4. Loss Estimation

4.1 Scope

This chapter provides data that may be used to perform estimates of probable repair costs for steel moment-frame buildings based on actuarial data obtained from the 1994 Northridge earthquake. These data may be used to estimate the cost of repair for these buildings, within levels of confidence, given limited data on the building characteristics and an estimate of ground motion intensity. A more detailed approach that incorporates the information obtained from a structural analysis of the building is contained in Appendix B of these *Recommended Criteria*.

When an earthquake damages a building, there are a number of potential sources of economic loss. One source of losses is the cost associated with repairing the damage and restoring the building to service. Such losses are known as direct loss. Other sources of economic loss can result from an inability to occupy space in the damaged structure until it is repaired, the need to rent space for temporary or alternative quarters, relocation costs, litigation, devaluation of property values and a general decline in the economic welfare of the affected region. These losses are generally termed indirect losses. These *Recommended Criteria* provide methods only for estimating direct losses due to earthquake ground shaking.

The direct losses that can be estimated using the methods of these *Recommended Criteria* typically represent only a small portion of the total losses caused by earthquakes. The other indirect losses are a function of a number of complex factors that relate to the economic and social makeup of the affected region, and the decision making process performed by individual owners and tenants and go far beyond the considerations of damage sustained by individual buildings. Therefore, although such losses are very important, they are considered to be beyond the scope of these *Recommended Criteria*.

Although the tools presented herein can be applied to building specific loss estimates, they were originally developed with the intent of application to broad populations of buildings. The estimation of losses that may occur to a specific building in future earthquakes of unknown source, magnitude and distance is fraught with great uncertainty. Users are cautioned that actual performance of specific buildings in response to specific earthquake demands can be substantially different from what would be suggested by the statistically based methods presented in this chapter.

4.2 Loss Estimation Methods

Two alternative methods are provided in these *Recommended Criteria* to estimate probable repair costs for buildings due to future earthquake ground motion. The Rapid Loss Estimation Method, contained in this chapter, provides estimates of losses as a function of basic information about the building and estimates of seismic demands. The Detailed Loss Estimation Method found in Appendix B, directly utilizes engineering data obtained from a detailed structural analysis of the specific building. This Detailed Loss Estimation Method is compatible with FEMA’s *HAZUS* (NIBS, 1997a,b) loss estimation software and can be used to generate building-specific vulnerability information for use with that system and other similar loss estimation models.

Commentary: The most common bases for producing loss estimates may be classified as historical experience, expert opinion, and engineering. All of these methods include significant uncertainty with regard to predicted damage and repair costs.

Historical experience-based estimates are developed based on statistics on the actual damage and costs incurred for given classes of structures subjected to estimated or recorded seismic demands. When such data are available, it is possible to determine the distribution of losses over the population contained in the database, including a median (best estimate of the loss for any structure in the class) and a measure of variation. This permits the loss for a structure similar to those in the database to be estimated within a range of confidence. Significant sources of uncertainty include the lack of database completeness, differences between the structure being evaluated and the general population in the database, and the seismic demand range captured in the database. No database is comprehensive.

The most commonly used loss estimation methodology is based on expert opinion of probable repair costs. ATC-13 (ATC, 1985) and other similar studies have developed damage functions by obtaining opinions from structural engineers and other experts on typical levels of damage for various classes of structures when subjected to different intensities of ground motion. Statistical data from such opinion surveys can then be used to derive loss estimates for other buildings. This approach also has much uncertainty and little to no direct tie to actual losses experienced in past events, other than as perceived by the experts. The 1994 Northridge earthquake illustrates the uncertainty inherent in expert opinion, in that the brittle fractures that occurred in steel moment-frame buildings had not previously been anticipated.

The Rapid Loss Estimation Method presented here uses both historical experience and expert opinion. A database of steel moment-frame building damage caused by the 1994 Northridge earthquake represented the historical experience. This was augmented by expert opinion where actuarial data were sparse or unreliable.

The Detailed Loss Estimation method uses engineering calculations to estimate the types of damage likely to be experienced by the structure. Probable repair costs are then determined based on this damage. Such an approach has not been widely used in the past. However, through a contract with the National Institute of Building Sciences, FEMA has recently prepared a general loss estimation methodology, known as HAZUS, that employs a generalized version of this approach. In the HAZUS methodology, building damage functions are based *on a standard capacity (pushover) curve for model building type and fragility curves that describe the probability of discrete states of damage. Separately, building loss functions convert damage to different types of loss including casualties, economic losses and loss of function. Damage state probabilities are a function of the spectral demand on the structure, determined by the intersection of building capacity and earthquake demand spectra. Uncertainty in building capacity, damage states, and ground shaking is included in the fragility functions that convert spectral demand into damage state probabilities. This approach is appealing in that it allows the direct use of the details of an individual building's construction that are important to its earthquake performance, including strength, stiffness, and configuration, in the loss estimation process. This approach has been adopted for the Detailed Loss Estimation Method found in Appendix B of these Recommended Criteria.*

4.2.1 Use of Loss Estimation Methods

Results from either the Rapid Loss Estimation or Detailed Loss Estimation methods may be used to estimate building damage and loss. These data can assist in making economic decisions regarding the building, e.g., benefit-cost studies to determine if structural upgrade is warranted. Estimates made using the rapid loss estimation method should be considered as representative only of *average* buildings. They should therefore be used with caution since the unique structural characteristics of any individual building will affect its vulnerability. While the detailed loss estimation method directly takes into account the structural characteristics of a building, it also uses general data for other aspects of the loss estimation process including the cost of repairing damage of given types, and the replacement value of the building. Hence, estimates performed by either of these techniques may require some adjustment by the user to better reflect the particular situation.

Commentary: When applying the rapid loss estimation method to a specific building, consideration should be given to such factors as the strength and stiffness of the lateral force resisting system, inherent redundancy, physical condition, quality of construction, and conformance with building code provisions. Buildings having substantial deficiencies would be expected to be significantly more vulnerable. Similarly, buildings that have superior earthquake resisting characteristics, relative to code requirements, would be expected to be less vulnerable. The detailed loss estimation method provides a direct method for evaluating these factors. In the rapid method, this can only be accounted for qualitatively, using the judgement of the evaluator.

In addition to these construction characteristics, known to affect building performance in earthquakes, a very significant factor that affects the costs associated with earthquake damage relates to building occupancy. It is much more difficult, and costly, to repair damage in buildings in critical occupancies, such as hospitals and semiconductor manufacturing clean rooms, than it is in buildings in standard office or residential occupancies. This is both because the *finishes and utilities that must be disturbed to conduct structural repairs are more complex and expensive, and also, because general working conditions are more restrictive. These factors are not directly accounted for by either of the methods.*

4.2.2 Scope of Loss Estimation Methods

The Rapid Loss Estimation and Detailed Loss Estimation methods may be used to estimate direct economic loss related to repair of building damage resulting from the effects of ground shaking. These direct losses include costs associated with inspection to determine the extent of damage, design and professional services fees, demolition and replacement costs for finished surfaces and utilities that must be removed and replaced to allow access for inspection and repair, and actual repair construction costs. The methodologies permit estimation of costs related to structural repair and to repair of non-structural building features including architectural finishes, mechanical and electrical equipment. The methodologies do not include losses related to contents including office equipment, inventory, and similar tenant property.

Ground shaking is the primary, but not the only source of earthquake induced damage, and therefore loss that occurs in earthquakes. Other hazards that can result in such losses include liquefaction, landsliding, earthquake induced fire and flood. While these hazards typically damage only a small percentage of the total inventory of buildings affected by an earthquake, they can be far more damaging to those properties that are affected than is ground shaking. Regardless, estimates of loss due to these effects are not included in these methodologies.

In addition to direct economic loss resulting from ground shaking, there are also many other types of loss that result from the effects of earthquakes. This includes life loss and injury, as well as large economic losses due to interruption of business. Estimation of these losses is also beyond the scope of the methodologies presented here.

4.3 Rapid Loss Estimation Method

4.3.1 Introduction

This section presents loss estimation functions that relate seismic demand, resulting primarily from ground shaking, to expected loss. The functions are presented in several formats so that users can adjust the various loss components to better reflect special knowledge about specific buildings. The functions were developed using 1994 Northridge earthquake damage data and are, therefore, expected to be representative of steel moment-frame buildings typical of California construction prior to 1994.

In this methodology, losses are quantified in three ways.

1. Damaged Moment Connections, expressed as a percentage of the total number of moment connections in the building.
2. Connection Restoration Cost, expressed as a percentage of the building replacement value.
3. Nonstructural Repair Cost, expressed as a percentage of the building replacement value. These other repair costs include costs related to restoration of non-structural elements,

including fascia, ceilings, and utilities. It does not include costs related to contents such as computer systems or stored inventories.

Commentary: The predictive models for building losses contained in this methodology are based on statistical data available from buildings affected by the 1994 Northridge earthquake. The damage surveys and database used in the development of the method dealt with the numbers and types of connection damage, and to a lesser extent, with repair costs and nonstructural damage. Hence, the primary parameter available and used in the statistical analysis was the quantity of damaged moment connections in affected buildings. Reported structural repair costs varied widely (some also included costs associated with defective welds as opposed to damaged connections), making it impossible to derive a reliable direct relationship between seismic demand and connection restoration cost. Instead, connection restoration costs were computed for each surveyed building as the estimated total number of damaged connections times average unit costs for connection repair. For other damage, including nonstructural repair costs and other structural repair costs, only very qualitative descriptions were reported. Therefore, these other repair costs could not readily be ascertained from the Northridge data. The unit costs used in the loss functions are provided so that users can adjust loss estimates to better reflect particular situations and so that should additional data become available in the future, the methodology can be extended in a consistent manner.

The only structural repair costs directly included in the loss functions presented in this methodology are costs related to repair of damaged moment resisting connections. Costs related to other structural repairs such as correcting permanent interstory drifts are not directly accounted for by these functions. However, Section 4.3.4 provides qualitative information that may allow the user to develop estimates of the potential additional costs that could be incurred in such repairs.

4.3.2 Seismic Demand Characterization

Direct damage repair costs are functions of seismic demand resulting primarily from ground shaking. The method presented here characterizes seismic demand in three alternative ways.

1. Modified Mercalli Intensity (MMI) at the building site. MMI is typically derived for a site, following an earthquake, based on observation of damage and other earthquake effects at the site. Several investigators have developed correlations between observed MMI and estimated ground shaking acceleration, velocity and displacement. The MMI values used in these *Recommended Criteria* were derived from estimated peak ground accelerations and velocities during the 1994 Northridge earthquake.
2. Peak Ground Acceleration (PGA) at the building site. This is the geometric mean (square root of the product) of the estimated peak values in each of the building's two principal directions.

3. Building Pseudo-Drift Ratio (S_d/H). This is defined as the spectral displacement S_d divided by the building height H from grade level to main roof. The spectral displacement is the geometric mean of the values in each of the building's two principal directions. The spectral displacement is that at the building fundamental period from a site-specific 5% damped response spectrum. Consistent units are used so that S_d/H is dimensionless.

Commentary: Seismic demands are intended to be those caused primarily by ground shaking. The Rapid Loss Estimation Method is not intended to cover losses governed by other hazards such as ground failure, inundation, and fires following earthquakes.

The damage patterns produced by the 1994 Northridge earthquake exhibited considerable scatter. Some buildings reported no connection damage whereas others in relatively close proximity had many damaged connections. The reasons for this are unclear; however, this random damage pattern has frequently been observed in other earthquakes. The scatter may be attributed to a number of factors including large uncertainties in the ground motion estimates for each site, the effects of individual building configuration and construction quality, and the relative thoroughness and accuracy of damage reporting for different buildings. Statistical data analysis using numerous different seismic demand measures (e.g., MMI, PGA, Peak Ground Velocity (PGV), and Peak Ground Displacement (PGD)) as damage predictors did not identify any single parameter as being clearly superior for prediction of percentage of damaged connections (FEMA-355E). Since no one measure of ground shaking intensity seemed to provide a best fit with the available Northridge data, the three measures of ground motion intensity presented in these Recommended Criteria were selected based on considerations of the probable needs of users.

MMI was chosen primarily because of its historical use in earlier loss studies and the fact that it continues to be used by many practitioners today. MMI is a highly subjective parameter intended to be determined after an earthquake, based on observed patterns of damage in different areas. It is of course problematic to use such an approach to characterize distributions of MMI for a future earthquake, that has not yet occurred. A number of researchers have attempted to develop correlation functions that relate observed MMI to less subjective measures of ground shaking including peak ground acceleration and peak ground velocity, which can then be predicted for future earthquakes using various attenuation relationships. These predictive models for MMI inherently incorporate significant variability and uncertainty. Nevertheless, most practitioners who use MMI based approaches to predict losses in future earthquakes, first use one of these predictive models for MMI upon which to index their loss estimates.

Consistent with this approach, the MMI values used in the loss functions presented here are those inferred from peak ground accelerations and velocities *recorded during the 1994 Northridge earthquake, using a predictive model by Wald et al. (1998). They are not based on actual damage observations. For a given site, there may be considerable difference between the observed MMI and the predicted MMI values.*

PGA was chosen because it is an unambiguous, commonly recorded and reported, earthquake intensity parameter. One of its shortcomings as a loss predictor, however, is that PGA is not reflective of the spectral content of ground shaking. Steel moment-frame buildings are typically long-period structures and theoretically their response should more closely be related to peak response velocity or displacement than to peak ground acceleration. However, these quantities are often unavailable for an individual building site, and did not provide significantly better correlation with the available data.

Engineering study of the behavior of steel moment-frame buildings indicates that interstory drift is a reasonable parameter for predicting the amount of damage experienced by a structure. Therefore, S_d/H was chosen as a ground motion intensity index for these Recommended Criteria because it is closely related to average interstory drift demands produced in steel moment-frame buildings. Also, it includes information about the seismic intensity at the site, and the dynamic characteristics of the ground shaking experienced as well as the particular building's dynamic response properties. Unfortunately, statistical analysis did not show this to be a better damage predictor than PGA. It is believed that the uncertainty in the survey data masks its predictive power. Nevertheless, its inclusion here is intended to promote the use of such engineering parameters in future loss studies.

4.3.3 Connection Damage Loss Functions

Figures 4-1, 4-2 and 4-3 present functions that may be used to estimate Connection Damage Ratio (CDR) as a function of Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA), and Pseudo Interstory Drift Ratio (PIDR), respectively. In these figures, connection damage is expressed as the percentage of moment connections within the total number of connections in the building's lateral-force-resisting system in all building directions, that are damaged as discussed in Section 2.3. A connection is defined as the attachment of one beam to one column. A connection is considered to be either damaged or undamaged (i.e., the relative severity of damage is not considered). A connection may be damaged at the beam bottom flange location, top flange, or both. Damage may also include the beam web connection and the column panel zone. No attempt is made to distinguish between these various types of damage. Defects at the roots of the CJP welds between beam and column flanges, which were often categorized as damage in buildings affected by the 1994 Northridge earthquake are not considered as damage herein.

Median and 90th percentile loss functions are presented. A set of typical buildings subjected to the same seismic demand will exhibit losses over a range. The median loss has the property of having the same numbers of buildings with smaller losses as there are with larger losses. The 90^{th} percentile loss has the property that 9 out of 10 buildings have losses equal to or lesser in magnitude.

Commentary: Connection damage was the key parameter that was statistically evaluated from the 1994 Northridge damage surveys. Connection restoration costs (Section 4.3.4) are derived from the connection damage by use of unit repair costs. The figures show plots of the actual recorded damage for buildings contained in the data set as well as smooth curves that approximately represent the median and 90^{th} percentile statistics. The curves were based in part on expert judgement that the extent of damage is dependent on seismic demand, even though the actual damage data indicates a weak correlation between damage and intensity. About ½ of the buildings in the database experienced no damaged connections, and hence many data points are clustered about the horizontal axis in the figures.

The building damage surveys used in the development of the functions presented are predominately from buildings covered by the City of Los Angeles Ordinance No. 170406 requiring the identification, inspection and repair of commercial steel moment-frame buildings subsequent to the 1994 Northridge earthquake. The database contained 185 buildings. Implicit in the use of this data for loss estimation is the assumption that this sample is representative of data for a major metropolitan area. Comparison of the aggregate building characteristics (e.g., height and gross area) against census tract data for the greater Los Angeles region suggests that the sample is indeed representative of the Los Angeles steel moment-frame building population. Whether the sample is representative of other metropolitan areas has not been studied. In addition, the sample does have certain qualities that are noteworthy. First, residential buildings were excluded from the Ordinance and hence are not in the sample. Second, most of the seismic demands were in a somewhat limited range (i.e., PGA from about 0.25g to 0.45g). Hence, data for PGAs that lie outside this range were sparse, and expert opinion was instrumental in defining the loss functions there.

Statistical analysis of the data found that building attributes such as height or redundancy (floor area per connection) were not significant parameters affecting the percentage of damaged connections. No adjustment factors for these characteristics were included herein, nor are they recommended, to adjust the estimates made using this data.

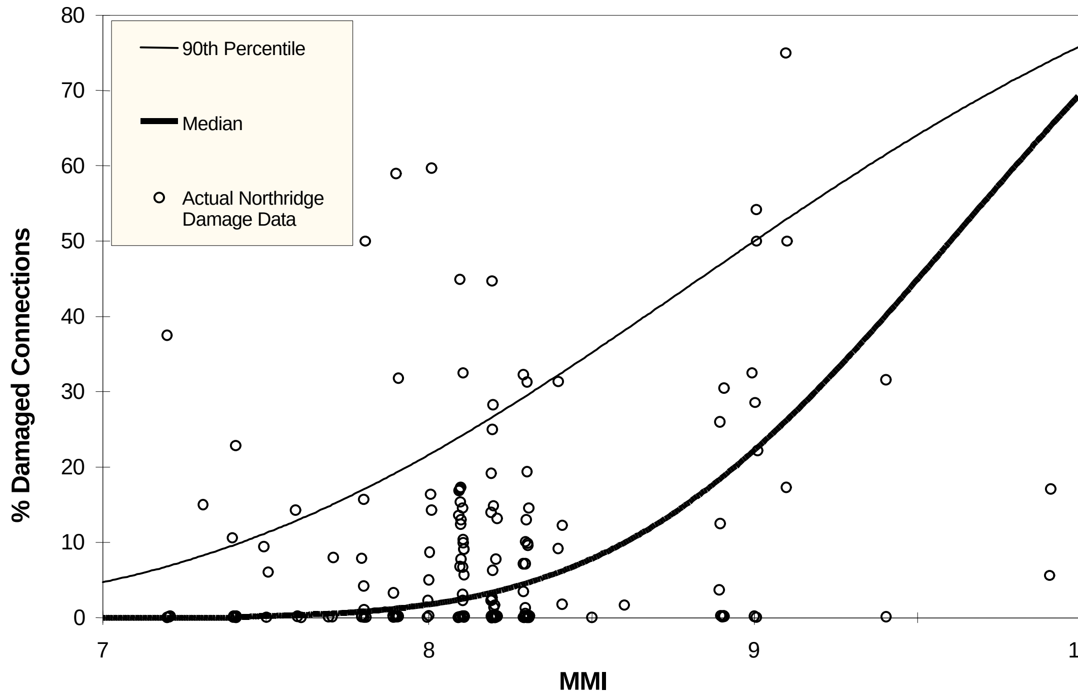

Figure 4-1 Connection Damage Ratio vs Modified Mercalli Intensity (MMI)

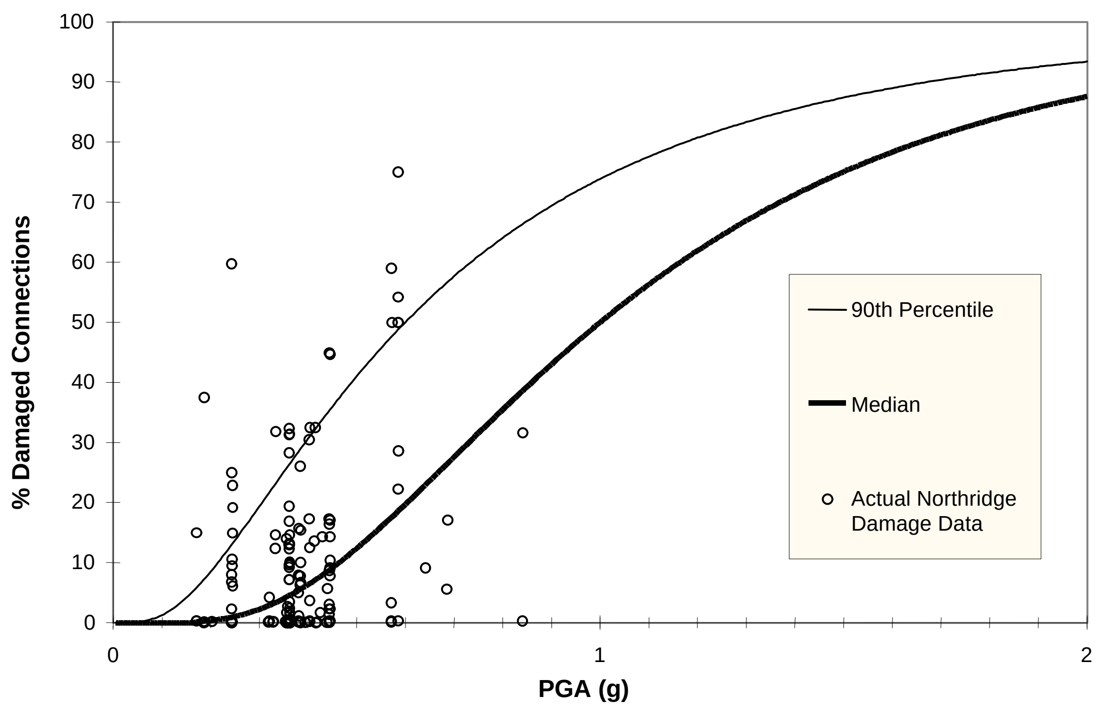

Figure 4-2 Connection Damage Ratio vs Peak Ground Acceleration (PGA)

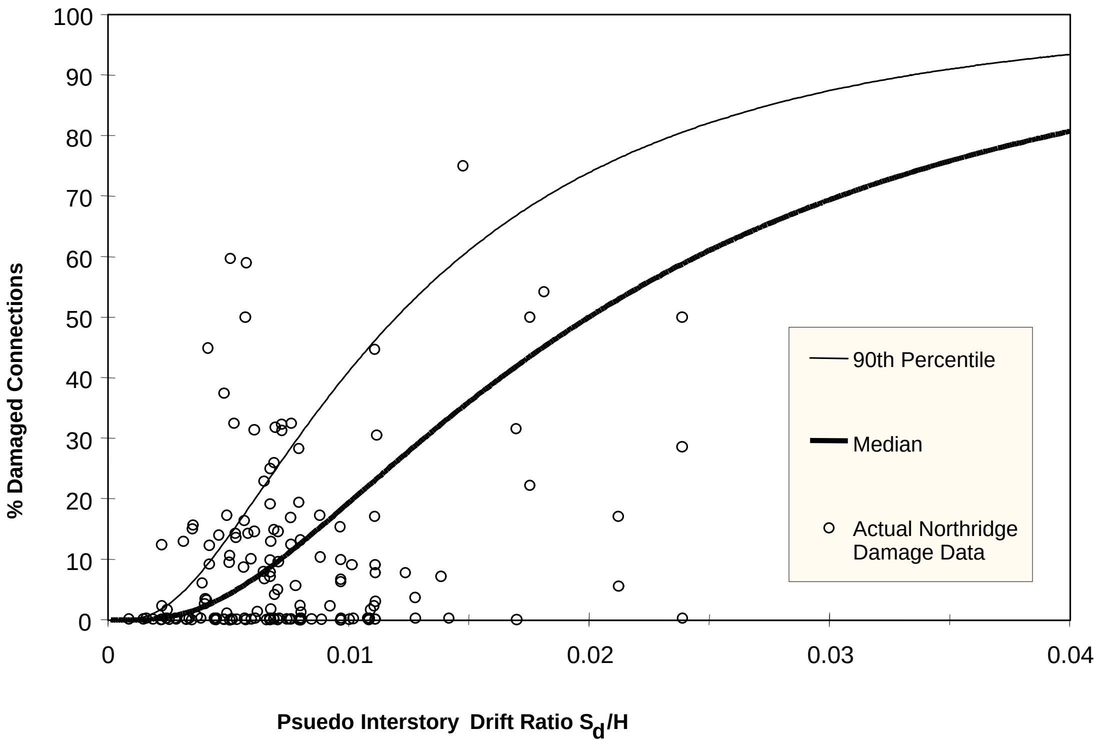

Figure 4-3 Connection Damage Ratio vs Building Pseudo Interstory Drift Ratio

4.3.4 Connection Restoration Cost Functions

Figures 4-4, 4-5, and 4-6 present connection restoration cost, expressed as a percentage of building replacement value, as a function of MMI, PGA and PIDR, respectively. In the development of the curves presented in the figures, the average unit cost for connection restoration has been taken as $20,000, including costs associated with selective demolition and restoration of finishes and utilities to provide access for repair. The building replacement value is taken as $125 per sq. ft times the gross building area.

> *Commentary: In the development of a typical steel moment-frame building, the cost of structural construction is approximately 25% of the total building development cost. Thus repair costs on the order of 20% or more approach the original cost of constructing the structure. The costs indicated in Figures 4-4, 4-5 and 4-6 do not include costs associated with repair of damage to elements other than moment-resisting connections, for example, column splices, and non-participating framing. However, in the 1994 Northridge earthquake, costs of these other repairs were not significant. In addition, the above costs do not consider the effect of large permanent lateral displacements that can occur in damaged frames. Several buildings damaged by the Northridge earthquake experienced permanent interstory drifts. Generally, when the permanent drift did not exceed a level that was visibly disturbing or interfered with operation of elevators, the buildings were not re-plumbed. Re-plumbing buildings that have experienced large permanent drifts can be costly, and in many cases may be*

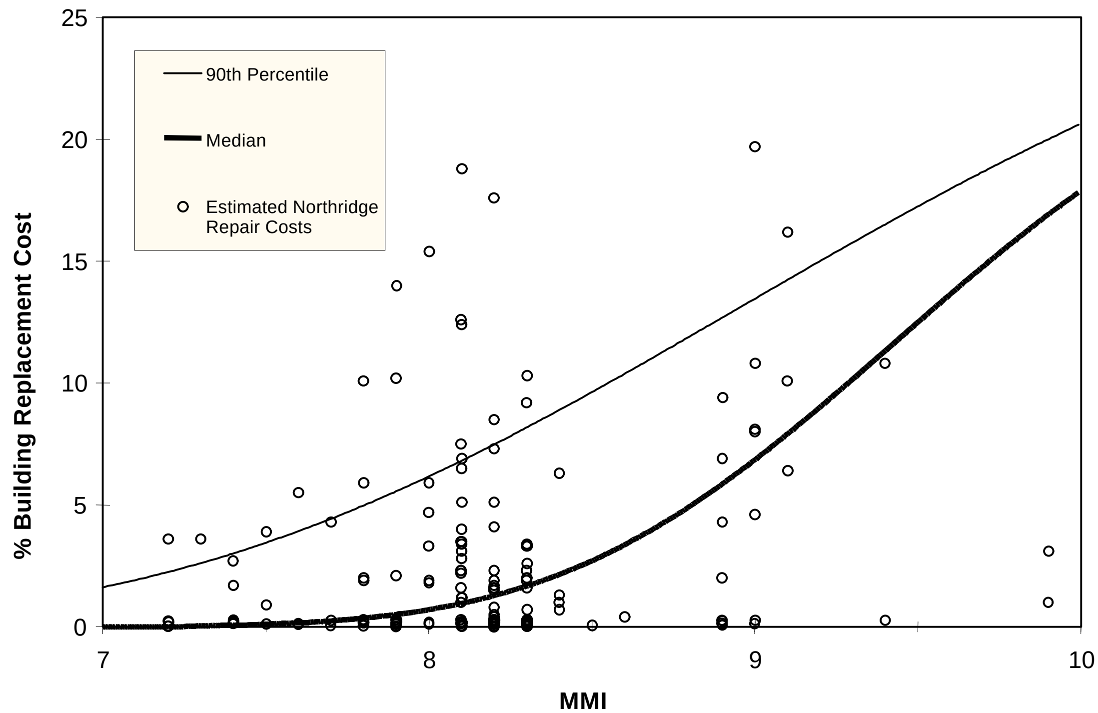

Figure 4-4 Connection Restoration Cost vs Modified Mercalli Intensity (MMI)

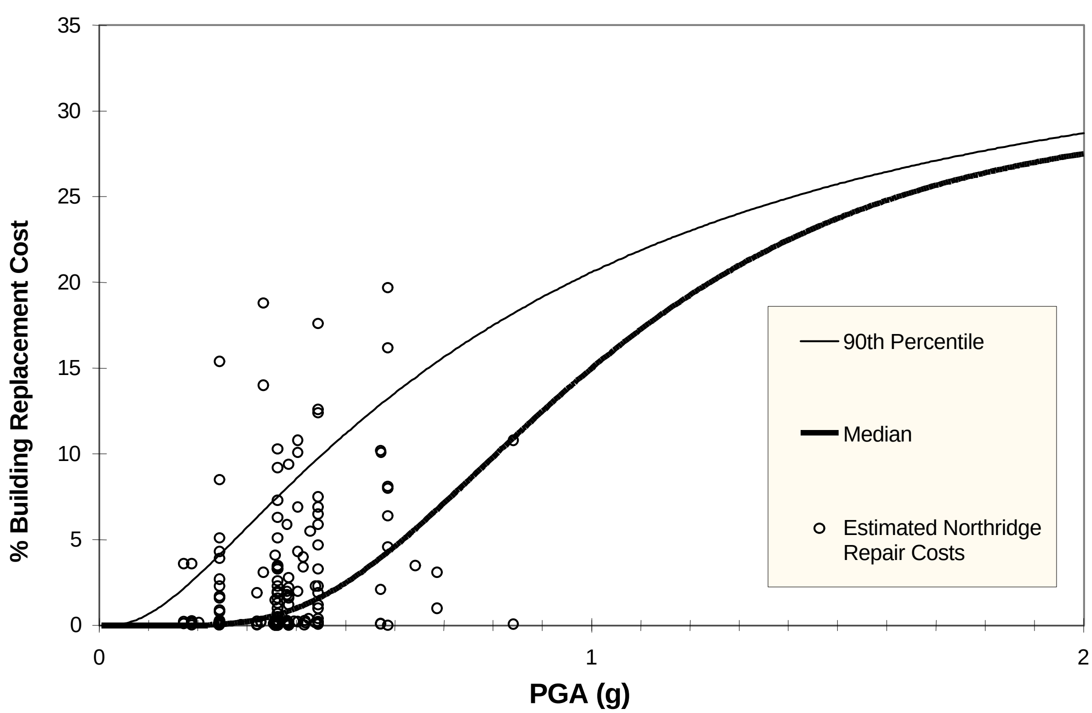

Figure 4-5 Connection Restoration Cost vs Peak Ground Acceleration (PGA)

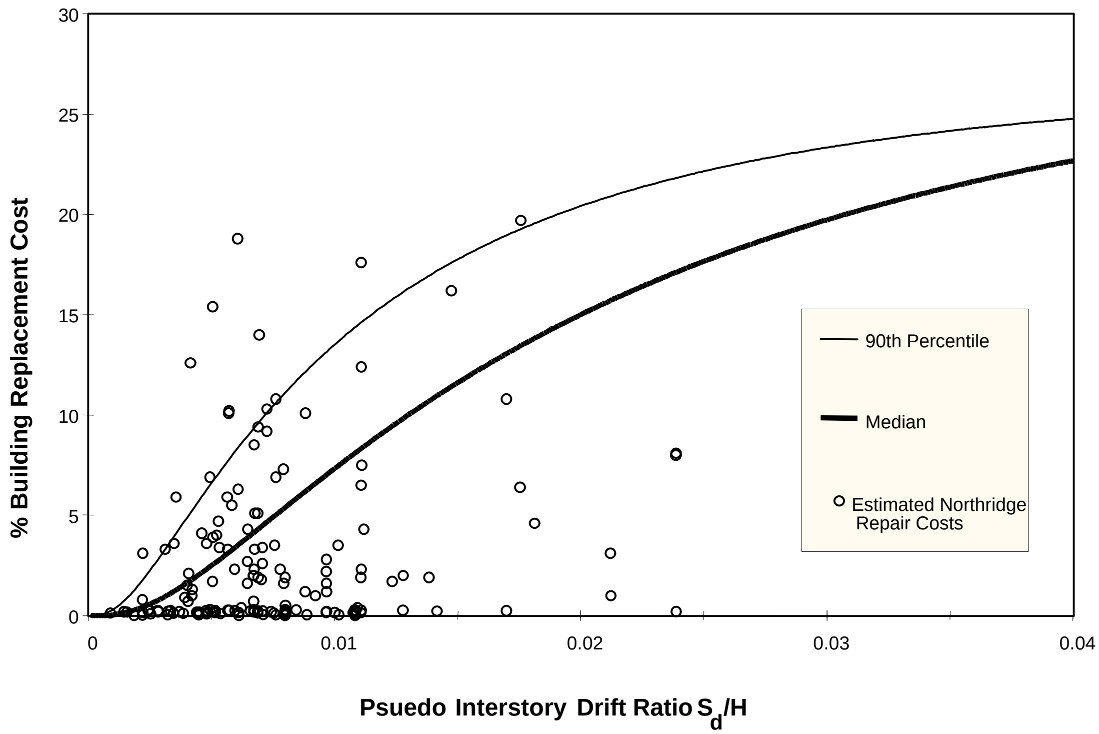

Figure 4-6 Connection Restoration Cost vs Building Pseudo Interstory Drift Ratio

impractical to accomplish. Thus if a building has experienced large permanent interstory drift, the effective cost of structural repair can be larger than indicated by these loss functions.

As a general rule, permanent interstory drift may be on the order of 1/3 to 1/2 of peak interstory drift. The AISC Standard Practice requires that erection of buildings produce a plumb within .005. Permanent interstory drifts of perhaps .01 may be tolerable in buildings, while drifts larger than this would probably require either straightening or loss of use of the building. These considerations have not been accounted for in the above loss functions.

4.3.5 Nonstructural Repair Cost Functions

Figures 4-7, 4-8 and 4-9 present nonstructural repair cost, expressed as a percentage of the building replacement value, as a function of MMI, PGA and PIDR, respectively. The costs are based on HAZUS unit costs and damage states and have been modified by expert opinion founded on 1994 Northridge earthquake experience and by engineering judgement. The unit costs are taken as Los Angeles commercial office types (professional, technical, and business services). Complete repair costs for acceleration-sensitive and drift-sensitive nonstructural building components are taken as $42 and $28 per sq. ft, respectively. These unit costs may serve as the basis for adjusting the loss functions for particular building situations.

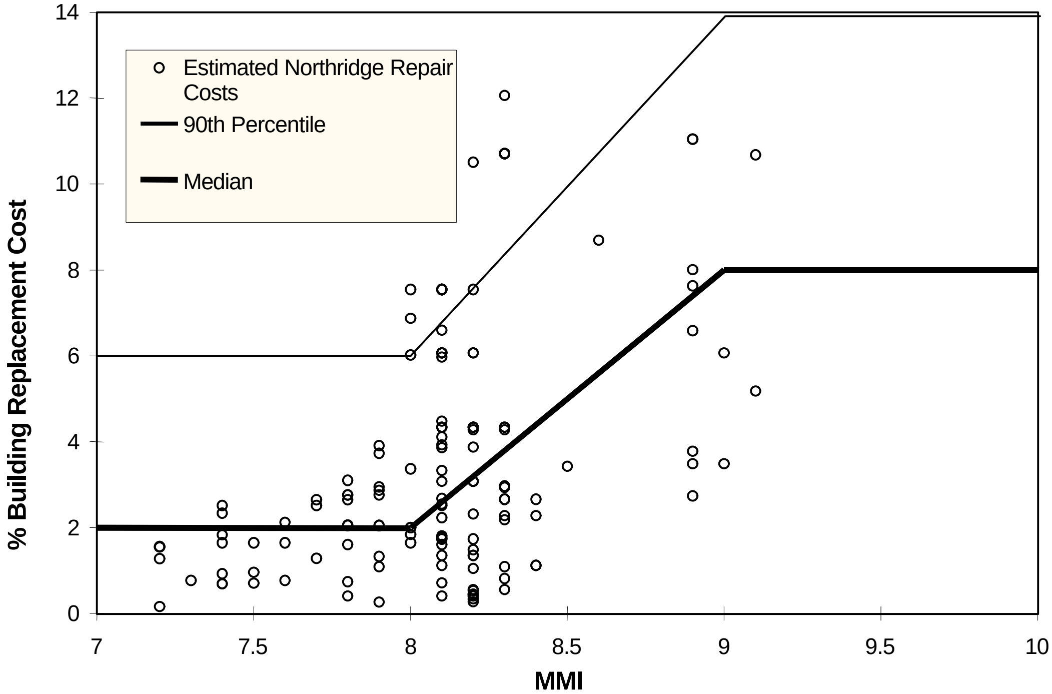

Figure 4-7 Nonstructural Repair Cost vs Modified Mercalli Intensity (MMI)

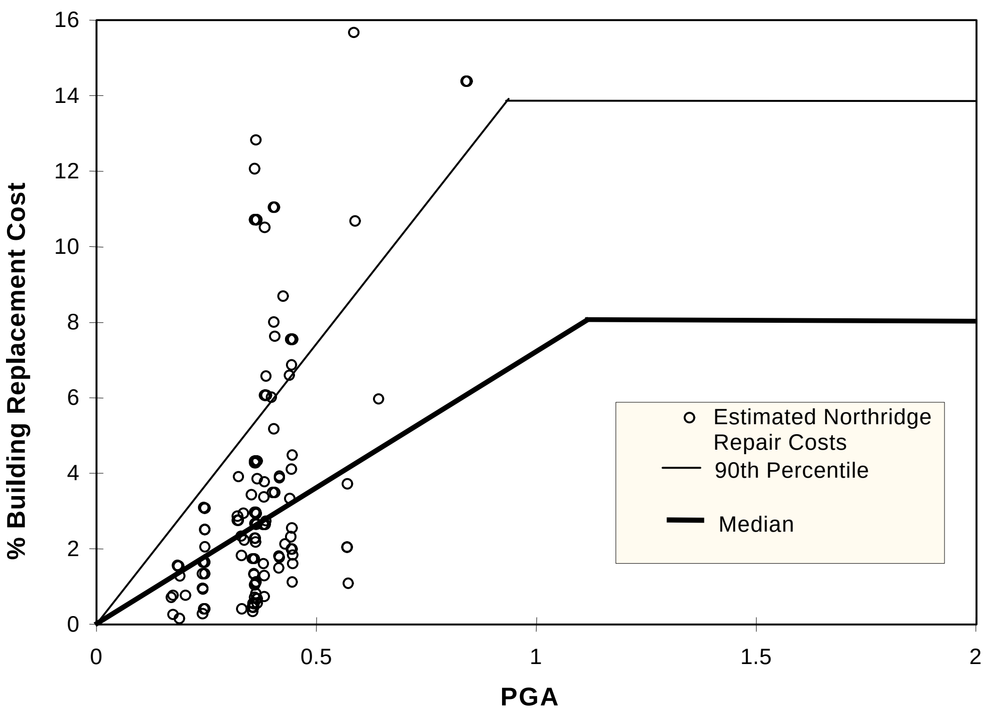

Figure 4-8 Non-Structural Repair Cost vs Peak Ground Acceleration (PGA)

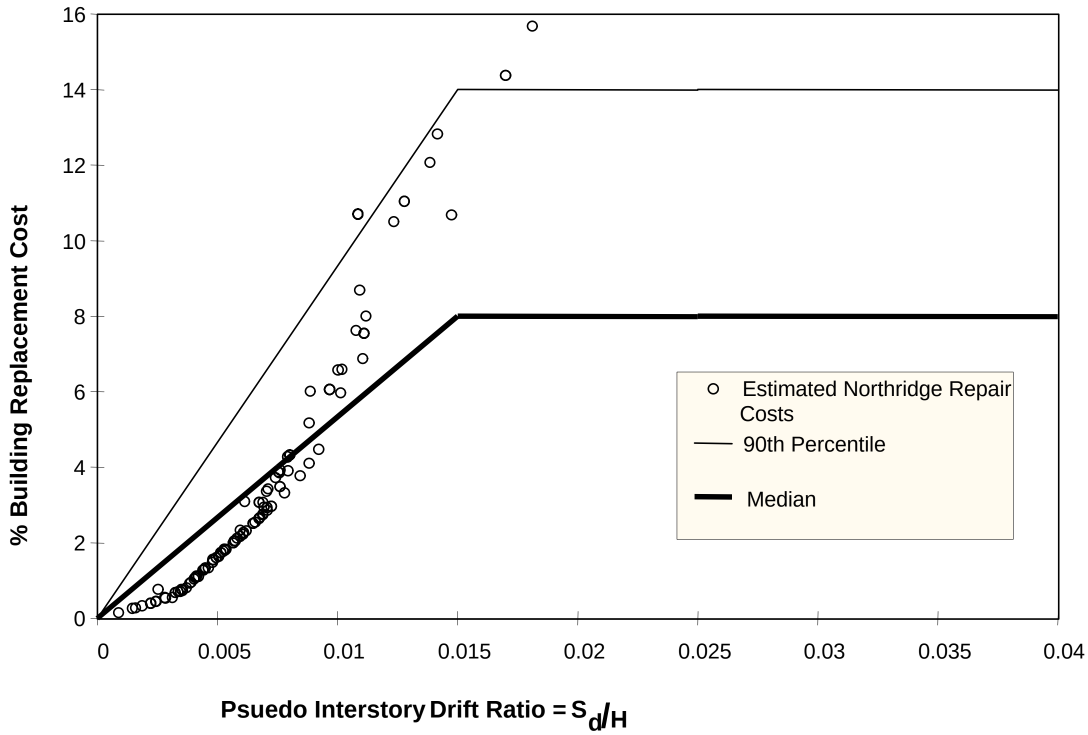

Figure 4-9 Nonstructural Repair Cost vs Building Pseudo Interstory Drift Ratio

Commentary: Nonstructural repair costs rely heavily on the information from the HAZUS project because very sparse quantitative information was available from the Northridge damage surveys. Pseudo (or implied) nonstructural repair costs were generated for each building in the sample and best-fit curves were generated by judgment. The descriptions of nonstructural damage from the Northridge building surveys suggested that the repair costs were generally less than that indicated by the curves. Hence, the curves were adjusted downward based on engineering judgement.