

EARTHQUAKE DAMAGE PROBABILITY MATRICES

by

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SYNOPSIS

A format is presented for organizing and portraying statistical data concerning damage to buildings caused by earthquake. This format uses 9 categories of damage, identified both by subjective word descriptions and by ratio of damage cost to building replacement cost. The form of such statistical damage information is illustrated by data collected for damage caused by the 1971 San Fernando earthquake, and the trends brought out by these data are discussed.

INTRODUCTION

In any systematic analysis of earthquake risk or optimum seismic protection (1, 5, 6), it is necessary to express the degree of damage that will be experienced by a set of buildings when these buildings are exposed to different intensities of ground shaking. Even similar buildings will respond somewhat differently to a given ground shaking. Moreover, minor details in the pattern of ground motion can significantly influence the response of a building, and these details vary among ground motions all having the same nominal intensity. Hence the degree of damage must be expressed in probabilistic terms. Fig. 1 shows the form of the damage probability matrix (DPM) used in this study. Each number in the matrix is the probability that a building will experience a particular level of damage as the result of a particular intensity. The probabilities in each column must sum to unity or to 100%.

Two general approaches may be used to develop DPMs. One approach is to compile statistics empirically from experiences during actual earthquakes. This first approach relates damage directly to some measure of intensity. Alternatively, the response (and damage) of buildings to various ground motions may be predicted by theoretical dynamic analysis.

This paper presents empirical DPMs compiled from a survey of damage to buildings, having 5 or more stories, shaken by the San Fernando

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earthquake of 9 February 1971.

DAMAGE STATES

To describe and categorize the damage that a building might experience, a set of damage states has been developed. This scale of damage, shown in Figs. 1 and 3, runs from 0 to 8. Each damage state is identified by: (a) a subjective description of physical damage, and (b) an objective ratio of repair cost to replacement cost. The relationship between the two identifiers has been developed from experience during the San Fernando earthquake, but is believed to have general applicability. While the DPMs presented in this paper are based upon actual repair costs; for other earthquakes, only the more qualitative damage information may be available. More specific and detailed damage descriptions have been developed, but must vary for different classes of buildings based upon the details of construction.

It must be emphasized that the cost ratios in Fig. 1 are primarily a means for identifying a damage state, and in general are not the true cost of a particular level of damage. Replacement cost at the time of the earthquake has been used since it is a more-or-less definite quantity and independent of changable factors such as assessing practice, market conditions and inflation. For certain types of risk studies, the ratio of repair cost to market value might be a more meaningful statistic; such a conversion can always be made by the user of the DPMs. More importantly, there may be important monetary, human and social costs in addition to the direct repair cost: injuries and death, loss of income, etc. Such associated costs, while linked to the damage state, vary depending upon the value attached to human and social losses.

A probability damage matrix is a set of probability mass functions for damage, given the intensity. As is true for most probability mass functions, it is difficult to evaluate with confidence each number in a column of a damage probability matrix. For some applications, it may suffice to use mean damage ratios (MDRs): that is, for each intensity, evaluate only the expected value of damage. If only repair costs were of interest, then the MDR as a function of intensity (plus possibly some measure of the variance from this mean) would provide essentially all of the information needed for risk studies. However, associated costs usually will be determined by the likelihood that high damage states will occur, and hence it usually is necessary to assume the specific probabilities for these higher states. However, MDR is at least a useful indication of the relative damage to different types of buildings during different earthquakes.

SAN FERNANDO EARTHQUAKE DAMAGE SURVEY

The ideal way to prepare damage statistics is to start with a complete list of buildings, together with their pertinent characteristics, and then determine the nature, and actual cost of repair, of damage. Buildings that were strongly shaken but had little or no damage are of as much interest as heavily damaged buildings, since they indicate a measure

of success in earthquake resistant design.

The MIT survey of damage caused by the San Fernando earthquake specifically covered buildings having 5 or more stories. There were several reasons for these restrictions: (a) others were studying damage to low residential buildings, and (b) there was a desire to focus upon buildings in which engineering design plays an important role. No list of such buildings was available at the start of the survey; hence it was necessary to piece together a list from various sources.

It was determined that there were approximately 1600 such buildings within area of the map in Fig. 2. About 40% of these buildings were built prior to 1933 when building codes did not specifically require earthquake resistant design. Another 56% were built since 1947 under modern code provisions. Ignoring the relatively few tall buildings constructed during the Depression and World War II (1933 - 1947), the distribution of these buildings according to age, height and intensity zone is given in Table 1. Thus far in the study, intensity of ground shaking has been represented by the modified Mercalli (MM) scale. Most of the buildings were within the zone of MM VII, where the measured peak horizontal ground accelerations ranged from about 0.1g to about 0.2g. (In a subsequent stage of the study, a more quantitative measure of the intensity of ground shaking will be used.) This final list undoubtedly still is not entirely correct, containing some structures that do not belong and omitting some that belong. However, this list gives a very adequate picture of the number and type of buildings shaken by the earthquake.

While considerable information was already available concerning buildings with considerable damage (2, 4), it became necessary to utilize a questionnaire to obtain statistics concerning less-damaged buildings. A sample, one-page questionnaire was developed, asking owners for data on building characteristics, total repair cost, and breakdown by type of damage (structural, partitions, mechanical, etc.). About 1240 questionnaires were sent, with a covering letter from the Building Owners and Managers Association (BOMA). Unanswered questionnaires were followed up by telephone and visits. By these questionnaires, plus lesser amounts of information from other sources, damage costs were assembled for about 370 buildings. Table 2 gives the breakdown of these buildings by age, intensity zone and height (omitting the few buildings built between 1933 - 1947).

All of the data concerning building characteristics and damage cost was digitized for storing and processing by computer. DPMS and MDRs can be generated by the computer for different building types, different ages of buildings, different assumptions concerning boundaries between intensity zones, different methods for relating replacement cost to building characteristics, etc. The results presented in the following section are based upon the intensity zones in Fig. 2; buildings in areas where the intensity clearly exceeded VIII are excluded from the survey. In constructing DPMS, buildings were assigned to damage states on the basis of damage ratio, using the best estimate for damage cost and the best estimate of replacement cost. Where possible, replacement cost was evaluated as the permit value inflated to the date of the San Fernando earthquake. Alter-

natively, replacement cost was evaluated from building area times an average building cost per unit area. MDRs were computed by averaging the actual, individual damage ratios.

DAMAGE MATRICES AND DAMAGE RATIOS FOR SAN FERNANDO EARTHQUAKE

The damage that occurred in MM VII of the San Fernando earthquake is summarized in Table 3 in the form of damage probabilities. Buildings have been divided into several different categories according to date of construction, height and type of construction (concrete or steel). The results do show clearly that buildings designed under modern codes did fare better than the older buildings. The apparent erratic behavior of the probabilities in any column may be due in part to the range of damage ratios used for each damage state.

Since data was obtained for fewer buildings in intensity MM VI and VIII, it is less meaningful to construct DPMs for different building heights and type of construction. Table 4 presents results when all buildings in an age group are lumped together. The expected increase in damage with increasing intensity is very evident. The damage was very small in MM VI. (Note that modern buildings actually had more damage than old buildings in this zone.) In MM VIII, the damage, especially to concrete buildings, was quite significant.

These trends emerge even more clearly when the mean damage ratios (MDRs) are examined. A few other observations may be made from study of the MDRs:

1. For the newer buildings in MM VII, the MDR decreases as the story height increases above the 8 to 13 story range (see Fig. 4). This may represent confirmation of the frequently heard belief that the current code is more conservative for very tall buildings than for short buildings. Alternatively, it may simply mean that more attention is paid to the design details of unusually tall buildings.
2. For the older steel buildings in MM VII (and also in MM VI although the data are not shown), the damage to steel buildings may indicate an adverse matching between the periods of the older, taller buildings and the predominant period of the ground motion at these moderate distances from an epicenter.
3. Considering all post-1947 buildings, the MDR attenuates more rapidly with distance for 5 to 7 stories than for 8 to 13 stories (see Fig. 5). These trends undoubtedly are related to differences in the rate of attenuation of high and low frequency components of the ground motion.
4. Considering all buildings, concrete buildings in zone VII were slightly more damaged than steel buildings. (However, in their specific groups this pattern might reverse.) The difference was marked in zone VIII: MDR = 16% for concrete vs. 0.4% for steel.

Since there were many buildings in each sample category, it is believed

that these trends are a realistic picture of actual behavior,

Information concerning the breakdown of total damage cost was also documented. For buildings in intensity zone VI, the damage was approximately 5% structural, 5% elevators and 90% partitions and finish. For newer buildings in zone VII, these numbers were approximately 20% structural, 5% mechanical, 10% elevators and 65% partitions and finish. In zone VIII, even though the total dollars spent for repairs increased, the percentage of these repairs spent on structural damage decreased.

Many of the trends noted above have already been observed by others based on limited data (4). This detailed and extensive study of damage caused by the San Fernando earthquake has served to document these trends in probabilistic terms.

STUDIES OF OTHER EARTHQUAKES

Damage probability matrices are also being generated for other earthquakes for which adequate records of both damage and non-damage are available or can be reconstructed. Since actual damage costs are usually not available, it has been necessary to use subjective descriptions of damage. The effort of compiling these DPMs, and comparing them with those for the San Fernando earthquake, is still in progress.

CONCLUSIONS

A methodology has been described for compiling and presenting statistics concerning damage to different types of buildings as result of earthquakes having different intensities. Statistics from the 1971 San Fernando earthquake have been presented, and the trends suggested by these statistics have been noted. While the data available today are adequate, when supplemented by theoretical studies, for initial estimates of earthquake risk, it will be important to document additional data of this type during future major earthquakes.

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Table 1
NUMBER OF HIGH-RISE BUILDINGS
SHAKEN BY EARTHQUAKE

No.	MM Intensity					
	Pre-1933			Post-1947		
Story	VI	VII	VIII	VI	VII	VIII
5-7	36	346	0	117	321	20
8-13	21	236	0	79	231	6
14-18	2	8	0	36	37	0
19+	0	2	0	12	41	0
Total	57	592	0	244	630	26

Table 2
NUMBER OF BUILDINGS WITH DOCUMENTATION
OF BUILDING VALUES AND DAMAGE COSTS

No.	MM Intensity					
	Pre-1933			Post-1947		
Story	VI	VII	VIII	VI	VII	VIII
5-7	10	33	14	41	14	
8-13	9	78	28	70	4	
14-18	0	2	12	19	0	
19+	0	1	3	26	0	
Total	19	114	57	156	18	

Table 3
DAMAGE PROBABILITIES (%) AND MEAN DAMAGE RATIOS (%) FOR
INTENSITY VII ZONE OF SAN FERNANDO EARTHQUAKE

Date Const.	Pre-1933				Post-1947					
	5-7		8-13		5-7		8-13		14-18	19+
No. Stories	Co	St	Co	St	Co	St	Co	St	St	St
Type of Const.	Co	St	Co	St	Co	St	Co	St	St	St
Damage State										
0	16	18	16	6	21	24	27	44	43	21
1	16	9	12	13	26	28	33	31	43	54
2	26	46	28	53	16	38	32	6	0	25
3	21	27	14	16	26	5	8	16	14	0
4	11	0	21	0	11	5	0	3	0	0
5	0	0	7	9	0	0	0	0	0	0
6	10	0	2	3	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
MDR - %	4.4	1.1	2.7	2.5	1.1	.66	.43	.52	.43	.24
No. Bldgs.	19	11	43	32	19	21	37	32	14	24

Table 4
 DAMAGE PROBABILITIES (%) AND MEAN DAMAGE RATIOS (%)
 FOR ALL BUILDINGS IN VARIOUS INTENSITY ZONES
 OF SAN FERNANDO EARTHQUAKE

<u>Date Const.</u>	<u>Pre-1933</u>		<u>Post 1947</u>		
	<u>VI</u>	<u>VII</u>	<u>VI</u>	<u>VII</u>	<u>VIII</u>
<u>Intensity</u>					
<u>Damage State</u>					
0	90	14	79	33	6
1	10	12	18	34	17
2	0	35	3	20	39
3	0	18	0	10	11
4	0	11	0	3	5
5	0	6	0	0	11
6	0	4	0	0	6
7	0	0	0	0	5
MDR - %	0.03	2.8	0.05	0.5	7.5
<u>No. Bldgs.</u>	<u>19</u>	<u>114</u>	<u>57</u>	<u>156</u>	<u>18</u>

<u>DAMAGE STATE</u>	<u>STRUCTURAL DAMAGE</u>	<u>NON-STRUCTURAL DAMAGE</u>	<u>DAMAGE RATIO (%)</u>	<u>INTENSITY OF EARTHQUAKE</u>				
				<u>V</u>	<u>VI</u>	<u>VII</u>	<u>VIII</u>	<u>IX</u>
0	None	None	0-0.05	X	X	X	X	X
1	None	Minor	0.05-0.3	X	X	X	X	X
2	None	Localized	0.3-1.25	X	X	X	X	X
3	Not noticeable	Widespread	1.25-3.5	X	X	X	X	X
4	Minor	Substantial	3.5-7.5	X	X	X	X	X
5	Substantial	Extensive	7.5-20	X	X	X	X	X
6	Major	Nearly total	20-65	X	X	X	X	X
7	Building Condemned		100	X	X	X	X	X
8	Collapse		100	X	X	X	X	X

Fig. 1 Format For Damage Probability Matrix

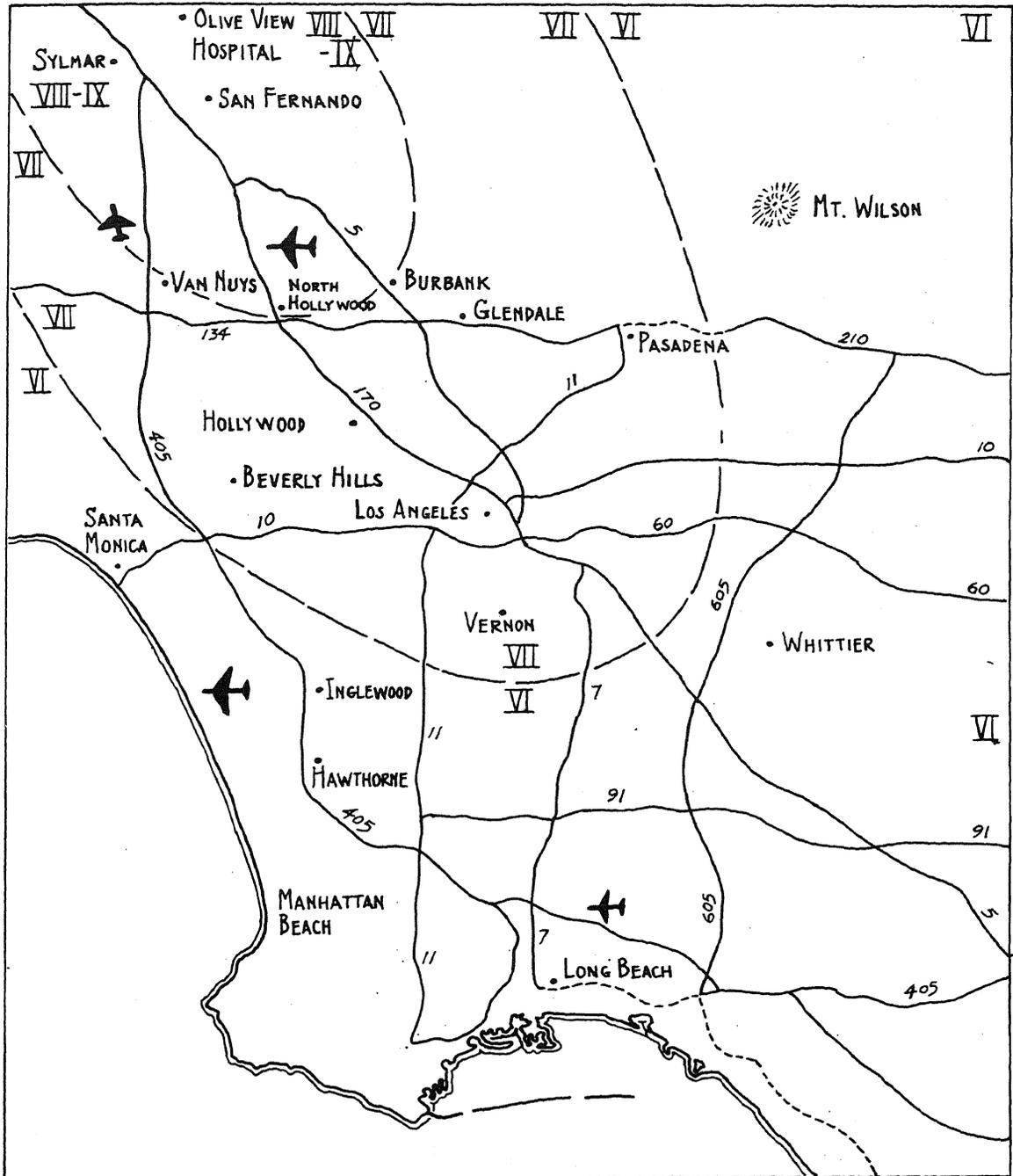


FIGURE 2 GEOGRAPHICAL AREA OF STUDY
 SHOWING FREEWAYS, AIRPORTS
 AND ISOSEISMALS

- 0 No Damage
- 1 Minor non-structural damage--a few walls and partitions cracked, incidental mechanical and electrical damage
- 2 Localized non-structural damage--more extensive cracking (but still not widespread); possibly damage to elevators and/or other mechanical electrical components
- 3 Widespread non-structural damage--possibly a few beams and columns cracked, although not noticeable
- 4 Minor structural damage--obvious cracking or yielding in a few structural members; substantial non-structural damage with widespread cracking
- 5 Substantial structural damage requiring repair or replacement of some structural members; associated extensive non-structural damage
- 6 Major structural damage requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs
- 7 Building Condemned
- 8 Collapse

FIG. 3 DESCRIPTION OF DAMAGE STATES

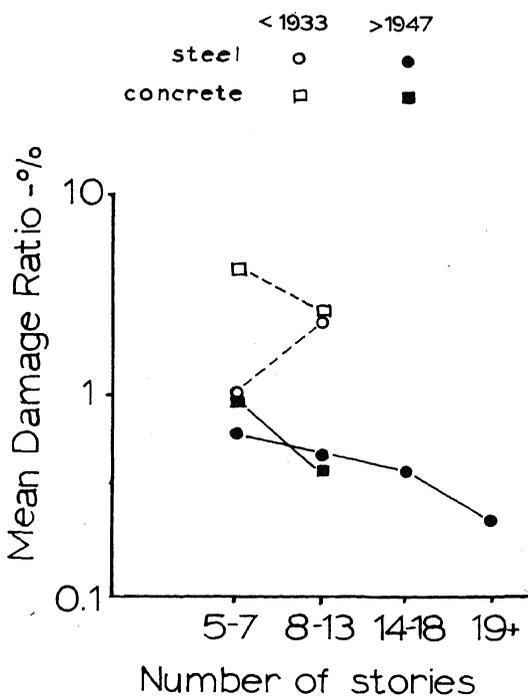


FIG. 4 VARIATION OF DAMAGE WITH BUILDING HEIGHT FOR INTENSITY VII

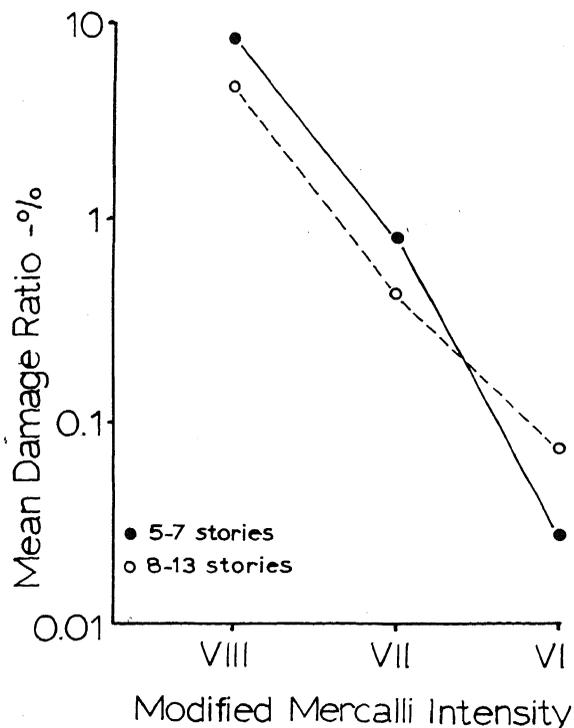


FIG. 5 VARIATION OF DAMAGE WITH INTENSITY FOR POST-1947 BUILDINGS