DAMAGING RESPONSE OF LOW-RISE BUILDINGS

by

R. E. Scholl[I] and J. A. Blume[II]

SYNOPSIS

Because low-rise buildings constitute a large percentage of buildings in inhabited earthquake-prone areas of the world, a large percentage of both economic and life losses sustained during past earthquakes have resulted from damage to low-rise buildings. This paper on such structures discusses the factors contributing to earthquake-caused damage, summarizes the available motion-damage relationship data, and presents some of the limitations of damage prediction and of earthquake-resistive design and construction.

INTRODUCTION

Damaging response of low-rise buildings to a severe earthquake will typically vary from what might be referred to as "threshold-damage" to "condemnation-level damage." In a severe earthquake, both damage extremes and the entire spectrum between them are likely to be exhibited. Frequently, the damage to individual structures is minor, but when large numbers of buildings are involved, the economic impact can be significant. At the other extreme, condemnation-level damage can be hazardous if it involves building collapse. A complete examination of low-rise building damage, therefore, includes consideration of both the economic loss as well as potential life loss. Most of the research on low-rise buildings has studied gross structural failures to identify framing techniques and materials that are particularly susceptible to collapse. Such studies have led to improvements in design and construction practice but have given little or no specific insight into the economic impact of damaging earthquakes to this class of structures.

URS/John A. Blume & Associates, Engineers (URS/Blume), has recently performed an intensive study of the response of low-rise buildings for the United States Energy Research and Development Administration (ERDA) in connection with its safety measures for underground nuclear explosions. A related study was conducted for the United States National Science Foundation. The objective of both studies was to improve low-rise response and damage prediction technology, particularly in the low-to-intermediate ground motion amplitude range, and this paper draws from both sets of data. URS/Blume research for ERDA included theoretical and experimental variation of parameter studies, experimental structural element tests, and the compilation of ground motion and damage data from earthquakes and underground nuclear explosions. The purpose of the threefold approach was to isolate various aspects of damage in order to identify an optimum assessment/prediction methodology.

[I] Director of Research, URS/John A. Blume & Associates, Engineers, San Francisco, California

[II] President, URS/John A. Blume & Associates, Engineers, San Francisco, California

DAMAGE PREDICTION FUNDAMENTALS

To predict damage requires consideration of the type of structures involved, associated damage criteria, and ground motion. Factors that contribute to or in some way influence damage must also be considered.

Low-Rise Structures. Low-rise structures include a broad range of materials, geometrical configurations, and types of assemblage. To develop a specific model for one building does little to identify the important aspects of another building. However, recognizing that damage manifests itself primarily through the overall deformation of a structure, that ground motions are rapidly time-varying, and that the deformations in a structure fall within the purview of dynamic response permits the formulation of some modeling generalizations for low-rise structure damage prediction purposes. The most important dynamic response characteristics are fundamental mode frequencies and damping, which fall generally in the range of 2 to 20 Hz, and 5 to 10% of critical, respectively.

Ground Motion. Earthquakes, high explosives, and underground nuclear blasting generate many forms of ground motions. The characteristics of ground motion that influence structure response are amplitudes, frequency content, duration, and periodicity. These characteristics are influenced by the source of the ground disturbance (earthquake, blast, etc.), the transmission path, and the receiving site. For most ground motion situations, however, the first two characteristics are of primary concern. Thus, different earthquakes as well as different underground blast configurations are likely to produce variations in ground motion and structure response.

Damage to Low-Rise Buildings. Damage to low-rise buildings occurs in various forms and degrees, depending on the type of construction (material and design) and the severity of ground shaking. The fundamental cause of damage is, of course, overstressing of structure members or connection failures. For intermediate-amplitude ground motions, the most frequently damaged components of low-rise buildings are (from most frequent to least frequent): masonry chimneys, interior walls, exterior walls, windows, and foundations. For low- to intermediate-amplitude ground motions, the damage is commonly in the form of minor cracking, with some failure of masonry chimneys. At high-amplitude ground motion, condemnation is not infrequent for wood-frame construction, and collapse is not uncommon for unreinforced masonry and adobe.

Other Factors. Damage prediction must also include consideration of differential foundation movement, shrinkage and expansion of materials, wind, ambient vibration, and aging. Most of these factors cause stresses and cracks in building members in much the same way as ground motion and must be recognized as inherent limitations to the precision of damage predictions, particularly for low-amplitude ground motion. Aging, because of the degradation implied, is an important factor for predictions involving high-amplitude ground motions.

MOTION-DAMAGE RELATIONSHIPS

Useful information from URS/Blume assessments of potential economic loss from earthquake or underground nuclear explosion-generated ground motion was derived from correlations of actual motion and damage data. Four sets of ground motion and corresponding low-rise building damage data were analyzed. Three of the data sets[1,2,3] were from underground nuclear explosions, and one was from the San Fernando, California, earthquake of February 9, 1974.[4]

The methodology used to correlate ground motion and damage for these various data sets consisted of relating two parameters -- damage ratio (DR) and damage factor (DF) -- with the corresponding 5%-damped response spectrum acceleration averaged over the frequency band of 5 to 20 Hz. The response spectrum curve used is the envelope of the two orthogonal horizontal components. The DR is the number of damaged buildings divided by the total number of buildings exposed (N), and the mean damage factor, m_{DF}, is

$$\frac{1}{N}\sum_{i=1}^{N} DF_i = \frac{1}{N}\sum_{i=1}^{N} \frac{\text{Damage Repair Cost for a Building}}{\text{Replacement Value of That Building}}$$

Figures 1 and 2, respectively, show plots of DR and m_{DF} versus spectral acceleration obtained from the four data sets. Each of the data points was from a single town or distinct area of a town and an event or earthquake. The curves drawn were established from a log domain linear regression analysis of the points in the 0.1g to 1.0g region and from a simple hand-fitted analysis through the NTS[2] and RIO BLANCO[3] data points in the 0.01g to 0.1g motion amplitude range. A measure of the variability of the damage factor statistics is given in Figure 3, with σ_{DF} defined by:

$$\sigma_{DF} = \left[\frac{1}{N-1}\sum_{i=1}^{N} (DF_i - m_{DF})^2\right]^{\frac{1}{2}}$$

The damage factor coefficient of variation, V_{DF}, is given in Figure 4. The information given in Figures 1 and 2 can be readily used to predict the expected (mean) damage for a given spectral acceleration. Information such as that given in Figures 3 and 4 can be used to predict bounds on dollar damage. A description of the methodology for predicting the bounds on damage is given in Chapter 6 of Reference 5.

DISCUSSION AND CONCLUSIONS

The motion-damage relationship information summarized here provides useful data for predicting damage to low-rise structures. These data have been derived for mostly wood-frame construction in the United States; therefore, judgment should be exercised in applying these results to other situations. The data in the low-amplitude range were verified in that the relationships derived from the NTS study[2] agree in substance with those derived from the RIO BLANCO study.[3]

A ground motion threshold for incipient damage has been under investigation for many years. The data presented here suggest that it is significantly lower than previously expected. Low-rise building damage seems to approach zero at a motion amplitude equivalent to the effects of differential ground movement, ambient vibrations, wind, and similar phenomena.

A substantial portion of the damage to low-rise buildings in the intermediate-amplitude range of motion involves the partial or complete failure of masonry chimneys.[4,5,6] Other studies[7,8] have also alluded to the severity of masonry chimney damage and show that economic loss and life risk are associated with this common low-rise structure component. While all forms of buildings (wood-frame, masonry, or adobe) are prone to damage from intermediate-amplitude ground motions, none except those of very poor construction present major life loss risk.

For high-amplitude ground motions such as those near the epicenter of a Richter Magnitude 6 or greater earthquake, severe damage (frequently approaching condemnation level) can be anticipated for almost any of the common construction methods. Most wood-frame buildings and the construction practices associated with them in the United States[8,9] have been shown to be highly resistant to collapse while experiencing condemnation-level damage. This superior performance is due to the materials used and also to the construction practice employed.

Recent severe earthquakes in South and Central America have shown that condemnation-level damage for low-rise buildings is nearly synonymous with collapse. The adobe and other materials commonly used in low-rise buildings are factors contributing to the collapse, but simple improvements in design and construction practice could nevertheless reduce life loss significantly with minor increase in cost.

REFERENCES

1. Scholl, R. E., and I. Farhoomand, "Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage," *Bulletin of the Seismological Society of America,* Vol. 63, No. 5, October 1973.
2. Scholl, R. E., "Low-Rise Building Damage for Low-Amplitude Ground Motions," *Bulletin of the Seismological Society of America,* December 1974.
3. Scholl, R. E., "Project RIO BLANCO Low-Rise Building Damage Study," URS/John A. Blume & Associates, Engineers, JAB-NSF-01, San Francisco, December 1975.
4. Scholl, R. E., "Statistical Analysis of Low-Rise Building Damage Caused by the San Fernando Earthquake," *Bulletin of the Seismological Society of America,* Vol. 64, No. 1, February 1974.
5. URS/John A. Blume & Associates, Engineers, *Effects Prediction Guidelines for Structures Subjected to Ground Motion,* JAB-99-115, U.S. Energy Research and Development Administration, July 1975.
6. Farhoomand, I., and R. E. Scholl, *Observations of Chimney Damage to Residential Buildings in Glendale, California: San Fernando Earthquake, February 1971,* John A. Blume & Associates Research Division, JAB-99-88, 1972.
7. Steinbrugge, K. V., F. E. McClure, and A. J. Snow, *Study in Seismicity and Earthquake Damage Statistics,* Environmental Science Services Administration, Coast and Geodetic Survey, 1969.
8. McClure, F. E., *Performance of Single Family Dwellings in the San Fernando Earthquake of February 9, 1971,* PB-226-293, Department of Housing and Urban Development, Washington, D.C., May 1973.
9. USDA Forest Service, *Wood Structure Performance in an Earthquake in Anchorage, Alaska,* U.S. Forest Products Laboratory, Madison, Wisconsin, August 1964.

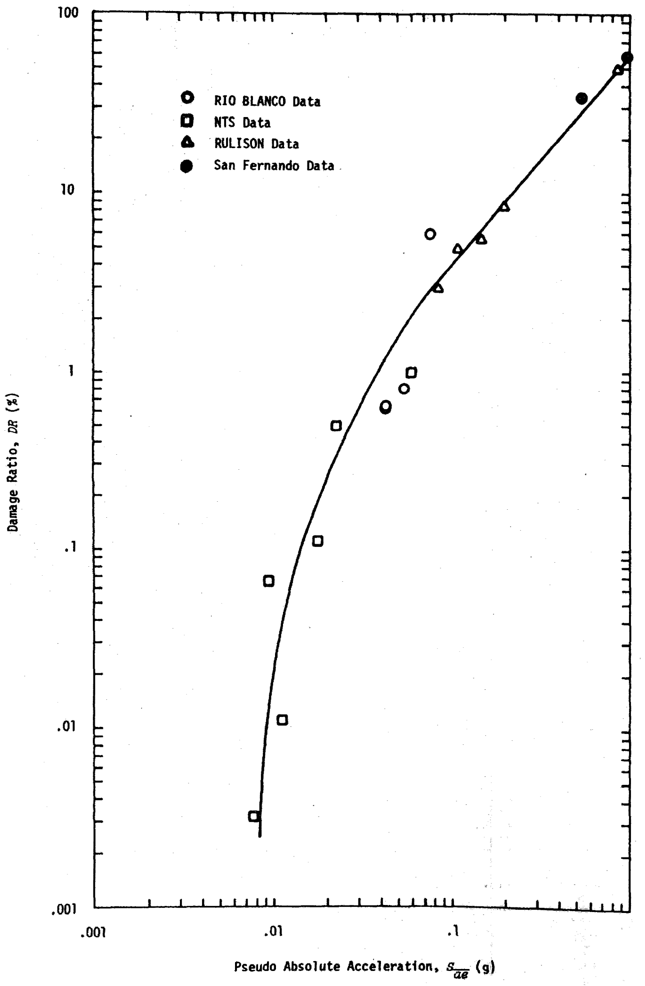

FIGURE 1 DAMAGE RATIO VERSUS SPECTRAL ACCELERATION

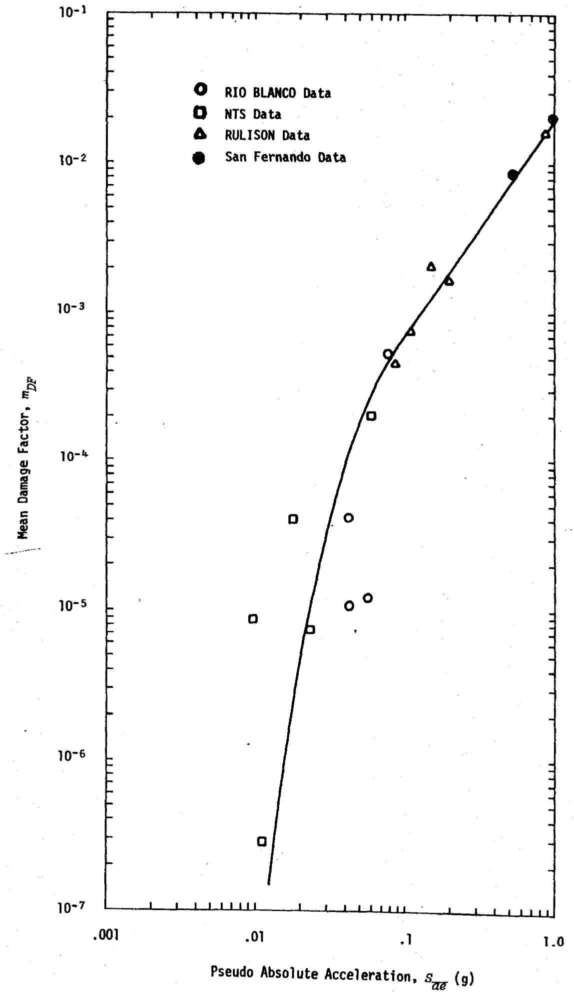

FIGURE 2 MEAN DAMAGE FACTOR VERSUS SPECTRAL ACCELERATION

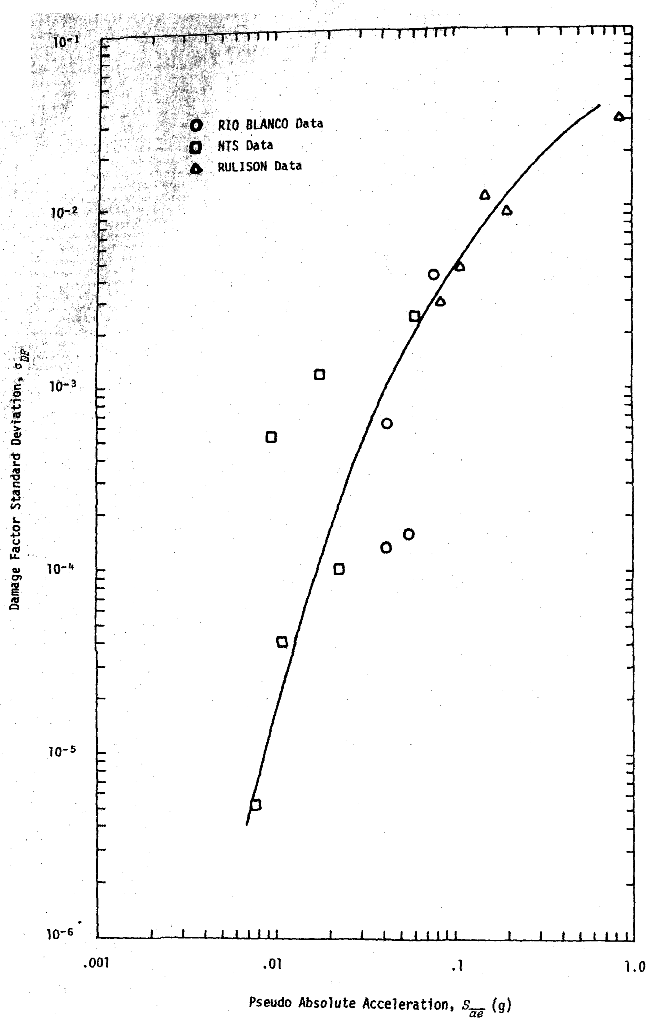

FIGURE 3 DAMAGE FACTOR STANDARD DEVIATION VERSUS SPECTRAL ACCELERATION

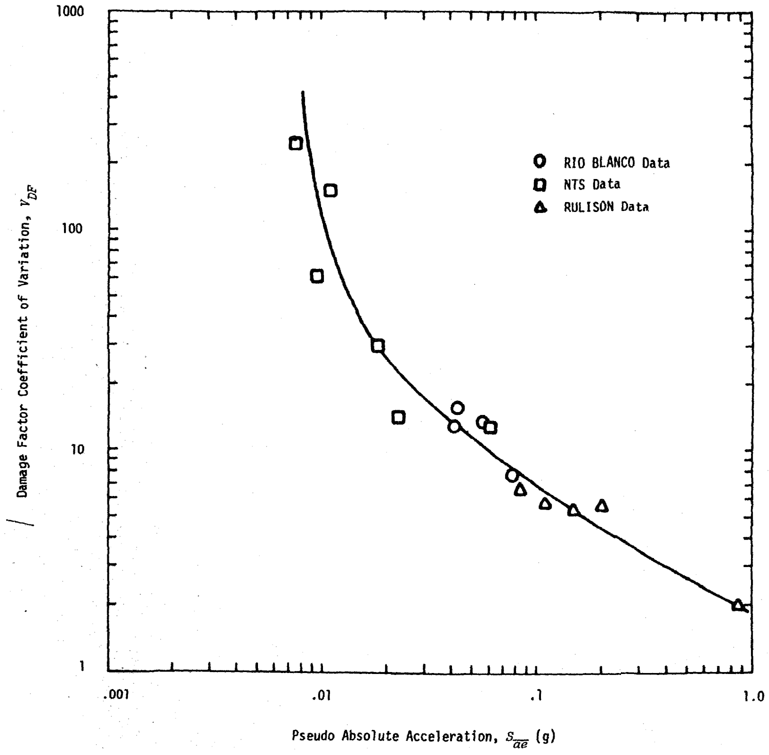

FIGURE 4 DAMAGE FACTOR COEFFICIENT OF VARIATION VERSUS SPECTRAL ACCELERATION