., Lighting and Power)
- Earthquake Name (e.g., Northridge, California, January 17, 1994)
- Building Name

- Damage description

The definition of the system and the component is the same as that shown in Chapter Two and each record is classified according to its system and component. The additional data are the name of the building. For each photo, a detailed description of damage is available.

4.2.2 Data Acquisition from Database

Figure 4.3 shows a typical tool used in many parts of the database as a search interface between the user and the program. As can be seen, the system and component can be selected. If a specific nonstructural system is selected, all components related to that system are shown in the second menu. Instead of a specific system, the user also can choose “Any” to look into all the records. Additionally, if the system is selected and the user chooses “Any” in the component level, all the components with the same system are shown. This method gives more flexibility to the database and its query system.

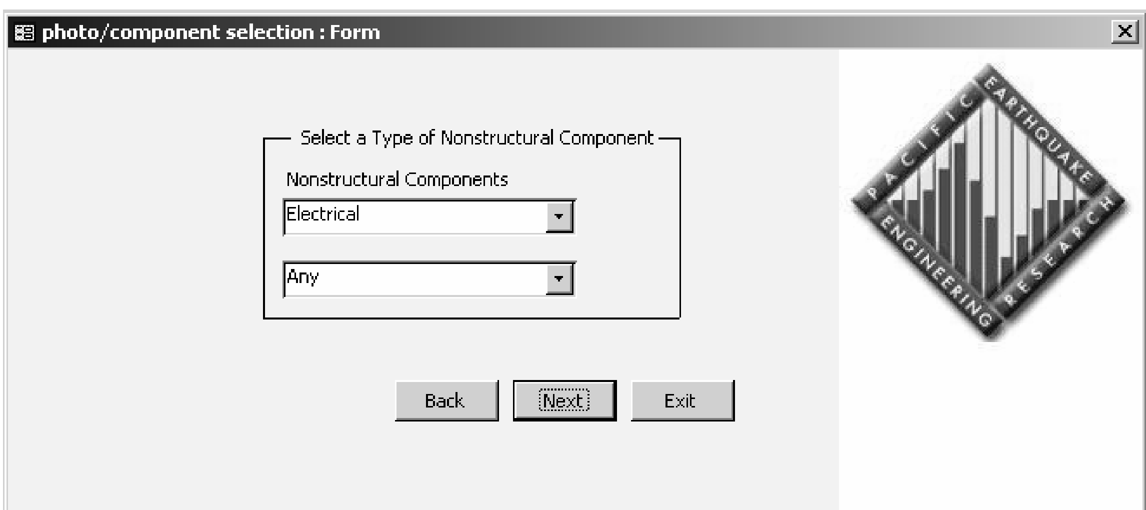

Figure 4.3 Typical interactive window used to build queries

A sample output of the database is shown in Figure 4.4. All six fields of information are shown in the output window. The following sample is an electrical system related to lighting and power components of a junior high school damaged in the 1994 Northridge earthquake. A larger view of the photo can be seen by clicking on the photo.

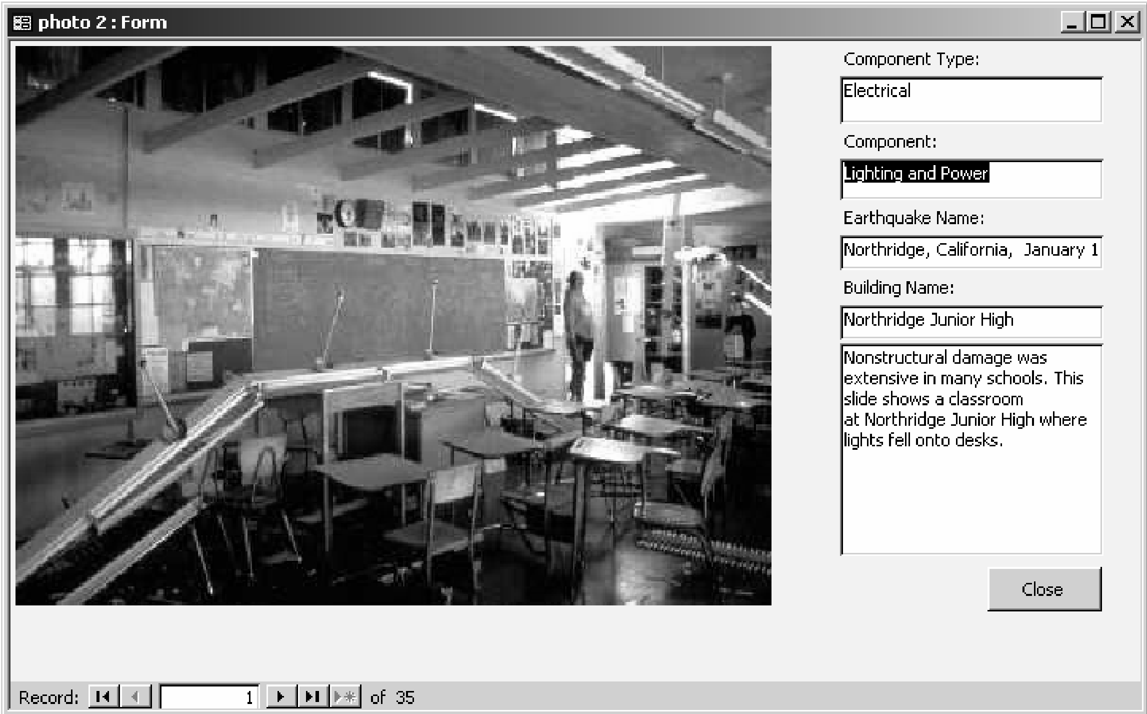

Figure 4.4 Output window for a damaged light fixture

4.3 PERFORMANCE OF NONSTRUCTURAL COMPONENTS IN PREVIOUS EARTHQUAKES

One of the main purposes of developing this database was to classify damaged components reported in previous earthquakes. The database is built on a database developed by Soong et al. (1999). That database provides valuable information gathered from more than 40 earthquakes, with approximately 3000 records about the damage to components, structural response for some of them, and information about the building and earthquake ground motion parameters. The data in this database have been collected from around 100 references listed for each record. Although the database is very informative in general, as noted previously, it has some disadvantages. For example, the data are not classified and the user is often not able to obtain the data wanted, partly because the database does not have a search engine. These disadvantages, along with valuable information this database does provide, motivated us to use its structure to develop a new database with improved capabilities.

The new database is partly based on the information from the Soong database, with additional information from the authors based on the study of the performance of components in previous earthquakes. The total number of records is more than 4000. The records are classified according to their system and components. Therefore it is possible for the user to search for a specific system or component. Also the records are classified based on the earthquake in which the damage has occurred. Another classification has been performed on the functionality of the primary structure. For example, it is possible to look for the data coming from hospitals and office buildings separately. Another field was added to the database to show the sensitive structural response parameter of the component.

4.3.1 Data Structure of Component's Performance Database

For each record of information are data regarding the component, damage, structural response, structural system, ground motion, and reference. These can be classified into the following four groups:

Building information: Building name, structural information (i.e., structural type, foundation, soil type); Building usage (Hospital, office, etc.); Location (i.e., distance from epicenter of earthquake); station number (i.e., number of the station recording the motions of the building); height (i.e., number of floors of the building).

Earthquake information: Name of earthquake (Northridge, Loma Prieta, etc.); earthquake magnitude, peak ground acceleration in horizontal direction (PGA H); peak ground acceleration in vertical direction (PGA V).

Damage information: System (Electrical, Mechanical, etc.); component (Doors, walls, cooling systems, etc.); damage description, damage level, floor (i.e., the floor in the building related to the damaged component); cost of repair (if available); photo (if available); drift (i.e., level of drift that the component has seen during the earthquake), floor acceleration (i.e., peak floor acceleration that the component has seen during the earthquake, drift sensitivity (i.e., "checked" if the component is drift sensitive, "Unchecked" if the component is not drift sensitive); acceleration sensitivity (i.e., "checked" if the component is acceleration sensitive, "Unchecked" if the component is not acceleration sensitive).

Reference information: Author, title, year of publication

4.3.2 Data Acquisition from Component's Performance Database

The available data can be retrieved using the search tool provided in the database. This search engine helps to narrow the range of information to find the desired data. The search engine is a sequence of windows that prompts the user to select a group of components. In the following, all steps and forms used in the search engine are shown:

Step one: Sensitivity

The components are classified based on their sensitive response parameters. Some of the components are drift sensitive, which means that the damage in these components is correlated to drift only. Partitions are an example of these components. Other components are only acceleration sensitive. This set of components is sensitive to acceleration, and damage states can be defined based on the acceleration of the component. Suspended ceilings are an example of these kinds of components.

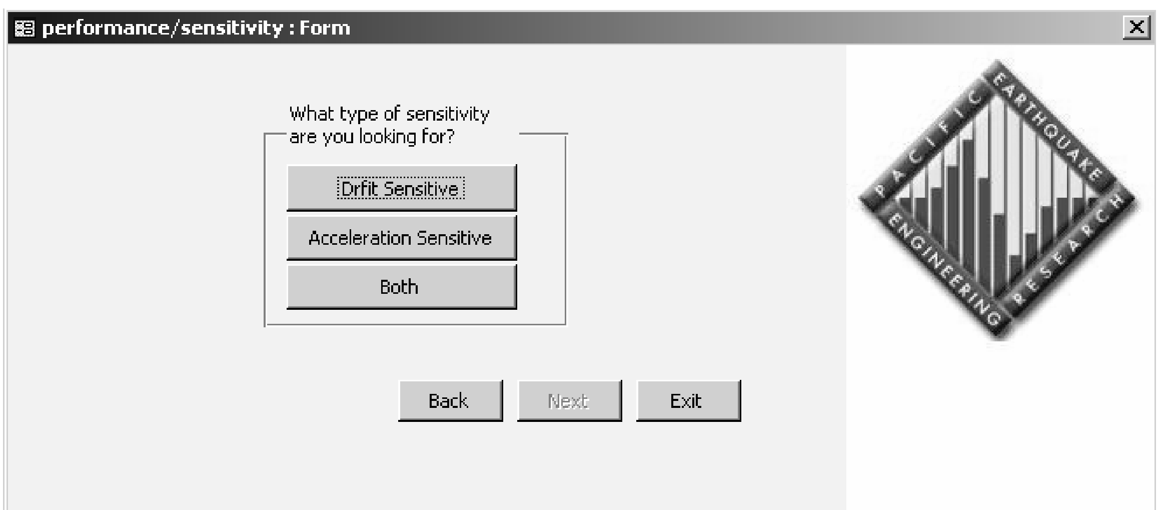

Figure 4.5 Interactive window for choosing sensitive parameter of component

There is another group of components that is sensitive to both drift and acceleration. In these components, both drift and acceleration can cause damage. Elevators are an example of this set of components, since some elevator components get damaged by acceleration and others by drift. Figure 4.5 shows the window for selecting the sensitive response parameter.

Step two: Type of component

The nonstructural system and component is selected at this step (Fig. 4.6). The selection tool is similar to what was previously explained.

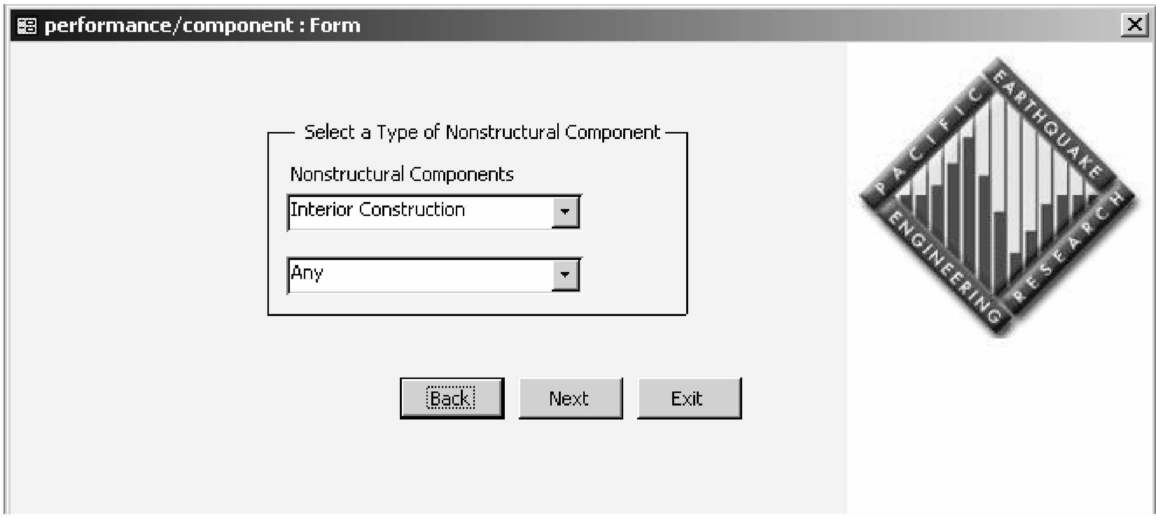

Figure 4.6 Interactive window for choosing the nonstructural component

Step three: Earthquake

This option lets the user study the damage to nonstructural components in a specific earthquake. This is useful because the type and level of damage may vary from earthquake to earthquake. The user is able to choose "Any" to see the information for all the earthquakes or to select just one of them (Figure 4.7).

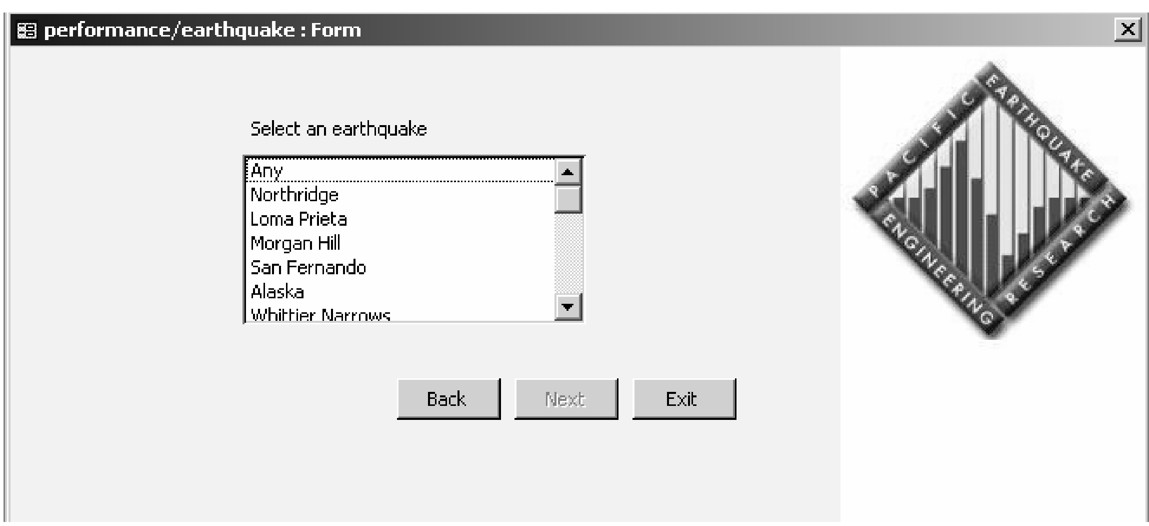

Figure 4.7 Interactive window for choosing a specific earthquake

Step four: Building functionality

As the last step, the user can select the information related to a certain type of building. Each item in the database is also classified according to the functionality of the primary structure; therefore the user is able to look for types of damage that have occurred in just a certain type of building such as hospitals or offices (Figure 4.8).

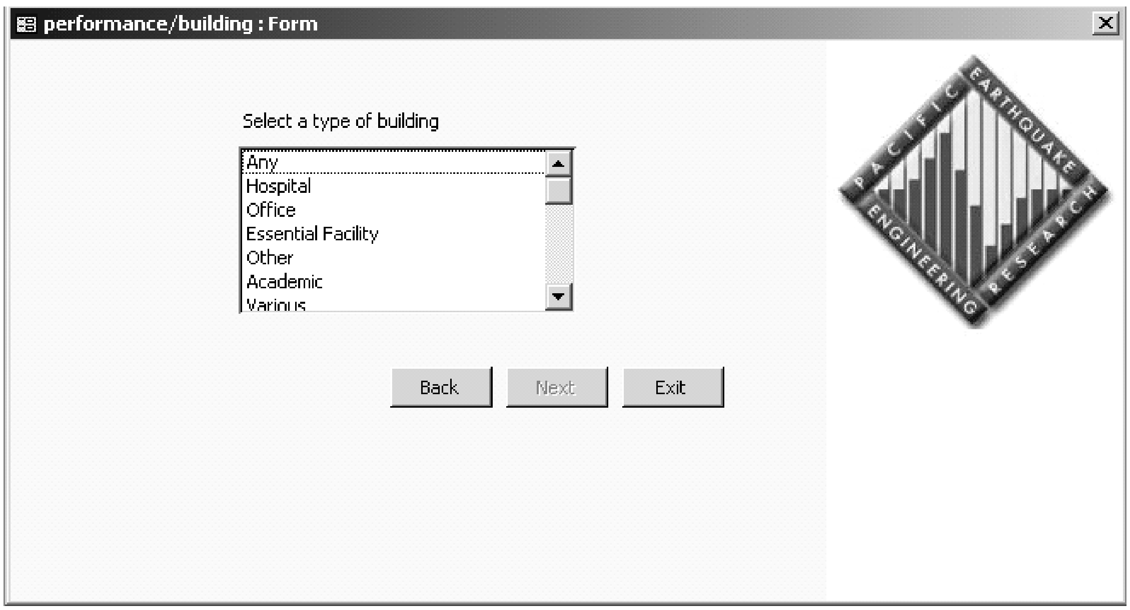

Figure 4.8 Interactive window for choosing between different types of buildings classified according to their functionalities

Figure 4.9 shows how the database presents information about the performance of components in previous earthquakes.

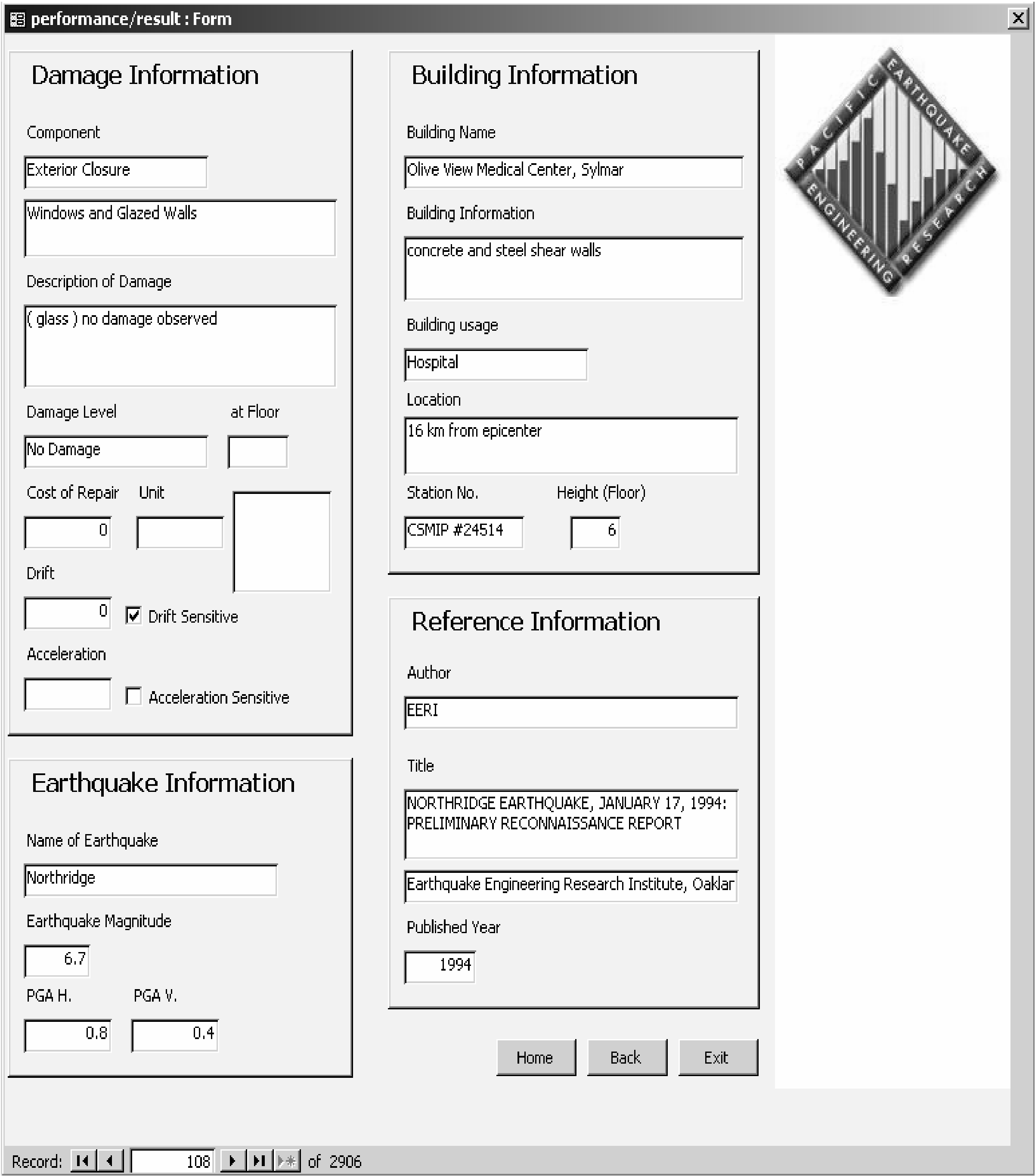

Figure 4.9 Presentation of performance of nonstructural components in previous earthquakes

4.4 TYPICAL DAMAGE TO NONSTRUCTURAL COMPONENTS

Damage to nonstructural components during earthquakes has been investigated by several researchers. Additionally experiments have been done to learn about the behavior of nonstructural components due to external loads. In the following, a summary of these studies is shown about the behavior of these components in previous earthquakes and experiments. For each component, the different states of damage that were commonly seen in previous earthquakes are explained. For more information about the damage and references, see the computer database.

4.4.1 Interior Construction

(a) Suspended ceilings

In a suspended ceiling system, the first damage realized during a seismic event tends to be to the acoustical tiles. Typically, these get dislodged and fall first around the perimeter of the room and around interior columns. In some buildings, the ceiling tiles are equipped with safety wires to keep them from falling. Under intense ground motions, damage to the grid frame and/or suspension system also takes place. The pounding of the ceiling against perimeter walls or columns, or the movement of fixtures embedded in the ceiling, can dislodge runners. Similarly, collisions with walls and columns, or moving piping and ductwork between the ceiling and the next floor can damage or cause failure in the suspension system. As to which occur first, it depends on the construction of each building. Systems with splay wires or struts outperform those without them. Water damage is also common in suspended ceilings, when an earthquake damages plumbing or fire sprinkler systems above the ceiling.

Figure 4.10 Olive View Medical Center, Sylmar, California, ceiling panel dislodged (NISEE Steinbrugge collection, photo by Robert Reitherman)

Figure 4.11 Medical Treatment building, Sylmar, California, ceiling failure (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(b) Non-suspended ceilings

Nonsuspended ceilings tend to be drywall, or plaster on a lath. Initial damage consists of minor cracking to the drywall or plaster. The cracking tends to get worse with intense ground motions. Some ceilings have insulation flocking, which will be shaken loose in an earthquake. In older buildings, the flocking sometimes contains asbestos, which can become airborne if pulverized.

Some ceilings are just plaster on the floor slab of the above floor. Aside from cracking plaster, these ceilings suffer little damage unless there is structural damage to the floor slab. A nonsuspended ceiling may collapse in heavy seismic events if the tie wires separate from the anchorage, or if they fail. Water damage and damage from interaction with sprinklers and other fixtures (pounding) is common in nonsuspended ceilings too.

Figure 4.12 Northridge earthquake, California, collapse of plaster ceiling (Courtesy EERI)

(c) Doors

The most common damage associated with doors is to the frame. Mild damage occurs with cracking of the frame. Sometimes these are only hairline cracks and can be neglected. Worse damage ensues with distortion to the frame. Frame deformation often jams the door in a single position. More severe distortion can result in damage to the door itself, or more commonly to damaged hardware (hinges, locks, door plates). Although it is uncommon for a door to suffer damage without damage to its frame, when part of the door is glass, this type of damage can happen. Sometimes a door will get jammed without damage to the frame. In this case, the hinges may have to be removed and sometimes replaced.

Specialty doors can have a variety of damage and need to be considered on an individual basis, depending on their hardware, location, and use. One example would be a garage door, where damaged or distorted rails of a roll-up door may jam or damage the door. Many times, walls begin cracking around the corners of a door.

Figure 4.13 Medical Treatment building, Sylmar, California, damage to frame (NISEE Steinbrugge collection, photo by Eugene Schader)

(d) Expansion joints

Damage to expansion joints usually begins with minor damage to the architectural covers of the joint located on the ceiling, floor, or wall. Expansion joints themselves may also get damaged in an earthquake, or their pounding may damage other components.

Figure 4.14 Hodge Building, Whittier, Alaska, buckled steel plate covering the 8-inch separation between central unit and west unit (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(e) Floor finishes

Ground motions or contents falling within a building as a result of ground motions often cause chipping or cracking of floor finishes. Tile can pop up and dislodge entirely. Brittle surfaces may shatter and create extensive debris. Damaged sprinklers or piping can result in water damage to wood surfaces and carpets.

(f) Partitions

For the typical plaster partition, damage usually consists of cracking of the plaster. Usually, the cracking is minor and can be repaired easily. However, under severe ground motions, the cracking gets worse and sometimes the wallboard underneath may be damaged. Damage to the wallboard often includes cracking or tearing, or screws dislodging that connect the wallboard to the studs. Other types of partitions (clay tile, masonry, stucco) suffer similar cracking and damage. Cracks in partitions are often located at the corners of interior door frames, or at the junction with the ceiling. The failure of partition walls, most commonly in brittle ones such as clay tile, can damage electrical and plumbing components inside the wall. Water damage from damaged plumbing or sprinklers can affect partitions as well.

Figure 4.15 Tehachapi Institution for Women, Cummings Valley, California, damage to hollow clay partitions (NISEE Steinbrugge collection, photo by Ralph Taylor)

Figure 4.16 Encino Office Park, California, cracking of gypsum wallboard in stairwell (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(g) Wall finishes

Common damage includes plaster cracking and spalling especially around doors and windows, and in stairwells. Severe shaking will lead to cracking of the wallboard beneath the plaster. Other interior finishes or exterior finishes suffer the same type of cracking. Tile finishes may break loose. Sometimes wall finishes may be decorative or historical, in which case damage repair can be very costly. Wallpaper may have to be removed and replaced to evaluate the damage beneath.

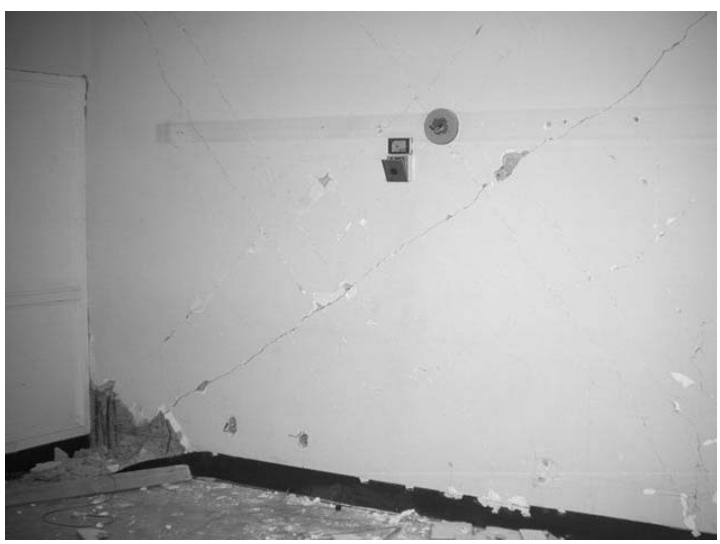

Figure 4.17 Pacoima Memorial Lutheran Hospital, Pacoima, California, crack in shear wall finish (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(h) Stairs

The most common damage associated with stairs is to the walls in the stairwell. Similar to all walls, damage in the stairwell initiates with the cracking of the plaster that, as ground motions intensify, may become more severe and crack the wallboard or infill. Other nonstructural stair damage includes the railings pulling out of the wall.

Figure 4.18 Hill Building, Anchorage, Alaska, damage to stair landing (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

4.4.2 Exterior Construction

(a) Façades

Façade damage is common in earthquakes. Typical materials used as facings are brick, concrete, glass, granite, marble, and ceramic, porcelain, or terra-cotta tile. In seismic events, these often crack and severely under strong ground motions. Façades may fail entirely and fall from the building. Sometimes they are not securely anchored to a building and may fail while the building suffers little other damage. Precast panels of exterior facing or localized pieces of the façade may come down causing damage to other components of the building or to the sidewalk or street below, and may even cause fatalities**.**

Figure 4.19 San Francisco City College, San Francisco, California, failure of 1" adhesion-type ceramic veneer (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(b) Exterior wall finishes

Nonstructural damage to perimeter walls usually consists of cracked plaster or cracking of some other finish surface. Cracks are often focused around windows and doors.

Figure 4.20 Los Palos Grande District, Caracas, damage to exterior walls around windows (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(c) Windows and glazed walls

Before glass breakage, windows sustain a lot of damage. The neoprene rubber packing for windows sometimes works its way out of the frame. For aluminum frames, gaskets may drop out of the frame. The frame, mullions, or sill may crack or buckle. Glass breakage occurs only after the relative movement between the top and bottom of the window exceeds a certain threshold.

Figure 4.21 Kaiser Permanente Building, Granada Hills, California, cladding offset (NISEE Steinbrugge collection, photo by Mark Aschheim)

(d) Parapets

Minor damage induced by earthquake ground motions includes localized, minor cracking, and losing mortar from brick joints. Increased ground motion worsens the cracking. In some cases, the parapets become unstable despite any failure, and have to be replaced or retrofitted. Serious damage begins when blocks begin to fall from the parapet. Often only localized parts of the parapet may fall, but under severe conditions the entire wall may topple causing serious damage as the debris falls onto the sidewalk or street below.

Figure 4.22 Watsonville, California, partial failure of parapet (NISEE Steinbrugge collection, photo by James Blacklock)

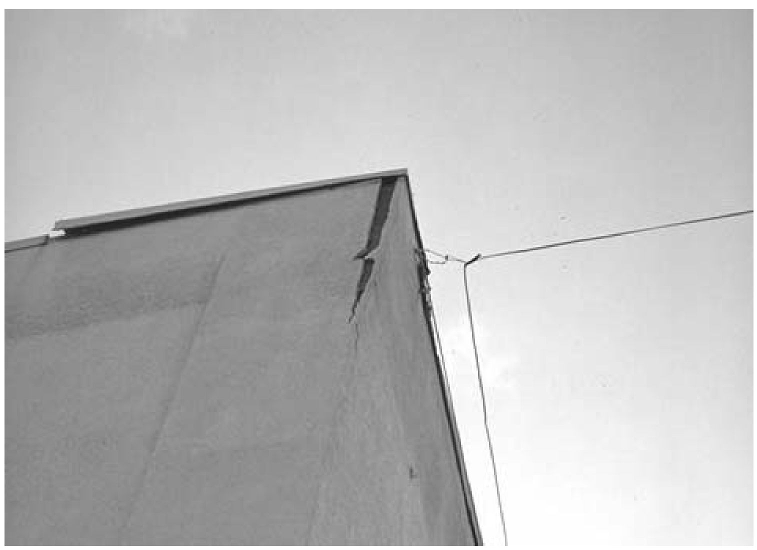

Figure 4.23 Seattle, Washington, crack in parapet still not falling (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

4.4.3 Roofing

Common roof damage includes dislodged roof tiles or damage from fallen debris from other components. Many cases of chimneys rotating above the roofline are reported at residences.

Figure 4.24 Seattle, Washington, damage to chimney and roof tiles (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

4.4.4 Mechanical Components

(a) Cooling systems

Cooling equipment often shifts off supports and moves or falls. Unanchored equipment is especially susceptible to movement. The movement may be a result of, or a cause damage to isolation restraints, which sometimes get bent, and/or anchorage systems. Some of the equipment holds fluids, and leaks may result from shifting or damaged equipment, or from damaged connections. Usually following an earthquake, air conditioning system fixtures have to be checked and minor repairs made. Pipes and ducting connected to moving cooling equipment often break or shift. Bolts serving as anchors, or connecting equipment often loosen or shear off. Equipment pads may crack or sustain other damage.

Figure 4.25 Holy Cross Medical Center, Los Angeles, California, sign damaged by dislodged fan unit (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(b) Ducts

Ducts often shift and/or fall during an earthquake. Seismic motion may cause ducts to twist or rotate, and the relative movement may loosen or fail joints between ducting. The same shifting and/or loosening may occur in the hangers or other duct support systems, which in turn can damage or fail the ducting. Other damage occurs when other equipment shifts or falls onto the ducting, or if a piece of equipment the ducting is connected to suffers damage. Ducting that runs across a seismic joint without an expansion joint may suffer damage to its connections or get torn apart.

Figure 4.26 Four-story building duct failure, Northridge earthquake, California

(c) Fire protection

The most common damage to sprinkler systems is damaged piping. Piping often fails when hit by other components, e.g., the ceiling, or ducting. Also, many times pipe hangers fail, which in turn may damage the piping. Hangers often fail from components falling into them, or because of loosening or shearing of fasteners. Common places for sprinkler piping to fail are at the connection just above the sprinkler heads or at the threaded elbow joint.

Other common damage is that associated with the moving ceiling. The movement of the ceiling during an earthquake stresses the embedded sprinklers, and often damages the sprinkler heads and/or piping at the screwed tee. As a result, all or part of the sprinkler head may have to be replaced, and water damage may ensue. The sprinkler head may also damage the ceiling, requiring repairs there too. The fire sprinkler pump and piping connected to it may also get damaged. Damage to the pump can afflict the rest of the system. Fire extinguishers may pull loose from fastenings and shift position.

Figure 4.27 Olive View Medical Center, Sylmar, California, sprinkler pipe broken at elbow connecting horizontal and vertical pipes (NISEE Steinbrugge collection, photo by Robert Reitherman)

(d) Tanks

Common damage to tanks occurs at the foundations. Often anchorages will suffer damage and bolts may shear. Tanks may move on their supports and in the worst cases, move off supports and topple over. Movement of a tank can cause spillage of its contents, and can damage pipes and other components connected to the tank. Flooding may occur as a result of a tank falling, especially if the tank is mounted on the roof. Buckling of the walls, known as an “elephant foot” can cause leaking and spillage.

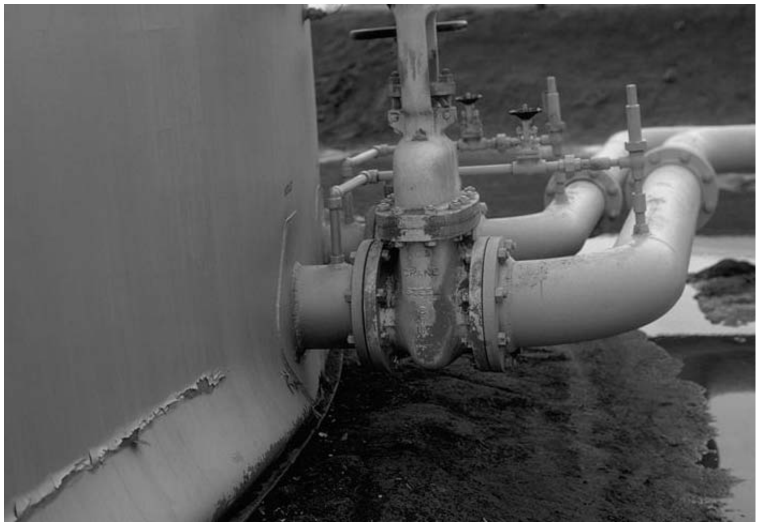

Figure 4.28 Anchorage International Airport, Anchorage, Alaska, buckling of the tank (NISEE Steinbrugge collection, photo by Robert Reitherman)

(e) Plumbing

Common earthquake damage is leaking or ruptured connections and pipes. Differential shaking of pipes may cause connection or pipe failure on its own, or a different component may hit and damage the plumbing. Common pipe damage is located in connections, such as caulked joints, hangers, nozzles, screwed fittings, seals to fixtures, and seismic joints. Damage to plumbing fixtures is also common. Faucets, sinks, and toilets are other commonly damaged plumbing components. Again, leaks are the most common types of damage to these components. Plumbing damage often results in water damage to other components.

Figure 4.29 Hole through copper waste line downstream of kitchen

(f) Heating system

A heating system may be inoperable following an earthquake due to damage to any number of its components. Damage to ductwork and plumbing, which are discussed separately elsewhere, can prevent a heating system from functioning, just like damage can to a boiler or heat exchanger. Boiler foundations can get damaged and boilers can shift. Foundations often get deformed, and/or anchorages may loosen or shear off. The movement of a piece of heating equipment may cause damage to other components near by or connected to it. For example, a shifted boiler may cause a water feed line connected to it to break. Reheat coils often get damaged. Tube reheat coils may get bent, begin leaking, or break entirely.

(g) HVAC

Like other mechanical equipment, common damage to HVAC equipment is breaking from its anchorages and shifting or falling. Sometimes the support frame fails entirely under the equipment. The falling or shifting of the equipment can cause damage elsewhere to equipment connected to it, or to components below. Specific damage to HVAC systems sometimes includes falling ducts and diffusers associated with the HVAC, or separation of two components of the system. Plumbing lines and heating coils may crack or rupture, often at connections. Pump fittings also often sustain damage. Damage to these components are often a result of other components falling on them, pounding damage, or failure of hanger or other supports.

4.4.5 Electrical Components

(a) Communication services

Communication equipment is often down for a few hours following an earthquake. This can be a result of power failures, damage to equipment in the system (amplifiers, antenna, cable connections, phone lines, water damage, or other complications. Earthquake accelerations may trip the switches of telephone equipment, which can throw a communication system into chaos. Computers, switchboards, telephones, and transmission equipment sometimes pull loose from their mounts and can shift or fall inside a building. Racks and supporting equipment may fall, which can lead to damage to the communication equipment supported by it.

Telecommunication lines are often damaged. Above-ground phone lines may fall, underground lines get damaged from ground movement and/or landslides, and cellular sites sustain damage to the instrumentation itself, or to the supporting structure.

Damage to electrical and power distribution includes the failing of power lines or damage to equipment. As with other electrical and mechanical equipment, damage is usually located at the support foundation, and results in shifting or falling equipment. Occasionally damage to equipment will be without moving, but it is usually from other equipment falling into it.

(b) Generators and transformers

Generators are often needed immediately following an earthquake when the power is out. However, many times generators will fail to work, even when not damaged, because they rely on a variety of other components to work, any of which may have been damaged instead. Generators that require batteries to operate may not start if the batteries have been damaged. Also, many generators need cooling water to operate, so if there is damage to their water tanks, or if they get their water from the municipal water supply and this has been shut off following the earthquake, then the generator will shut down.

Common damage to generators and transformers is shifting or getting knocked off platforms. This can be a result of damage to their support structure or damage to the anchorages. Moving generators or transformers can damage other components, including piping and fuel line connections. With transformers, sometimes oil sloshes out through the ceramic bushings. Oil also sometimes will leak through cracks at the “O” rings that are used to seal the units. Earthquake ground motions can trip delicate fail-safe devices on transformers.

Figure 4.30 Anchorage Power Plant, Anchorage, Alaska, shifted transformer (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

Figure 4.31 Olive View Hospital, Sylmar, California, failure of batteries required for standby power (NISEE Steinbrugge collection, photo by Karl Steinbrugge)

(c) Lightings

Damage to light fixtures begins with the failure of the individual components. The lamp itself, light covers, disks, grilles, or any other component sometimes becomes loose or falls. More severe damage occurs when the light fixture support fails. Chain-suspended fixtures may detach from their chain hooks; pendant hung fixtures can fail at their stem supports, swivel joints, or fixture housings; surface-mounted fixtures may become loose or fall from the ceiling; and recessed fixtures can be dislocated or damaged when the ceiling suspension system fails. The most documented type of damage to light fixtures was either loosening or falling of the entire fixture. Some light fixtures have safety wires to prevent them from falling. The movement of light fixtures can also damage the ceiling, or other components.

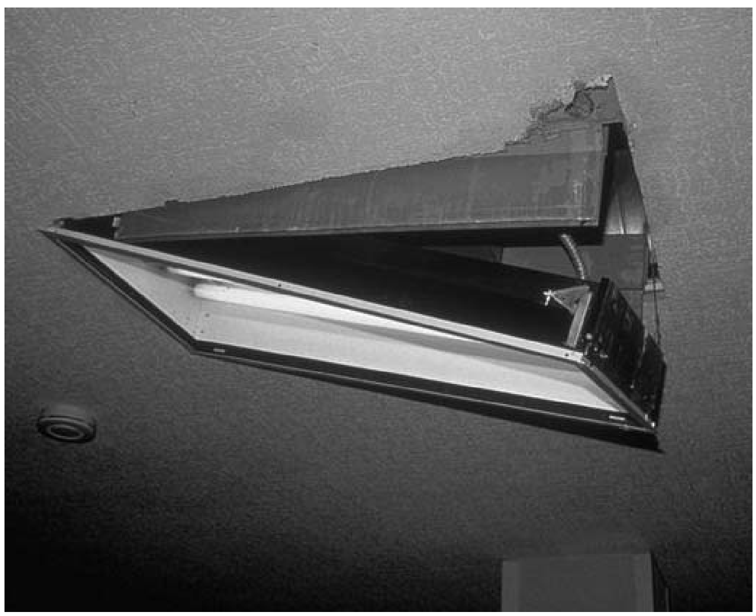

Figure 4.32 Olive View Medical Center, Sylmar, California, light fixture hanging from safety wires (NISEE Steinbrugge collection, photo by Robert Reitherman)

Figure 4.33 Olive View Medical Center, Sylmar, California, light fixture dangling by one safety wire (NISEE Steinbrugge collection, photo by Robert Reitherman)

4.4.6 Conveying systems

Elevators

Elevators are often temporarily inoperable following an earthquake. Many times, an elevator may be inoperable due to a mechanical failure or a loss of power, thus the elevator may be out of commission despite having no damage. Elevator damage usually involves components involved in the mechanical process, rather than the car itself. Controllers, machines, motor generators, governor anchors, stabilizers, and their supports and anchorages are the components often damaged in earthquakes. Cables may wrap around components or get twisted. Damage to hydraulic elevators may include oil pumps, tanks, or piping lines involved in the system. These components may shift or fall, get out of plumb, or rupture. Damage to piping, pumps, or tanks may result in oil leaks.

More serious damage tends to involve shaft walls or the counterweights. Plaster cracking on shaft walls is relatively common under rather moderate shaking. The cracking worsens as ground motion intensifies. Bricks or other debris from different walls may fall and damage the car or make it get stuck. Damage to elevator counterweights is common as well. Counterweights will often come out of their guide rails and will sometimes get tangled with the elevator cables. Moving counterweights may damage other components of the system, shaft walls, or the elevator car itself. Frames supporting the counterweights, counterweight guide rails, and brackets are often damaged when the counterweights begin moving freely. Serious damage includes deformed shaft walls and deformed guide rails. The elevator can become stuck between floors and require substantial repair. Typically, elevators are one of the first components fixed following an earthquake to allow access to other parts of the building. The guide rails of the elevator car rarely suffer damage because they are designed to withstand eccentric live loads and are fastened directly (without brackets) to the structural frame.

Figure 4.34 Union Oil Building, San Fernando, California, elevator counterweights out of tracks (NISEE Steinbrugge collection, photo by Eugene Schader)

4.4.7 Contents

(a) Medical contents

Damage to medical equipment in a hospital is common. Equipment may become inoperable with insufficient resources to run them. For example, radiology services may not be available during a power shortage or when no water is available to develop the film. Contents often fall off cabinets, shelves, and out of drawers. Blood analyzers, lab equipment, x-ray machines, or other sensitive equipment not securely anchored may also get damaged. Biological, chemical, and pharmaceutical spills in a hospital can be a costly and hazardous mess to clean up.

(b) Office contents

Common interior damage includes damage to shelving and cabinets, and spillage of contents. In libraries, unanchored shelves may list 30-45 degrees without falling. In laboratories, spilled chemicals can pose serious clean-up complications. In houses, damage to appliances, artwork, china, and clocks are common. Fallen computers and other electronic equipment can be expensive to replace. Water damage can be extensive and costly. Unanchored contents and equipment can slide across rooms and damage other equipment.

Figure 4.35 Medical Treatment Building, Sylmar, California, interior of medical treatment building (NISEE Steinbrugge collection, photo by Eugene Schader)

5 Costs and Losses of Nonstructural Components

In most buildings, the biggest contributor to economic losses resulting from earthquakes is damage to nonstructural components is primarily because the nonstructural components represent a large percentage of the total construction cost.. For example, in the case of commercial buildings, nonstructural components typically account for 65% to 85% of the total cost of the building. Hence, there is far more investment at risk with these components than with structural components. Unfortunately, nonstructural components have been treated as secondary components, since the theory driving building codes has been to protect the structure and not the components. Recent attention to nonstructural components comes from the development of performance-based design, in which the performance of a building in an earthquake is defined not only by the performance of the structural components, such as beams and columns, but also by that of the nonstructural components and contents, such as ceilings and windows. Therefore, identification of the nonstructural components used most often in buildings and their contribution to the total building cost are the primary steps toward a more comprehensive performance assessment and loss estimation of buildings as a result of damage to these components.

In this chapter, the types of data collected in the database regarding common nonstructural components and their cost contribution to the total cost of buildings are considered. Cost functions are also explained and a sample cost function is provided.

5.1 TYPICAL NONSTRUCTURAL COMPONENTS AND THEIR COSTS

Identification of common nonstructural components in buildings provides better understanding of what is going to be attached or built into the building, and therefore allows engineers to design these components properly. A section of the database has focused on the nonstructural components that are most commonly used in buildings. More than 200 components including interior constructions such as ceilings, partitions and doors; exterior closures such as windows, parapets and claddings; mechanical systems such as piping, fire sprinklers, and boilers; electrical devices such as generators, lightings, and wiring; and conveying systems such as elevators and escalators, are listed in the database.

For each component, the following information is available in the database:

- Description of the component
- Cost of material
- Cost of installation
- Photo of the component (for some components)

The costs presented in this section are based on R.S. Means Co. (2001a, b). The records have been classified according to Means (RSMeans, 2001a). Interior constructions, mechanical systems, or electrical systems are examples of systems. In the next step, each system is classified into components, e.g., windows or doors as interior construction. Using this classification, the user is able to find the desired information without browsing through all the components. Figure 5.1 shows how the database has been designed to allow the user to search for the desired information.

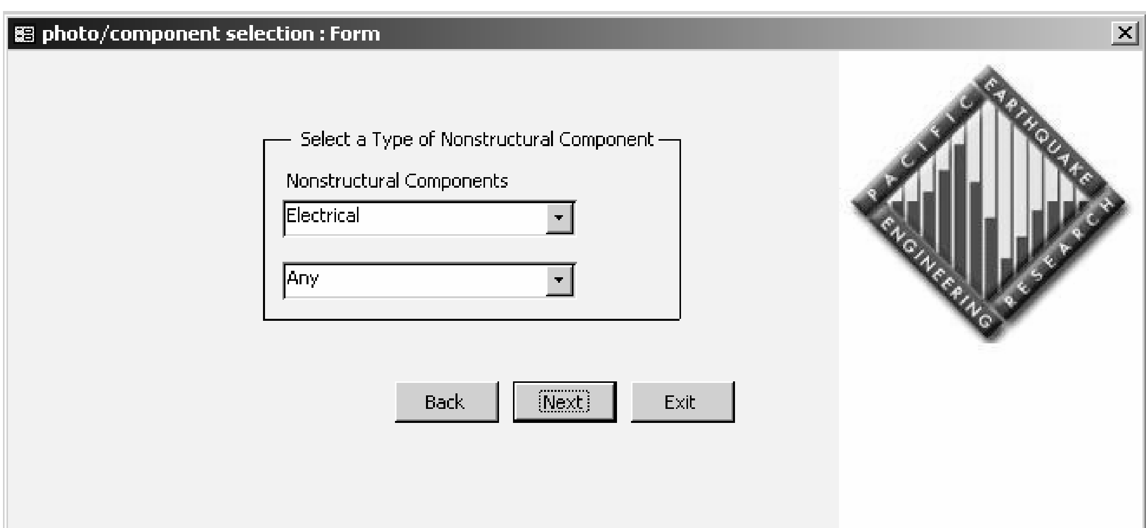

Figure 5.1 Typical interactive window used to build queries

Figure 5.1 shows a typical tool used in many parts of the database that is a search interface between the user and program. As can be seen in Figure 5.1, the system and component can be selected. If a specific nonstructural system is selected, all components related to that system are shown in the second menu. Also instead of a specific system, the user can choose “Any” to look into all the records. Also if the system is selected and the user chooses “Any” in the component level, all the components with the same system are shown. This method gives more flexibility to the database and its query system.

Figure 5.2 is a sample output of the database regarding common components and basic information of the component. A larger view of the photo is shown by clicking on the photo.

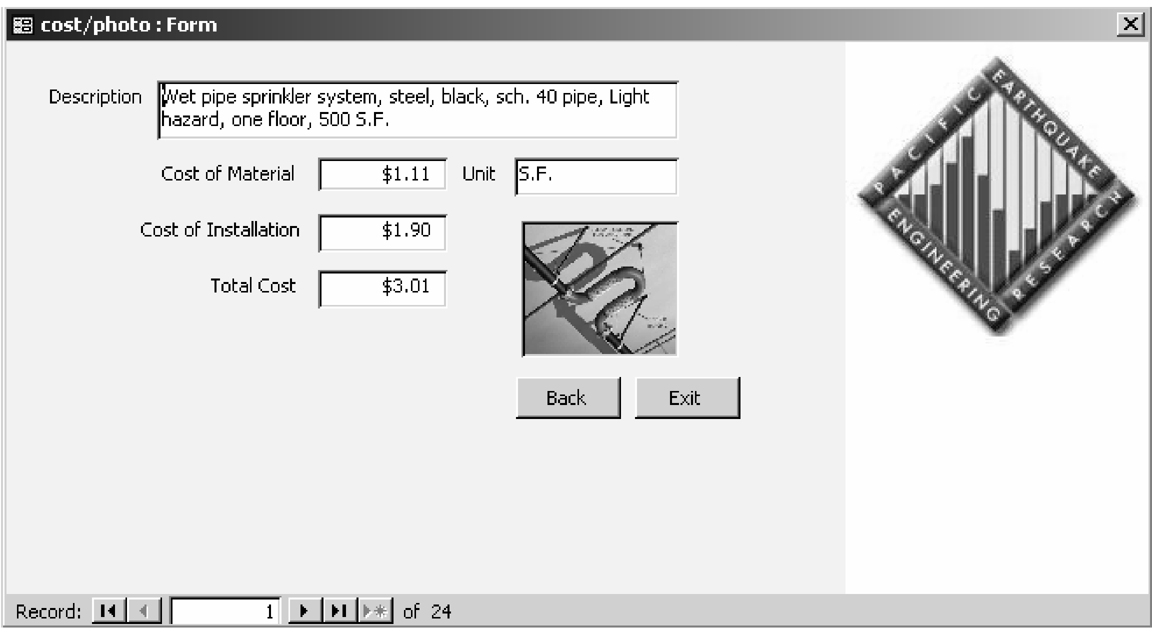

Figure 5.2 Output window for cost information of common nonstructural components.

5.2 COST BREAKDOWN OF BUILDINGS

It is important and useful to know how this 60%–80% of the cost of buildings spent on nonstructural components is distributed since they constitute the biggest portion of the total investment risk.

5.2.1 Cost Data and Input/Output Forms in Database

Information detailing costs of structural and nonstructural components of 23 buildings is presented in the database. The costs are based on R. S. Means (2001a). The same classification of components explained before are used for systems and components. For each building, data are presented in one of the following three formats:

- Typical components with descriptions of the most common types of components used for that specific type of building
- Typical components along with cost per square foot of the components
- Typical components along with cost percentages of the components

The following window (Fig. 5.3) is used to select between these three categories and also for selection of the building. For each building type, there are several samples according to the number of stories.

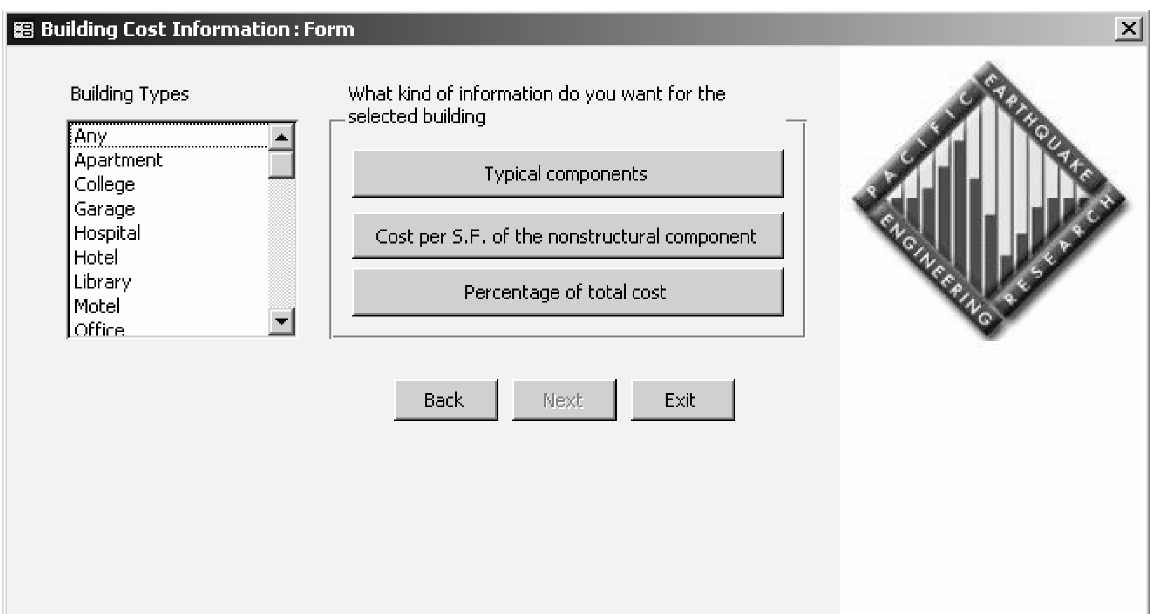

Figure 5.3 Interactive window for selection of different kinds of buildings and format of the output results

Total cost of each system per square foot or total cost percentage of component and also total cost of nonstructural and structural components per square foot or in percentage format are presented for each building. Since the cost is a function of the time and location of construction of the building, the modification to these costs in the database has been according to selection of a specific city and year of construction.

Figure 5.4 shows a sample building with a brief description of components, cost per square foot of components, cost per square foot of systems, total cost of structural and nonstructural components, city of construction, year of construction, building type, and number of stories.

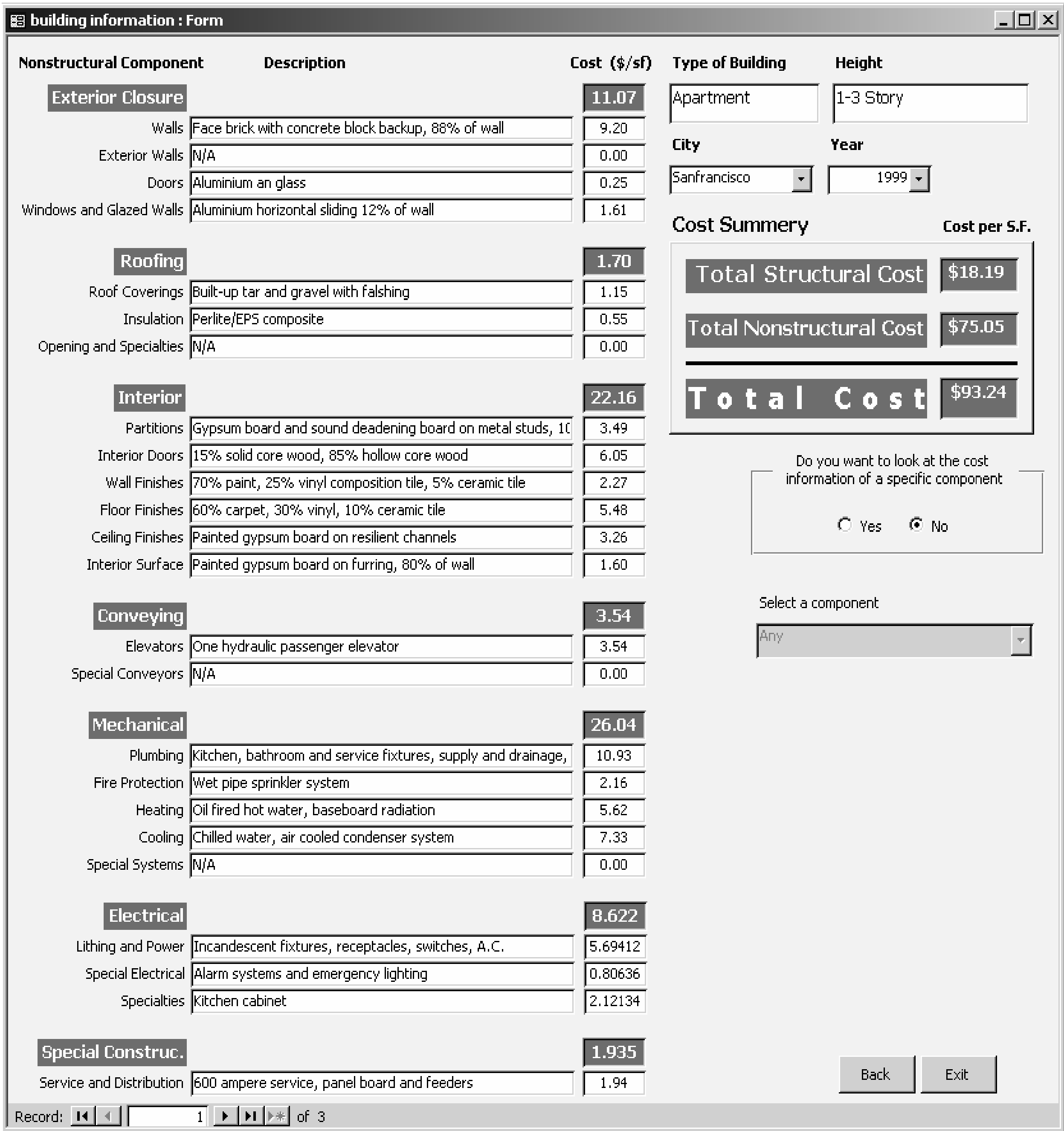

Figure 5.4 Dollar cost breakdown of a typical 1–3 story apartment

Figure 5.5 shows the same building except that the cost percentages are presented instead of actual dollar cost per square foot.

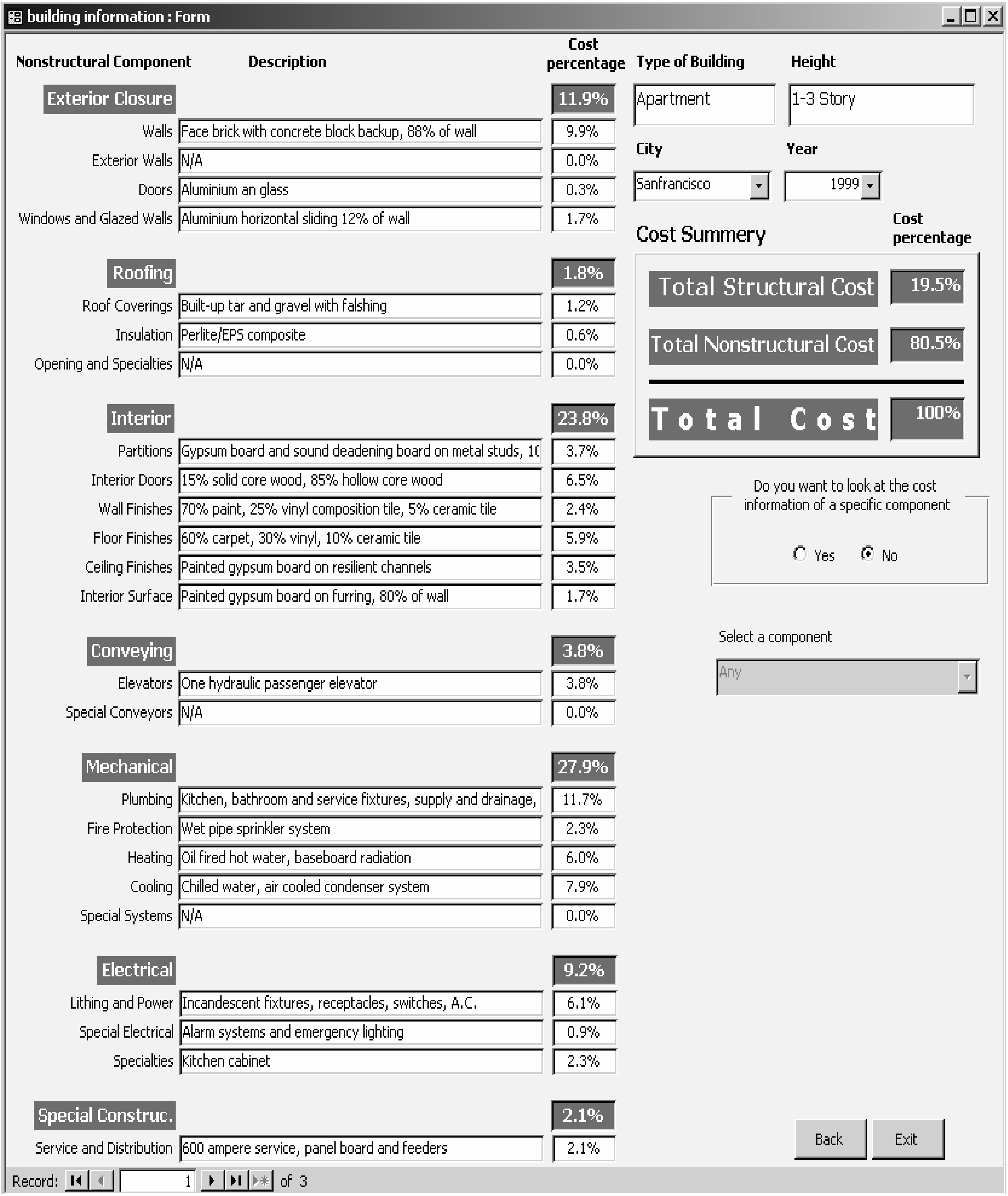

Figure 5.5 Cost percentage breakdown of a typical 1–3 story apartment

5.2.2 Cost Distribution Study of Some Example Buildings

Various types of buildings were investigated to study the cost distribution of the different components of buildings. In the first effort, the total building cost was divided into the cost of structural components, nonstructural components, and contents. Figure 5.6 presents the cost distribution of three sample buildings including hotels, office buildings, and hospitals. It can be seen that office buildings have the largest portion of structural costs, which is still only 18% of the total cost of construction. The same figure shows that for hotels, this value reduces to 13%, and for hospitals; as low as 8%.

The cost of nonstructural components is highest in hotels, where approximately 70% of total construction costs are nonstructural. This value is 62% in office buildings and 48% in hospitals. Based on these numbers, it can be seen that the ratio between the cost of structural to nonstructural components is 29% percent, 19% percent, and 17% for office buildings, hotels, and hospitals, respectively.

Contents also make up a significant portion of the total cost. As expected, hospitals have considerable inventories of expensive medical equipment that, according to our study, makes up 44% of the total cost of hospitals. This number reduces to 20% for office buildings and to 17% for hotels. The following graph shows this cost breakdown for the aforementioned buildings.

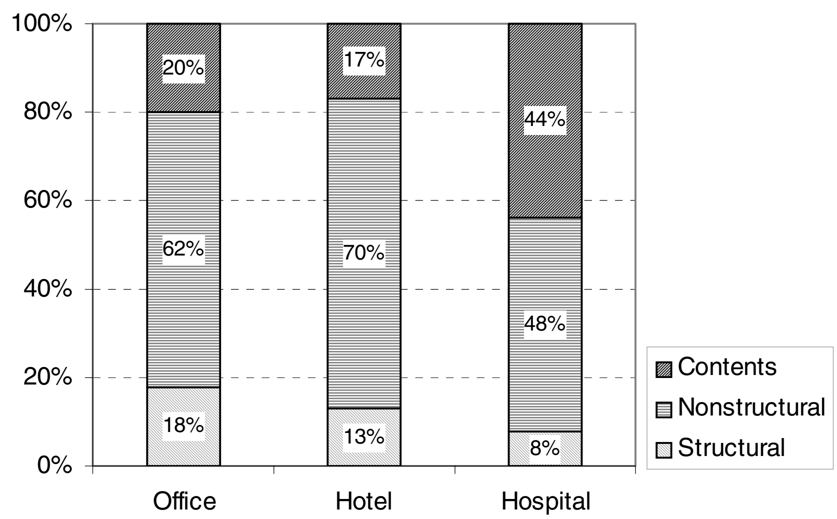

Figure 5.6 Cost breakdown of office buildings, hotels, and hospitals

The following graph (Figure 5.7) has been constructed based on the information collected in database. It shows how the contribution of different nonstructural systems may vary when the functionality of the building changes. This example shows the cost distribution for a mid-rise apartment, hospital and office building, and a high-rise hotel. In all, mechanical systems and interior constructions are the major source of cost (from 20%–30%); electrical systems and exterior closure make up almost 10% of the total cost, with about 5% of the total cost spent on elevators or escalators.

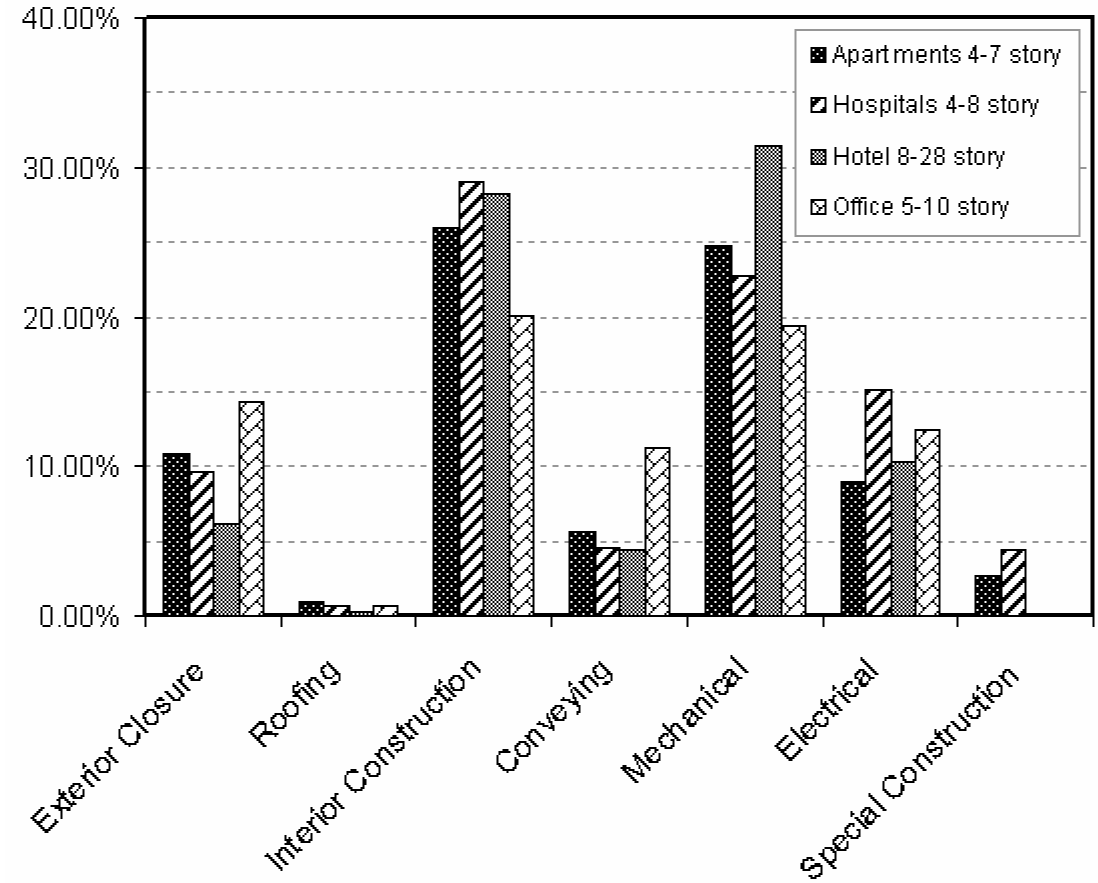

Figure 5.7 Nonstructural components cost breakdown of four sample buildings

5.3 COST FUNCTIONS

5.3.1 Representation of Cost-Damage Relationship

Aside from the fragility function, another piece of information that is needed in loss estimation and the performance assessment of buildings is the loss function. Loss functions represent the probable loss of a component in the event of an earthquake for each damage state of the component. A rational way to account for the uncertainty in the cost of repair or replacement of a component is through the use of a probabilistic cost function, which describes the probability of exceeding a certain cost given a certain damage state. Hence a cost function describes the probability of exceedance of the repair or replacement cost conditioned on the damage state. An example is shown in Figure 5.8. The horizontal axis is the ratio of the repair cost to the cost of a new component, and the vertical axis is the probability that the ratio of the repair cost to the cost of a new component is less than the value on the horizontal axis.

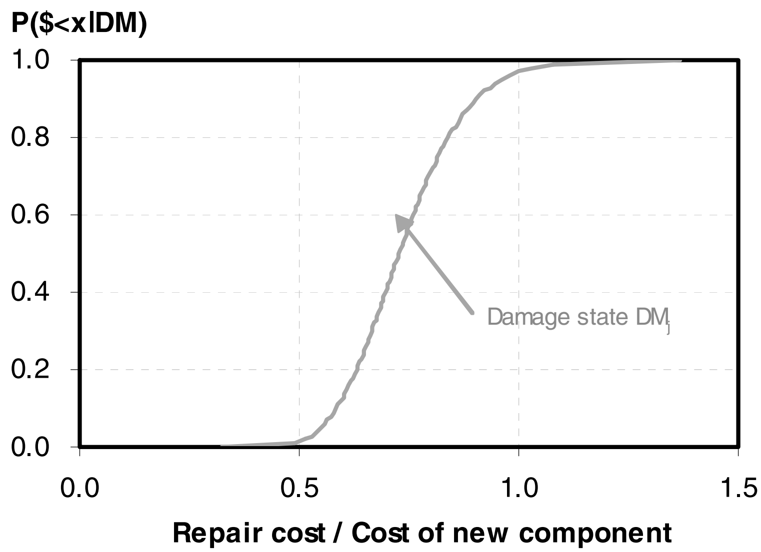

Figure 5.8 Repair cost cumulative probability distribution for a specific damage state

5.3.2 Example of Development of Repair Cost Function

In the following, the development of a damage state-cost relation is shown for a drywall partition. The following steps must be completed to develop the curves:

(a) Identifying different parts of the component

For a drywall partition on metal studs, the following items constitute the total cost of the component:

- *Metal studs 3-5/8" 16" O.C.*
- *Gypsum board 5/8" on both sides*

- *Tape and paste*
- *Paint on both sides*

(b) Defining damage states

In this study it is proposed that the damage states not only represent different levels of physical damage, but also levels of damage associated with different repair actions. For the component under study, three damage states are defined as follows:

- *Damage state 1 — Cracking that can be repaired with tape, paste and paint*
- *Damage state 2 — Replacement of gypsum boards but not the frames*
- *Damage state 3 — Total replacement*

(c) Relating the items in step 1 with each damage state in step 2

- *Damage state 1:* Tape and finish; paint with roller on both sides
- *Damage state 2:* Removal of damaged gypsum boards; gypsum board 5/8" on both sides; Tape and finish, paint with roller on both sides
- *Damage state 3:* Removal of damaged gypsum boards; removal of damaged metal frames; metal studs 3-5/8" 16" O.C.; gypsum board 5/8" on both sides; tape and finish; paint with roller on both sides

(d) Cost evaluation for each damage state

At this step, for each damage state, the repair cost has to be evaluated according to the items that were shown in step 3. The costs must be gathered from several sources such that the total repair cost can be presented in the probabilistic format explained earlier.

In the following, the cost evaluation of this component is based on R. S. Means (2001a, b) and also on some assumptions for the cost of removal that appears at damage states 2 and 3.

Table 5.1 Construction cost of an interior drywall partition

Construction cost of a new drywall partition on 3 5/8″ metal stud				
DESCRIPTION	MATERIAL	LABOR	TOTAL	TOTAL WITH O&P
Metal studs 3-5/8" 16" O.C.	$ 0.29	$ 0.61	$ 0.90	$ 1.27
Gypsum board 5/8" on both sides	$ 0.58	$ 0.46	$ 1.04	$ 1.36
Tape and finish	$ 0.04	$ 0.25	$ 0.29	$ 0.44
Paint with roller on both sides	$ 0.10	$ 0.36	$ 0.46	$ 0.68
Total per square foot				$ 3.75

Table 5.1 *(continued)* Construction cost and repair cost of a sample drywall partition

DAMAGE LEVEL 1 Cracking that can be repaired with tape, paste, and paint				
DESCRIPTION	MATERIAL	LABOR	TOTAL	TOTAL WITH O&P
Tape and finish	$ 0.04	$ 0.33	$ 0.36	$ 0.54
Paint with roller on both sides	$ 0.11	$ 0.48	$ 0.56	$ 0.84
Total				$ 1.38
	Repair cost / Cost of New			0.299
DAMAGE LEVEL 2 – Replacement of gypsum boards but not the frames				
DESCRIPTION	MATERIAL	LABOR	TOTAL	TOTAL WITH O&P
Removal of damaged gypsum boards	$ -	$ 0.20	$ 0.20	$ 0.30
Gypsum board 5/8" on both sides	$ 0.65	$ 0.62	$ 1.28	$ 1.67
Tape and finish	$ 0.04	$ 0.33	$ 0.36	$ 0.54
Paint with roller on both sides	$ 0.11	$ 0.48	$ 0.56	$ 0.84
Total				$ 3.35
	Repair cost / Cost of New			0.727
DAMAGE LEVEL 3 - Total replacement				
DESCRIPTION	MATERIAL	LABOR	TOTAL	TOTAL WITH O&P
Removal of damaged gypsum boards	$ -	$ 0.20	$ 0.20	$ 0.30
Removal of damaged metal frames	$ -	$ 0.24	$ 0.24	$ 0.37
Metal studs 3-5/8" 16" O.C.	$ 0.32	$ 0.82	$ 1.10	$ 1.56
Gypsum board 5/8" on both sides	$ 0.65	$ 0.62	$ 1.28	$ 1.67
Tape and finish	$ 0.04	$ 0.33	$ 0.36	$ 0.54
Paint with roller on both sides	$ 0.11	$ 0.48	$ 0.56	$ 0.84
Total				$ 5.28
	Repair cost / Cost of New			1.145

(e) Finding appropriate curves passing through points

After calculating the repair cost for different damage states and redoing it for the information coming from different sources, we need to transform these repair cost-damage state pairs into the format explained earlier in this section. In this example, since only one cost evaluation is presented, we are not able to show the development of the cost function, so for demonstrating the method it is assumed that the cost obeys a lognormal shape. The above costs are assumed to be the mean values, with the dispersions assumed to be 0.15 for damage state one (green line), 0.17 for damage state two (orange line), and 0.19 for damage state three (red line). The cost function is presented in Figure 5.9. For example, if the damage state of interest is the second one, there is an 80% probability that the repair cost compared to the cost of a new component is less than 0.8.

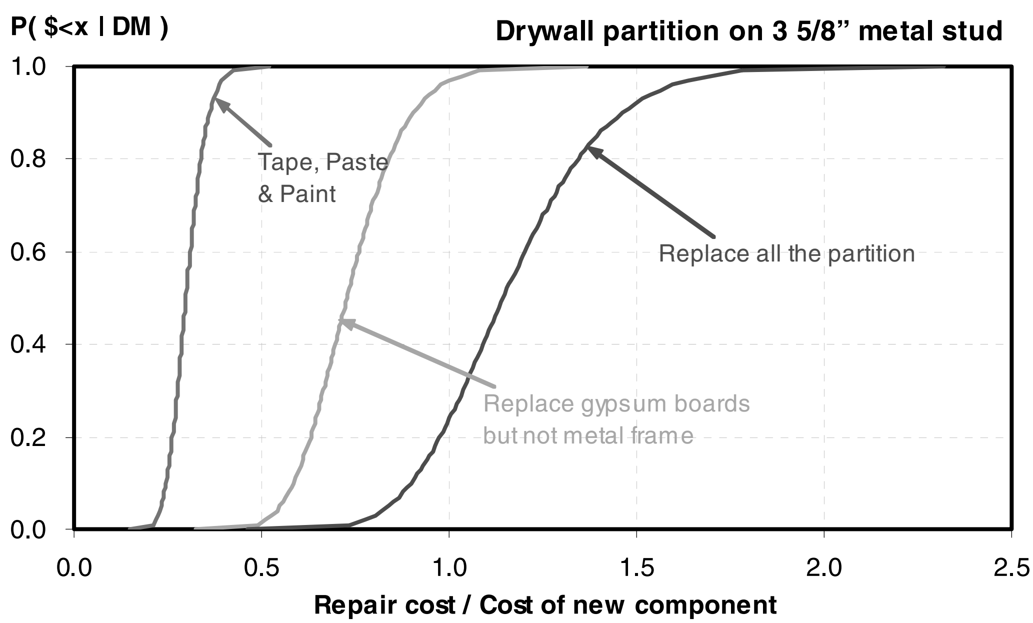

Figure 5.9 Cost function of a drywall partition for three damage states

6 Summary

A review of the performance of the nonstructural components in commercial buildings during past earthquakes has been presented in this study. The information gathered following these earthquakes shows that most of the economic loss comes from damage to nonstructural components. There are two reasons for this. First, most of the total construction cost is spent on nonstructural components. The structure typically costs only about 20% of the whole building cost and the rest is spent of nonstructural components and contents. Also, damage to nonstructural components is more frequent compared to damage to structural components.

A taxonomy has been presented for nonstructural components. The new proposed classification has been designed based on the needs of performance-based design. The components are classified according to their system and functionality in buildings. For each component, the damage states are defined and the sensitive structural response parameter presented. Several repercussions are listed for each damage state of a component. These repercussions include the repair actions needed to repair the component and return it to a functional component for each damage state; the damage consequences, which list the secondary effects of the damage to a component including the effect on other components or the whole building for each damage state; the life hazard, which defines the level of life hazard that the component may produce in each damage state; the loss of function, which represents how the component is functional after the earthquake for each damage state; and the building functionality, which shows how the functionality of the building is affected by the damage to a specific component at each damage state.

A comprehensive database of nonstructural components has been presented that covers different aspects of nonstructural components in commercial buildings. The database provides information on common nonstructural components installed in commercial buildings in order to give insight to engineers and designers, who are not usually familiar with nonstructural components. The typical components are listed with photos for selected components.

A portion of the database provides information about the damageability of components in earthquakes. The data can be divided into three main categories:

(i) performance of nonstructural components in previous earthquakes along with information about structural response, ground motion, and structural system. This information provides the basis for the development of damage-motion pairs used to develop the fragility curves of components.

(ii) Image library of damaged nonstructural components. This part of the database shows the photo of the damaged component with a description of the damage to provide a visual understanding of damage states.

(iii) Fragility curves that represent the damage of a component as a function of structural motion.

Another part of the database is devoted to cost information about nonstructural components. In one section, the costs of typical components are shown including the cost of materials and construction. Also a cost breakdown of a number of buildings is available in the database. Using this information, the user is able to understand the distribution of costs in buildings, which is helpful to relate to investment risk. In other words, the more a component costs, the more likely damage to it will result in economic loss in the building. This information plus the information obtained from different sources on repair costs of components at different states of damage provide data to develop the cost functions of nonstructural components.

The database has a powerful search engine and the information in the database is classified similarly as in the taxonomy. Its user-friendly interface allows valuable information to be obtained about nonstructural components that have not been possible before to this extent.

By use of this database and similar information, it is possible to better understand the behavior of nonstructural components and to develop their fragility curves. Adding more data to the database, such as more information on the performance of nonstructural components in previous earthquakes and also information about fragility curves and cost functions in the future, can make this database more helpful.

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Appendix I   Nisqually Earthquake

The February 28, 2001, Nisqually (Seattle), Washington, earthquake struck the south Puget Sound area at 10:55 a.m. (PST), causing minor building damage over parts of western Washington. This earthquake, with a moment magnitude Mw = 6.8, was slightly smaller than the 1949 earthquake in the Olympia area, which measured 7.1. Damage from the Nisqually earthquake was also less than the 1965 Seattle-Tacoma earthquake, which had a magnitude of 6.5. Because the recent Nisqually earthquake occurred at a depth of 32 miles (52 km), ground shaking and associated structural damage were relatively limited, although the earthquake was felt throughout most of the populated areas of western Washington. It is postulated that the fault responsible for the earthquake was 18.5 x 6 miles (30 x 10 km) in area and had approximately 3 feet (1 m) of vertical movement. This movement occurred within the descending ocean crust, which acts like a conveyor belt transporting the ocean floor under the North American continent. Maximum accelerations were approximately 0.3g in the Olympia and Seattle areas, compared to a maximum of approximately 0.93g in the 1994 Northridge and 0.64g in the 1989 Loma Prieta, California, earthquakes. Ground shaking from the Nisqually earthquake tended to be strongest in river valleys draining into Puget Sound. Liquefaction, which occurs when strong shaking in loose, water-saturated sandy soils causes the soils to liquefy much like quicksand, resulted in sand boils and lateral spreading that was usually found in low-lying areas around Puget Sound. Numerous areas experienced landslides, and there are reports of at least one rockslide in the Cascades and an underwater slide in Lake Washington.

Structural damage was most prevalent in older unreinforced masonry buildings and their nonstructural members, such as chimneys and parapet walls. Failure of masonry walls, parapets, and chimneys occurred in Olympia, Seattle, Tacoma, and their outlying areas. Minor damage was found in wood-frame, concrete, and steel-frame structures. Much of the damage was to the nonstructural parts of buildings, including contents and architectural finishes. Some of the more widely reported damage, such as the control tower at the Seattle-Tacoma International Airport, was a result of its age and design; for the most part steel-frame and concrete buildings fared well. Minor structural damage has also been observed on a number of the area's bridges, such as spalled concrete on support columns and flaked paint where steel members yielded, but only four of the area's older bridges received significant damage (Filiatrault 2001). Fortunately damage in the Puget Sound area from deep-seated earthquakes over the past 50 years has been relatively limited; however historical records suggest that larger and more damaging earthquakes associated with subduction zone and crustal earthquakes have occurred throughout history.

Since the objective of this research is to evaluate the performance of nonstructural components, the review and evaluation of the damage of this earthquake makes some important and useful results. In order to gather the information, several sources of information were considered:

- Owners of damaged buildings
- Local contractors
- Structural engineering firms
- Insurance companies

Owners of buildings were able to provide the most valuable cost information because of their direct contact with the damage and repair process and the associated costs. The local contractors, structural engineers, and insurance companies involved in repair and damage evaluation of the buildings were also a good source of information. A questionnaire was designed and distributed among the owners of damaged buildings, local contractors, and structural engineers in the area. The questionnaire, shown in Figure A1.1, was posted for the above-mentioned people. A total of 400 letters were posted: 280 for contractors, 90 for owners, 20 for engineering firms, and 10 for insurance companies. Also, a group of three people went to the area to investigate further and to obtain more information and photos of damaged buildings. The damage information and photos are included in the database.

Nonstructural Damage Inquiry Form

General Information

Name of Building: ______________________________ **Occupancy**
Address: ______________________________
☐Residential
____
☐Commercial
Number of floors: _____
☐Hotel
Approx. area / floor: _______ sf. (_____ ft X _____ ft)
☐Hospital
☐Other

Severity of Damage	Extent of Damage
L: Little	1: Localized
M: Moderate	2: Intermediate
S: Severe	3: Widespread

Suspended ceilings ☐Aluminium sheet ☐Plasterboard Other: __________
Does your building have this component? Yes ____ No____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Dropped acoustical tile	☐	☐	☐	☐	☐	☐
☐ Perimeter damage	☐	☐	☐	☐	☐	☐
☐ Seperation of runners	☐	☐	☐	☐	☐	☐
☐ Other: ______________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Non-suspended Ceilings ☐Plaster ☐Drywall ☐Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Collapse	☐	☐	☐	☐	☐	☐
☐ Local spalling	☐	☐	☐	☐	☐	☐
☐ Cracking	☐	☐	☐	☐	☐	☐
☐ Other: ______________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Non-glazing cladding ☐Stone ☐Tile ☐Glass ☐Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Falling form building	☐	☐	☐	☐	☐	☐
☐ Damaged panels and connections	☐	☐	☐	☐	☐	☐
☐ Crush	☐	☐	☐	☐	☐	☐
☐ Other: ______________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Glazing ☐Wood frame ☐Steel frame ☐Aluminium frame ☐ Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Only Cracking	☐	☐	☐	☐	☐	☐
☐ Fall out	☐	☐	☐	☐	☐	☐
☐ Frame distortion	☐	☐	☐	☐	☐	☐
☐ Other: ______________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Figure A1.1 Questionnaire sent after Nisqually earthquake

Doors ☐Sollid wood ☐Hollow wood ☐Hollow metal ☐ Other: ____________
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Crushing	☐	☐	☐	☐	☐	☐
☐ Frame distortion	☐	☐	☐	☐	☐	☐
☐ Cracking	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ _________

Internal partitions ☐Drywall ☐Gypsum ☐Other: ___________
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Collapse	☐	☐	☐	☐	☐	☐
☐ Cracking	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ _________

Unreinforced masonary walls ☐Hollow block ☐Solid Block ☐ther: __________
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Parapet crushing	☐	☐	☐	☐	☐	☐
☐ Parapet collapse	☐	☐	☐	☐	☐	☐
☐ Parapet locally falling out	☐	☐	☐	☐	☐	☐
☐ Parapet cracking	☐	☐	☐	☐	☐	☐
☐ Wall crushing	☐	☐	☐	☐	☐	☐
☐ Wall collapse	☐	☐	☐	☐	☐	☐
☐ Wall locally falling out	☐	☐	☐	☐	☐	☐
☐ Wall cracking	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ _________

Heating systems ☐Unit heater ☐Boiler ☐Other: ___________
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Sliding	☐	☐	☐	☐	☐	☐
☐ Broken gas and exhaust lines	☐	☐	☐	☐	☐	☐
☐ Broken /bent steam and relies lines	☐	☐	☐	☐	☐	☐
☐ Broken/bent bolts	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ _________

Cooling systems ☐Packaged chiller ☐Rooftop air conditioner ☐ther: ___________
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Sliding	☐	☐	☐	☐	☐	☐
☐ Overturning	☐	☐	☐	☐	☐	☐
☐ Loss of function	☐	☐	☐	☐	☐	☐
☐ Leaking refrigerant	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ _________

Emergency generators
Does your building have this component? Yes ____ No ____

Type of damage	Seviertity of damage			Extent of damage		
	L	M	S	1	2	3
☐ Broken fuel, signal and fuel lines	☐	☐	☐	☐	☐	☐
☐ Loss of function	☐	☐	☐	☐	☐	☐
☐ Broken exhaust lines	☐	☐	☐	☐	☐	☐
☐ Other: ____________________	☐	☐	☐	☐	☐	☐

Figure A1.1 *(continued)* Questionnaire sent after Nisqually earthquake

Tanks
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Tank or vessel rupture	☐	☐	☐	☐	☐	☐
☐ Pipe break	☐	☐	☐	☐	☐	☐
☐ Other: ________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Elevators ☐Traction geared ☐Hydraulic ☐Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Counterweights out of guide rail	☐	☐	☐	☐	☐	☐
☐ Cables out of sheaves	☐	☐	☐	☐	☐	☐
☐ Dislodged equipment	☐	☐	☐	☐	☐	☐
☐ Damage to rails	☐	☐	☐	☐	☐	☐
☐ Other: ________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Piping ☐Cast iron ☐Plastic ☐Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Broken	☐	☐	☐	☐	☐	☐
☐ Leaking	☐	☐	☐	☐	☐	☐
☐ Other: ________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Fire sprinkler ☐Wet pipe ☐Dry pipe ☐Other: __________
Does your building have this component? Yes ____ No ____

Type of damage	Sevierity of damage L	M	S	Extent of damage 1	2	3
☐ Broken	☐	☐	☐	☐	☐	☐
☐ Leaking	☐	☐	☐	☐	☐	☐
☐ Other: ________________	☐	☐	☐	☐	☐	☐

Total cost to repair this component $ ________

Total cost to repair the building: $ __________

Name of contractor/subcontractors involved in the repairs:

____

____

Contact information:

____

____

Name of contractor/subcontractors involved in the repairs:

____

____

Contact information:

____

____

**Please add any other type of information and damage that is not tabulated here in a separate sheet.

Figure A1.1 *(continued)* Questioner sent after Nisqually earthquake

Appendix II Loss Estimation Methodology

The aim of PEER's loss-estimation efforts is to describe seismic performance quantitatively by continuous variables rather than by discrete and sometimes subjective performance levels. The building-specific loss estimation methodology described in this report provides such continuous and quantitative measure of seismic performance in terms of economic losses in a specific building. In particular, the ultimate goal is to compute the mean annual probability of exceedance of different levels of dollar losses. This information will allow decision makers to respond to questions such as what is the probability of facing an economic loss higher than $1.0 million dollar in my structure. In this report, however, we concentrate on summarizing our efforts aimed at the estimation of the expected annual loss in the building, $E[L_{Bldg}]$, that corresponds to the average loss that owners have *every year* in their building structure. Consequently, the decision variable, DV, in this investigation is the expected annual loss in the building, i.e., $DV=E[L_{Bldg}]$.

The PEER framework equation is given by [Cornell and Krawinkler, 2000]:

$$\lambda(DV) = \iint G(DV \mid DM)\, dG(DM \mid IM)\, d\lambda(IM) \tag{A2.1}$$

where $G(DV|DM)$ is the probability that the decision variable exceeds specific values given (i.e., conditional on knowing) that the engineering Damage Measures (e.g., the maximum interstory drift, and/or the vector of cumulative hysteretic energies in all elements) are equal to particular values. Further, $G(DM|IM)$ is the probability that the Damage Measure(s) exceed these values given that the Intensity Measure(s) (such as spectral acceleration at the fundamental mode frequency, and/or spectral shape parameters and/or duration) equal particular values. Finally, $\lambda(IM)$ is the mean annual frequency of the Intensity Measure(s) which for small values is equal to the annual probability of exceedance of the Intensity Measure(s).

More recently, Krawinkler (2002) modified the above equation to more adequately distinguish between structural response parameters such as interstory drift ratio, absolute floor acceleration, cumulative hysteretic energy, etc., from different damage states in structural and nonstructural components. The first are referred to as "Engineering Demand Parameters (*EDP*) " while the damage states are referred to as "Damage Measures (*DM*)". The modified framework equation is given by

$$\lambda(DV) = \iiint G(DV \mid DM)\,dG(DM \mid EDP)\,dG(EDP \mid IM)\,d\lambda(IM) \tag{A2.2}$$

Equation (A2.2) assumes that all four variables (*IM, EDP, DM and DV*) are continuous random variables. However, economic losses in individual components are associated with repair actions, which may be discretely triggered at certain levels of damage. For example, the replacement of glass in a window is triggered when the glass is cracked or broken, so in these cases the damage measures become discrete, and the above equation needs to be modified as will be shown below.

In order to compute the mean annual frequency of exceedance in the building, it is first necessary to compute the losses in individual components. The annual probability of exceeding a loss level l in the jth component (either a structural or nonstructural component) considering discrete damage states is given by

$$P[L_j > l] = \sum_{i=1}^{m} \int_0^{\infty}\int_0^{\infty} P[L_l > l \mid DM = dm_i]\, P(DM = dm_i \mid EDP_j = edp)\, P(EDP_j > edp \mid IM = im) \left|\frac{d\nu(IM)}{dIM}\right| dEDP\, dIM \tag{A2.3}$$

where m is the number of damage states in jth component, $P[L_j > l \mid DM = dm_i]$ is the annual probability of exceedance of a loss l in the jth component conditioned on knowing that the component is in the ith damage state, $P(DM = dm_i \mid EDP_j = edp)$ is the probability that the jth component will be in damage state i given that the component has been subjected to an *EDP* equal to *edp*, $P(EDP_j > edp \mid IM = im)$ is the probability that the *EDP* affecting component j will exceed a certain value *edp* given that the ground motion intensity measure *IM* is equal to *im*, and finally $\left|\frac{d\nu(IM)}{dIM}\right|$ is the slope of the seismic hazard curve corresponding to the intensity measure *IM*.

In equation A2.3, the probability that the jth component will be in damage state i given that the component has been subjected to an *EDP* equal to *edp* is computed as

$$P(DM_j = dm_i \mid EDP_j = edp) = P(DM_j > dm_i \mid EDP_j = edp) - P(DM_j > dm_{i+1} \mid EDP_j = edp) \tag{A2.4}$$

where $P(DM_j > dm_i \mid EDP_j = edp)$ is the probability of exceeding damage state i in the jth component given that it has been subjected to an *EDP* equal to *edp*, $P(DM_j > dm_{i+1} \mid EDP_j = edp)$ is the probability of exceeding damage state i+1 in the jth component given that it has been subjected to an *EDP* equal to *edp*. Functions $P(DM_j > dm_i \mid EDP_j = edp)$ and $P(DM_j > dm_{i+1} \mid EDP_j = edp)$ correspond to the ith and ith+1 fragility functions of a jth component as a function of *EDP*, which describe the vulnerability or damageability of the jth component with increasing levels of *EDP*.

The expected annual loss in the jth component is obtained by replacing $P[L_j > l \mid DM = dm_i]$ in equation A2.3 by the expected value of the loss in the jth component given that it is in damage state *I*, $E[L_j \mid DM = dm_i]$, as follows:

$$E[L_j] = \sum_{i=1}^{m} \int_0^{\infty}\int_0^{\infty} E[L_j \mid DM = dm_i]\, P(DM = dm_i \mid EDP_j = edp)\, P(EDP_j > edp \mid IM = im) \left| \frac{d\nu(IM)}{dIM} \right| dEDP\, dIM \quad \text{(A2.5)}$$

The expected annual loss for the whole building resulting from direct physical damage is then computed as the sum of the expected losses in each individual component in the building, that is

$$E[L_{Bldg.}] = E[L_{j=1}] + E[L_{j=2}] + E[L_{j=3}] + ... + E[L_{j=n}] = \sum_{j=1}^{n} E\left[L_j\right] \quad \text{(A2.6)}$$

where n is the total number of components in the building.

Although the summation and integrals in equation (A2.5) can be solved in any order, certain sequences provide intermediate results that also provide valuable information to the structural engineer, owner(s), and the interested parties of the seismic performance of the building.

For example, the expected value of the loss in jth component given that it has been subjected to an engineering demand parameter can be computed as

$$E[L_j \mid EDP_j = edp] = E[L_j \mid DM = dm_i]\, P(DM = dm_i \mid EDP_j = edp) \quad \text{(A2.7)}$$

where $P(DM = dm_i \mid EDP_j = edp)$ is given by equation (A2.4). Then the variation (increase) of dollar loss in the jth component with changes (increase) in *EDP* can then be obtained by plotting

$EDPj$ versus $E[L_j \mid EDP_j = edp]$. Similarly, the variation of dollar loss from drift-sensitive structural and nonstructural components in the kth floor of the building can be obtained by plotting EDP_k versus $\sum_{j=1}^{p} E[L_j \mid DM = dm_i]\, P(DM = dm_i \mid EDP_j = edp)$ where p is the number of drift-sensitive components in the kth floor of the building.

Similarly, the expected value of the dollar loss in the jth component, given that the building has been subjected to a ground motion with intensity im can be computed as

$$E[L_j \mid IM = im] = \int_0^\infty E[L_j \mid EDP_j = edp]\, dP(EDP_j > edp \mid IM = im) \qquad \text{(A2.8)}$$

The expected value of the dollar loss in the building as a function of the level of ground motion intensity is hence computed as

$$E[L_{Bldg} \mid IM = im] = \sum_{j=1}^{n} E[L_j \mid IM = im] \qquad \text{(A2.9)}$$

A plot of IM versus $E[L_{Bldg} \mid IM = im]$ provides information on how the expected value of the loss (i.e., the average loss in the building) increases when the ground motion intensity increases.

Finally the expected annual loss in the building can be computed as

$$E[L_{Bldg}] = \int_0^\infty E[L_{Bldg} \mid IM = im]\, d\nu(IM) \qquad \text{(A2.10)}$$

where $d\nu(IM)$ can be written as

$$d\nu(IM) = \left| \frac{d\nu(IM)}{dIM} \right| dIM \qquad \text{(A2.11)}$$

Substituting (2.11) in (2.10)

$$E[L_{Bldg}] = \int_0^\infty E[L_{Bldg} \mid IM = im] \left| \frac{d\nu(IM)}{dIM} \right| dIM \qquad \text{(A2.12)}$$

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