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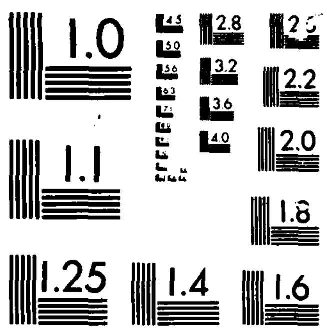
UNCLASSIFIED F/G 13/13 NL



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R-918

March 1986

By T.K. Lew

Sponsored By Naval Facilities
Engineering Command

NCEL
Technical Report

HISTORIC EARTHQUAKE DAMAGE FOR BUILDINGS AND DAMAGE ESTIMATED BY THE RAPID SEISMIC ANALYSIS PROCEDURE: A COMPARISON

ABSTRACT As part of the Navy's earthquake hazard reduction program, selected structures at various Navy activities were analyzed by the rapid seismic analysis (RSA) procedure to determine their seismic adequacy. Those buildings found to be inadequate were then analyzed in detail to determine the estimated cost. The RSA-estimated damages for steel, concrete, masonry, wood, and brick buildings were compared with historic earthquake damage data. Results indicate reasonably good agreement between the RSA-estimated damage and historic earthquake damage data.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

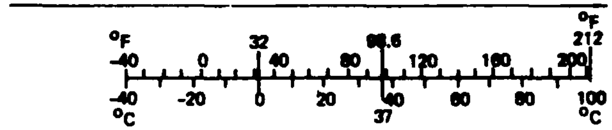
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ADA 166963

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: TR-918	2. GOVT ACCESSION NO.: DN887078	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): HISTORIC EARTHQUAKE DAMAGE FOR BUILDINGS AND DAMAGE ESTIMATED BY THE RAPID SEISMIC ANALYSIS PROCEDURE: A COMPARISON		5. TYPE OF REPORT & PERIOD COVERED: Final; Oct 1984 – Sep 1985
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): T. K. Lew		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: NAVAL CIVIL ENGINEERING LABORATORY, Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 51-086
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Facilities Engineering Command, Alexandria, Virginia 22332		12. REPORT DATE: March 1986
		13. NUMBER OF PAGES: 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report): Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Damage function, earthquake damage, maximum ground acceleration, replacement cost

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

As part of the Navy's earthquake hazard reduction program, selected structures at various Navy activities were analyzed by the rapid seismic analysis (RSA) procedure to determine their seismic adequacy. Those buildings found to be inadequate were then analyzed in detail to determine the degree of strengthening required to reduce the potential damage and the estimated cost. The RSA-estimated damages for steel, concrete, masonry, wood, and brick buildings were compared with historic earthquake damage data. Results indicate

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20. Continued

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TR-918 38 pp illus March 1986 Unclassified

1. Earthquake damage 2. Replacement cost I. 51-086

As part of the Navy's earthquake hazard reduction program, selected structures at various Navy activities were analyzed by the rapid seismic analysis (RSA) procedure to determine their seismic adequacy. Those buildings found to be inadequate were then analyzed in detail to determine the degree of strengthening required to reduce the potential damage and the estimated cost. The RSA-estimated damages for steel, concrete, masonry, wood, and brick buildings were compared with historic earthquake damage data. Results indicate reasonably good agreement between the RSA-estimated damage and historic earthquake damage data.

CONTENTS

INTRODUCTION

Before the 1933 Long Beach, Calif., earthquake, seismic effects were generally not considered in the design and construction of Navy structures. Some seismic design and construction requirements were relaxed during World War II because of the shortage of material and skilled workers. Since then, essentially all Navy structures have been designed and constructed according to the prevalent codes. Earthquake design force levels, however, have increased, and design criteria have changed over the years as more earthquake ground motion and damage data become available. Consequently, a building completed 15 years ago may not be able to satisfy the current seismic design criteria.

As part of the Navy's earthquake hazard reduction program, essential*, critical**, and other important structures at various Navy activities have been analyzed by the rapid seismic analysis (RSA) procedure (Ref 1 and 2) to determine their seismic adequacy according to the current Naval Facilities Engineering Command (NAVFAC) ground motion criterion: of maximum ground acceleration with an 80% probability of not being exceeded in 50 years. The aim of the RSA procedure is to identify those buildings that may be susceptible to severe damage.

The RSA procedure was initially developed by John A. Blume and Associates in a pilot study of a relatively large number of buildings at the Puget Sound Naval Shipyard in 1973. Since then, the procedure has been formalized and enhanced by the Naval Civil Engineering Laboratory (NCEL).

The seismic investigation at a Navy activity may be divided into two phases. In Phase I, the selected buildings at the activity are analyzed by the RSA procedure. Those buildings found to be inadequate in Phase I are analyzed in detail during Phase II to determine the degree of strengthening required to reduce the potential damage and the estimated cost.

The major steps of the RSA procedure*** are:

- Select the buildings (by screening and visual inspection).
- Investigate geological site hazards.
- Perform a visual survey of lifeline utilities.

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*Essential structures are those that provide disaster control, recovery, and communications capability. Mission-essential structures are those that serve a military mission that requires them to remain functional during and after an earthquake.

**Critical structures are those that contain material that if released would create a secondary hazard to surrounding structures and personnel nearby.

***For more details about the RSA procedure, the reader should refer to References 1 and 2.

- Determine the site response spectra.

- Estimate the structural properties (natural periods, damping, and base shear capacities) at the yield and ultimate levels for the transverse and longitudinal directions of each building.

- Estimate the damage from the demands by the site response spectra and base shear capacities of the building.

- Select the buildings for detailed analysis according to the estimated damage and engineering experience and judgment.

Because of the large number of structures at each Navy activity, it is generally not economically feasible nor practical to screen or perform rapid analysis on all the buildings. The following criteria are used to select buildings for field screening:

1. Structures constructed before 1973.

2. Buildings with greater than 3,000 ft^2 of floor area.

3. Structures in seismic zones 3 and 4, and only essential structures in seismic zone 2.

4. Structures not earth covered.

5. Structures with a replacement cost of more than $200,000.

6. Structures not scheduled for replacement within 5 years.

7. One-story, lightweight timber or preengineered steel buildings.

8. Other structures selected by the Public Works Office at the activity.

Structures constructed after 1973 are generally more seismic resistant than those constructed before because of the lessons learned from the 1971 San Fernando earthquake and later code changes to reflect these lessons. Criteria 2 and 5 eliminate the smaller buildings in the 2,500- to 3,000-ft^2 range. These smaller buildings have generally responded well in past major earthquakes because of their relatively large linear foot of wall per square foot of floor area as compared to buildings with larger floor areas. Both results of analyses and experience in past major earthquakes indicate that earth-covered structures are generally quite resistant to earthquake damage. Criterion 6 may eliminate some of the weaker structures (i.e., structures scheduled for replacement are likely to be weaker than the general building population).

Even with the screening criteria, there are still too many buildings that have to be analyzed by the RSA procedure at the current (1985) cost of about $2,000 per building in Phase I. The following criteria are suggested for eliminating buildings from further study:

1. Buildings that are essentially identical to those chosen for analysis. Results of those analyzed are applicable to those not investigated.

2. Buildings with foundation problems, such as extreme ground settlement which results in footing or pile damage. Such buildings should be analyzed in detail and repaired as part of the normal maintenance program.

3. Structures that cannot be reliably analyzed with the RSA procedure, such as large buildings with complex lateral force-resisting systems whose vertical or horizontal configurations are highly irregular. Such buildings should be analyzed in detail during Phase II.

In general, the criteria used to screen and select buildings for analysis by the RSA procedure eliminate the more seismic resistant or newer buildings at a given site. Thus, the buildings analyzed tended to be biased toward the weaker ones. The estimated damage for the buildings is expected to be somewhat larger than the historic damage for the same type of buildings.

The site response spectra determine the demand or loading on the structures analyzed by the RSA procedure. Because of the procedures used and conservatism involved in the determination of the maximum ground accelerations (50 percentile) and the site response spectra (84 percentile), the loading thus obtained for a given maximum ground acceleration at the site represents a near upper bound value. That is, there is less than about a 10% chance that the loading experienced by a building with a given damping and natural period would be greater than that indicated by the response spectrum (Ref 3).

In determining the damping and compute the natural periods and base shear capacities, necessary assumptions were made at each step along the way. The rapid analysis results are compared with historic damage data from past major earthquakes to assess the adequacy of the RSA procedure in predicting earthquake damage.

Currently, Phase I of the rapid seismic investigations is about 80% completed. Over 1,500 buildings at more than 50 different Navy activities have been analyzed. Detailed seismic analysis has been performed on some of the buildings. Seismic strengthening has been carried out on a few of these buildings.

Objective

The objective of this investigation is to compare the RSA-estimated damages for steel, concrete, masonry, wood, and brick buildings with historic earthquake damage data for similar buildings.

Approach

To satisfy the objectives of this investigation, average historic earthquake damage data for 10 different types of construction in the form of percent damage versus the Modified Mercalli Intensity (Ref 4)

(MMI) were transformed to percent damage versus maximum ground acceleration (MGA). The RSA data for 750 buildings at 22 different selected Navy activities were separated into five groups: steel, reinforced concrete, reinforced masonry, wood, and unreinforced brick. The estimated average damages for each building group were computed for MGAs between 0.05 and 0.5g at 0.05g increments. The RSA damage data were compared with the appropriate historic damage data and the differences were noted.

HISTORIC EARTHQUAKE DAMAGE DATA

In this section, the average historic earthquake damage data for buildings are presented. The available historic damage data are in the form of damage versus Modified Mercalli Intensity (MMI). By contrast, the RSA data are in the form of damage versus maximum ground acceleration (MGA). Hence, the MMI values must be transformed to equivalent MGA values before comparisons can be made.

The Modified Mercalli Intensity scale, with its 12 levels, is an attempt to measure the severity of earthquake ground shaking intensity. Developed more than 50 years ago, the MMI scale relates human response or structural response to ground shaking intensity. The scale is based on the subjective judgment of the evaluators, materials of construction, construction techniques, and human response to earthquake effects. Structures generally are not damaged at MMI $\leq$ VI. For MMI $\geq$ IX, the MMI scale is overly sensitive to the response of the soil. That is, a given level ground shaking response at a site can occur under a wide range of ground shaking intensities, depending on the soil profile at the site, the properties of soil layers within the profile, and site topography. The advantage of the MMI scale is that it directly relates building damage to the intensity scale, making it a convenient tool for determining earthquake insurance premiums.

In studying damage prediction for earthquake insurance, Sauter (Ref 5) developed average historic earthquake damage versus Modified Mercalli Intensity relationships for different types of building construction using the empirical approach. Because the adequacy of the method depends on the reliability of the available information, an exhaustive search for existing data from numerous sources was conducted. These sources include government agencies, research centers, university libraries, and insurance companies. A detailed compilation of all collected data including sources and interpretation is given in Reference 6. The damage relationships available for buildings were simplified into 10 groups:

1. Adobe

2. Unreinforced masonry - low quality

3. Reinforced concrete frames - without seismic design

4. Steel frames - without seismic design

5. Reinforced masonry - medium quality without seismic design

6. Reinforced concrete frames - with seismic design

7. Reinforced concrete shear walls - with seismic design

8. Wooden frame dwellings

9. Steel frames - with seismic design

10. Reinforced masonry - high quality with seismic design

These average damage relationships are shown in Figure 1. Damage is expressed in percent of the current total replacement cost. THE RELATIONSHIPS SHOWN ARE BASED ON RECORDED SEISMOLOGICAL INFORMATION FOR LESS THAN 90 YEARS. INSTRUMENTED ACCELERATION RECORDS ARE ONLY AVAILABLE FOR ABOUT 50 YEARS. FUTURE DAMAGE AND PREDICTED DAMAGE BASED ON PAST EVENTS CAN DIFFER CONSIDERABLY. IN ADDITION, THE DAMAGE FOR A PARTICULAR BUILDING CAN VARY CONSIDERABLY FROM THE AVERAGE DAMAGE RELATIONSHIP FOR THE BUILDING GROUP, DEPENDING ON ITS STRUCTURAL CONFIGURATION, EXPERIENCE AND JUDGMENT OF THE DESIGNER, AND QUALITY OF WORKMANSHIP, ETC. THUS, THE INHERENT LIMITATIONS OF THE EMPIRICAL DAMAGE RELATIONSHIPS MUST BE KEPT IN MIND WHEN USING THEM TO PREDICT EARTHQUAKE DAMAGE.

The historic damage versus MMI relationships shown in Figure 1 are transformed into historic damage versus maximum ground acceleration (MGA) by establishing a relationship between MMI and MGA. There are many empirical relationships between MMI and MGA in the literature (e.g., Ref 7 through 11). It is the general consensus that a range of MGAs exists for each MMI level. Furthermore, Murphy and O'Brien (Ref 11) found that the MGA value for a given MMI level is a function of the earthquake magnitude and distance from the earthquake source, information generally not available for MMI data before about 1933. The MMI versus MGA relationship used in this study is shown in Figure 2. The relationship is superimposed on a plot of the maximum acceleration data recorded between 1933 and 1973. It is based on 70% of the mid-range of values given by Sauter and Shah (Ref 9). The MGA from the curve shown in the figure for each MMI level is generally about 20% larger than the values given by Murphy and O'Brien (Ref 11) except at MMI level X, where it is 6% smaller. Incidentally, Murphy and O'Brien found that the MGA distribution at each MMI level is log-normal. Of the 1,465 acceleration data points used in their study, less than 2% of the total had values larger than 0.3g.

From the plot shown in Figure 2, it is apparent that there is considerable scatter in maximum ground acceleration values at each MMI level. It is the author's opinion that the extremely high peaks at the various MMI levels are caused by local site amplification, such as local topography or soil properties. For example, the 1.25g acceleration between MMI VIII and IX was recorded near the abutment of the Pacoima Dam during the 1971 San Fernando earthquake. The spurious peak was caused by the amplification of the base motion through the rock ridge and the fracturing of the ridge during the earthquake.

The resulting historic damage versus maximum ground acceleration relationships or damage functions are given in Figure 3. From the functions shown, it is apparent that adobe buildings on the average

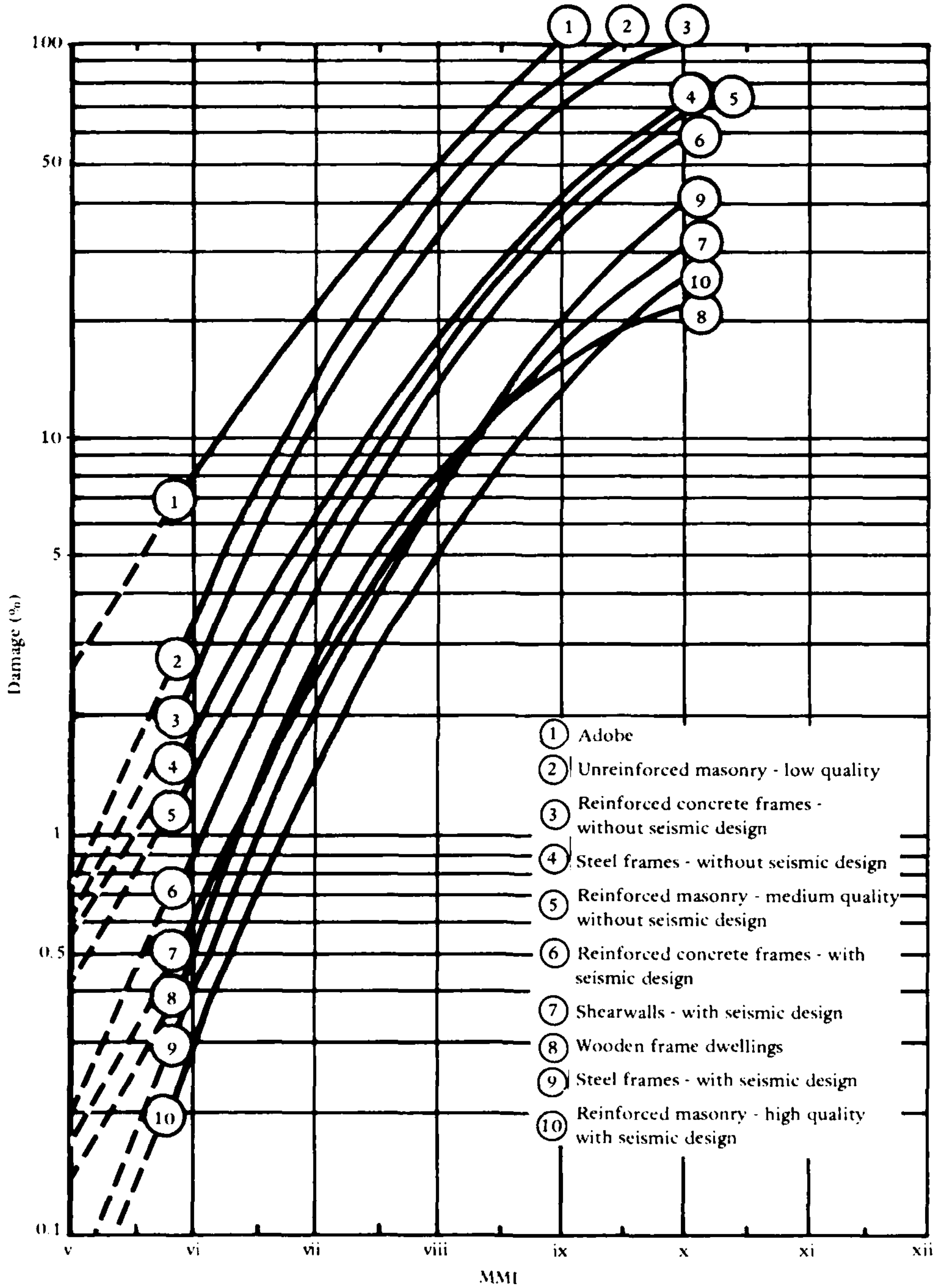

Figure 1. Average historic earthquake damage versus Modified Mercalli Intensity (MMI) relationships for buildings (from Ref 6).

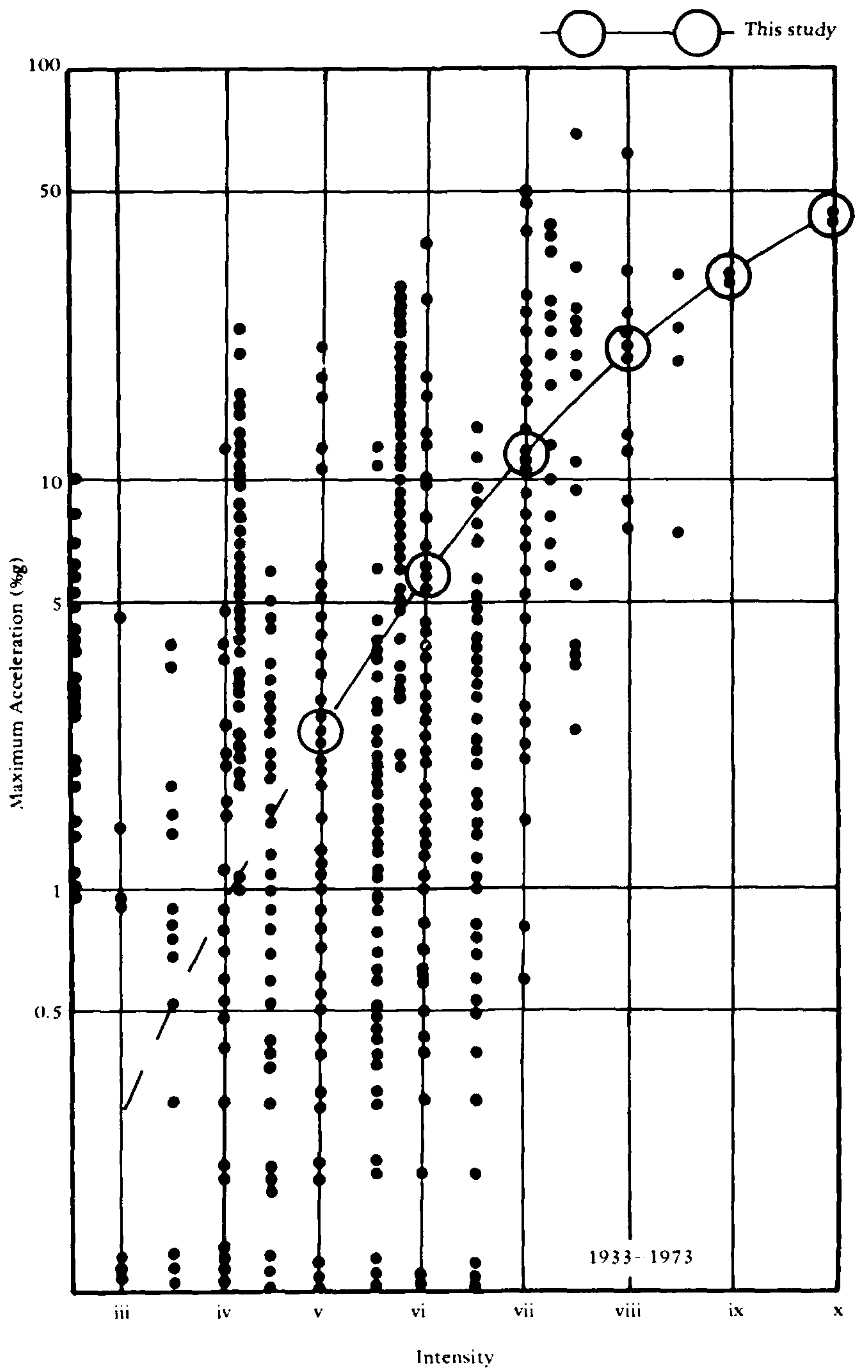

Figure 2. Maximum ground acceleration versus the Modified Mercalli Intensity scale, as observed in earthquakes occurring between 1933 and 1973 (after Ref 8).

experience the greatest damage for a given maximum ground acceleration. Brick buildings are expected to be severely damaged or collapse at a maximum ground acceleration between 0.2 and 0.3g. By contrast, wooden frame dwellings and high-quality reinforced masonry buildings with seismic design are expected to only experience nominal damage at a maximum ground acceleration of about 0.5g.

The damage functions given in Figure 3 can be used to estimate the earthquake damage to buildings not analyzed by the RSA procedure at the various Navy activities. However, as mentioned earlier, one should be cautious about using empirical data to predict future earthquake damage.

EARTHQUAKE DAMAGE ESTIMATED BY THE RAPID SEISMIC ANALYSIS PROCEDURE

The earthquake damage data estimated by the rapid seismic analysis procedure are presented in this section. First, a description of the building data is given, including the location of the activity, types of buildings and their approximate distribution according to type, and date of design/construction. Then, the response spectra used in the analysis are presented. Finally, the resulting damage functions for the buildings are given. The buildings are separated into 5 groups:

- Steel
- Concrete
- Masonry
- Wood
- Brick

The sorted data are input into a modified version of the CEL 9 computer program (Ref 1) together with the digitized site response spectra data. The program computes average estimated earthquake damage, the standard deviation, and the coefficient of variation for each building group from 0.05 to 0.50g at 0.05g increments. The resulting damage versus maximum ground acceleration relationships (damage functions) for each building group are presented in tabular and graphical form. The significance of the estimated damage is discussed.

Data Base

The RSA data for 750 buildings from 22 selected Navy activities out of 26 that were stored in the PRIME computer were used in this study. The RSA data from the other Navy activities have not been entered into the PRIME computer. Data for nonbuildings, such as elevated water towers and radio antenna towers, were excluded.

The site identifications, number of buildings in each group at each site, and the total number of buildings in each group are given in Table 1. With the exception of Bangor, Jim Creek, Puget Sound, Whidbey Island, Guam, and Sabana Seca, all the sites are in California. Bangor,

Table 1. Number of Buildings in Each Category Analyzed by the Rapid Seismic Analysis Procedure at the 22 Selected Navy Activities

Site	No. of Buildings in Category				
	Steel	Concrete	Masonry	Wood	Brick
Alameda	7	19	1	8	0
Bangor	8	7	27	6	4
China Lake	3	25	5	2	0
Concord	3	15	4	2	0
Coronado	0	6	5	4	3
Guam	0	8	0	0	0
Jim Creek	0	6	0	1	0
Lemoore	6	15	40	1	0
Long Beach	7	8	0	0	0
Mare Island	15	19	0	1	15
Miramar	3	34	25	12	0
Moffett	7	21	5	10	0
North Island	2	27	5	1	3
Point Mugu	5	8	9	0	0
Port Hueneme	8	6	6	6	0
Puget Sound	22	13	0	19	27
Sabana Seca	0	34	2	0	0
San Francisco	7	6	0	5	0
Seal Beach	7	7	3	11	1
Skaggs Island	0	4	1	0	0
Subic Bay	4	17	10	0	0
Whidbey Island	4	12	8	13	0
Total	118	317	156	106	53

Jim Creek, Puget Sound, and Whidbey Island are in the state of Washington. Guam is one of the Mariana Islands in the Pacific Ocean. Sabana Seca is in Puerto Rico in the Caribbean Sea. The distribution of buildings in each category is as follows:

Type	No.
Steel	118
Concrete	317
Masonry	156
Wood	106
Brick	53

All the buildings are in the low-rise category ($\leq$ six stories), with the great majority of them having three stories or less.

These buildings were constructed between 1858 and 1973. The following is an approximate distribution of the construction dates of the buildings:

Construction Date	Percent
Before 1940	24.7
1940s	44.4
1950s	13.0
1960s	14.3
1970s	3.6
	100.0

About 70% of these buildings were built before or during the 1940s, with 44.4% of them built during the 1940s. As mentioned in the INTRODUCTION section, some construction standards were relaxed during World War II because of a shortage of materials and skilled workers. About 28% of the buildings were constructed during the 1950s and 1960s. The remaining about 4% of the buildings were constructed during the earlier part of the 1970s.

There is no assurance, however, that a building designed and constructed according to the minimum provisions of the prevalent seismic code in California during the 1960s or 1970s will have the intended seismic resistance characteristics. Whether a building has the desirable seismic resistance characteristics intended by the design code depends primarily on the experience and judgment of the designer or engineer and the quality of workmanship. This fact has been proven many times by observing building damage in past earthquakes.

For instance, essentially all of the buildings at the Naval Air Station, Lemoore, Calif., were designed and constructed during the 1960s. Most of the buildings were constructed of reinforced masonry. Results from the rapid seismic analysis (RSA) indicate that the estimated damage for steel buildings were somewhat higher than buildings constructed from other materials, primarily from the lack of vertical bracing. The masonry buildings generally have precast or cast-in-place concrete roofs and reinforced, fully grouted concrete block masonry for resisting lateral loads. The RSA results show that masonry buildings generally have lower estimated damage than other buildings. However, damage estimates for some of the masonry buildings were high because of heavy roofs or lack of effective shear walls. In several cases, the lateral resistance of the masonry shear walls was impaired by too many openings. In other cases, the shear walls were not connected to the roof diaphragm and, hence, provided no lateral resistance. During the 1979 Imperial Valley, Calif., earthquake (magnitude 6.9), the newly designed (according to code provisions) and constructed Imperial County Services Building suffered severe damage and had to be demolished because of faulty design judgment.

About two thirds of the rapid seismic analyses were performed before the modifications for enhancing the procedure were developed (Ref 2). Whenever possible, these modifications were made on the data before they were used in this investigation. A steel yield strength of 30 ksi was used on the majority of the analyses. However, most of the Navy's steel buildings were constructed after 1940, and a yield strength of 36 ksi would be more appropriate. Because it was rather difficult and time consuming to make the appropriate changes in the base shear capacity data, the steel building data were left unmodified. The effects of this increase in yield strength on the RSA-estimated damages are investigated by a sensitivity analysis.

Response Spectra

The majority of Navy activities are at sites with an intermediate soil profile. An intermediate soil profile is defined as one with deep cohesionless or stiff clay conditions, including sites where the soil depth exceeds 200 feet and soil types overlying the bedrock are stable deposits of sands, gravels, or stiff clays.

For consistency, the response spectra developed by the author for the Long Beach Naval Ship Yard, Calif., were used to analyze all the building data (Figure 4). The curves shown in the figure are for an intermediate soil site and correspond to about the 84 percentile values. That is, given the maximum ground acceleration at the site, there is only about a 16% chance that the loading experienced by the buildings will be greater than that indicated by the response spectra.

Damage Functions

Results from the computer analyses for the steel, concrete, masonry, wood, and brick building are tabulated in Table 2. The average damage, standard deviation (σ), and coefficient of variation (COV) are given in percent of the total current replacement cost of the building. The standard deviation tended to level off to between 30 and 40% at average damage of greater than about 40%. The coefficient of variation (COV), a good indicator of the dispersion of the data about the average value, is the largest for reinforced concrete and masonry buildings. This large scatter of the data about the average value is most likely due to variation in the architectural layout inherent to these types of buildings. The variation in the architectural layout can have a significant effect on the base shear capacities of these buildings.

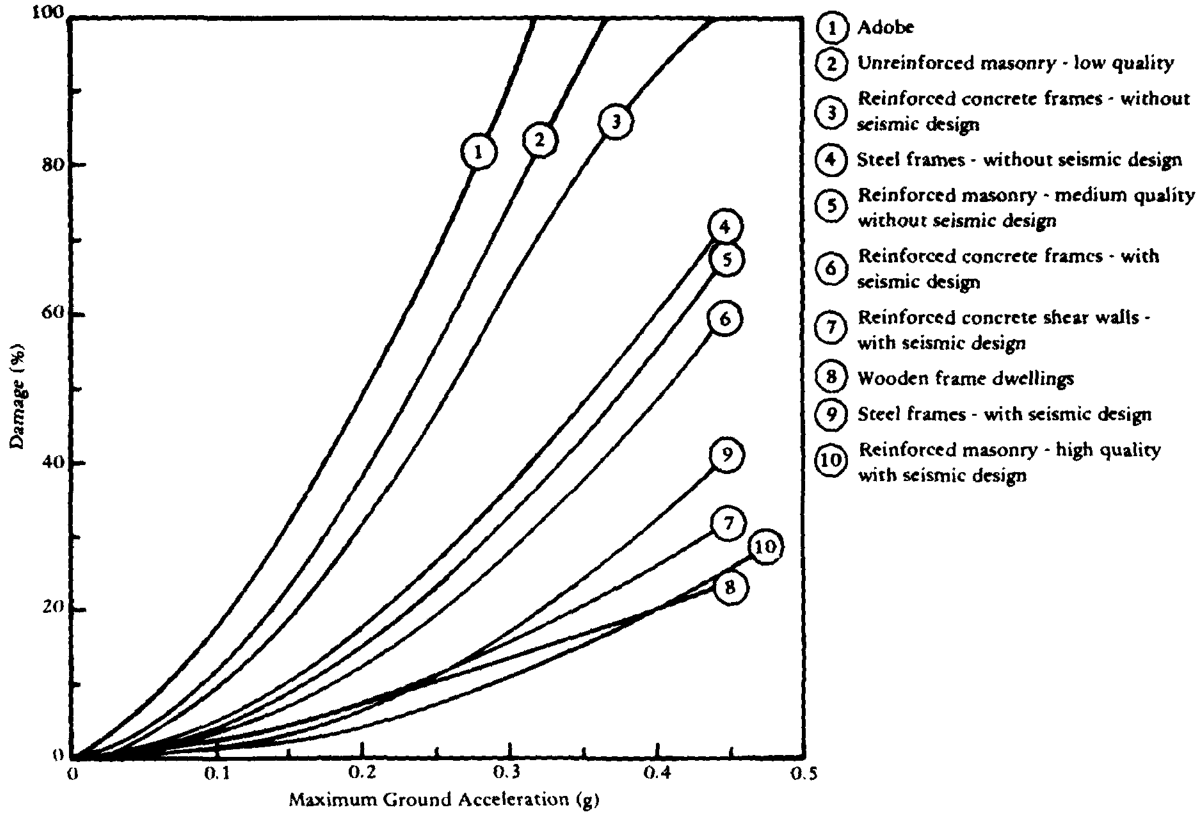

Figure 3. Historic earthquake damage functions for buildings.

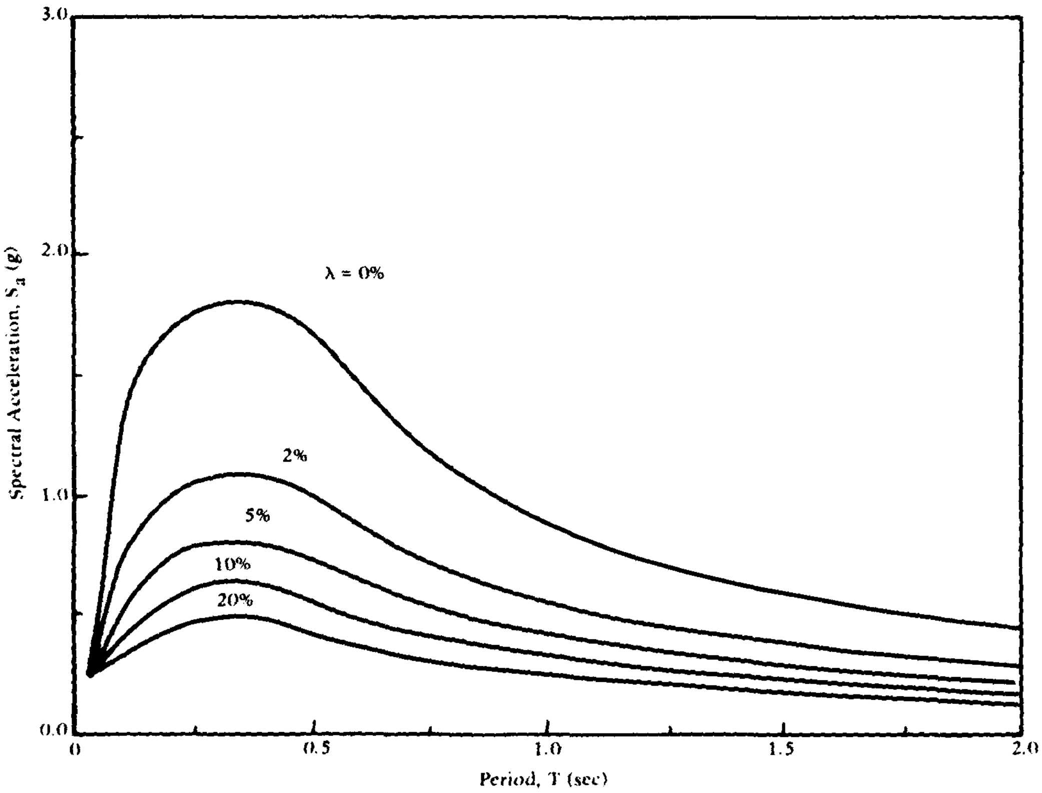

Figure 4. Site response spectra for Long Beach Naval Shipyard, Long Beach, Calif.

Table 2. Earthquake Damage (% of Replacement Cost) From the Rapid Seismic Analysis of Navy Buildings in Seismic Zones 3 and 4

Maximum Ground Acceleration (g)	Steel			Concrete			Masonry			Wood			Brick		
	Average Damage (%)	σ[a] (%)	COV[b]	Average Damage (%)	σ[a] (%)	COV[b]	Average Damage (%)	σ[a] (%)	COV[b]	Average Damage (%)	σ[a] (%)	COV[b]	Average Damage (%)	σ[a] (%)	COV[b]
0.05	3.9	10.3	2.68	2.5	11.7	4.75	1.4	9.8	6.86	7.9	13.9	1.76	12.9	18.9	1.47
0.10	13.6	18.6	1.37	8.8	22.5	2.55	4.5	14.2	3.15	26.4	24.5	0.93	39.0	32.6	0.84
0.15	27.0	22.4	0.83	16.3	30.2	1.85	10.9	22.0	2.02	41.6	27.4	0.66	54.9	36.8	0.67
0.20	38.8	24.1	0.62	23.6	34.0	1.44	20.1	29.9	1.48	53.1	27.6	0.52	65.3	37.4	0.57
0.25	48.0	24.7	0.51	32.4	36.8	1.14	28.0	34.7	1.24	61.6	26.5	0.43	71.3	35.6	0.50
0.30	55.2	24.9	0.45	40.3	38.6	0.96	35.1	37.4	1.07	68.2	24.4	0.36	75.1	33.6	0.45
0.35	60.9	24.3	0.40	47.5	40.1	0.85	42.0	39.7	0.94	73.4	22.1	0.30	78.3	32.2	0.41
0.40	65.9	23.7	0.36	52.8	40.9	0.77	46.8	40.3	0.86	77.5	20.1	0.26	81.0	31.6	0.39
0.45	69.7	23.0	0.33	56.7	41.0	0.72	51.2	40.6	0.79	80.9	18.0	0.22	82.9	31.0	0.37
0.50	72.9	22.2	0.30	59.9	40.7	0.68	55.3	40.9	0.74	83.6	16.3	0.19	84.4	30.7	0.36

[a]Standard deviation.

[b]Coefficient of variation.

Assume that the data for the 750 buildings represent a random sampling of the overall Navy building population in seismic zones 3 and 4. Results from calculations using the theory of sampling indicate that there is 99.7% assurance (confidence level) that the computed average damages shown in Table 2 for steel, concrete, masonry, wood, and brick buildings will generally be within ±6.9*, ±9.9, ±8.0, and ±15.4%, respectively, of the "true" average damage or the value that would have been obtained had all the buildings been included.

The RSA damage functions for the different buildings are shown in Figure 5. As expected, the unreinforced brick buildings generally have the greatest estimated damage at all maximum ground acceleration levels. The wooden buildings have the next to the largest damage. This is not surprising because the majority of these buildings are large-span structures, such as industrial shops, theaters, gymnasiums, and warehouses. Earthquake performance of such large-span structures tends to be poor because of their large seismic-demand-to-base-shear-capacity ratios as compared to short-span structures. Wooden residential dwellings, short-span structures that have performed well in past earthquakes, were virtually eliminated by the RSA building screening and selection criteria. Reinforced concrete and masonry buildings have the lowest estimated damage, with masonry buildings the lower of the two. The estimated damage for steel buildings is between brick and masonry buildings.

To check the sensitivity of the estimated damage for steel and wooden buildings to increases in the natural periods and base shear capacities at the yield and ultimate levels, the estimated damage for these buildings were computed for a 20 and 50% increase in these parameters. The original (unmodified) damages are compared with the modified damages for steel and wooden buildings in Tables 3 and 4, respectively. The results indicate that increasing the base shear capacities at the yield and ultimate levels by 20 and 50% will reduce the estimated damage by about 7 and 16%, respectively. Based on available information, increasing the base shear capacities for steel buildings by 20% is justifiable. Increasing the base shear capacities for wooden buildings by 20% cannot be justified, let alone 50%. The estimated damages for the steel and wooden buildings are rather insensitive to increases in the natural periods.

The RSA-estimated damages agree qualitatively with those observed during the magnitude 6.61 1971 San Fernando earthquake (Ref 12). For pre-1933 buildings, the damage threshold is 0.15g. Maximum ground accelerations of 0.3g or greater are associated with hazardous damage and collapse of most of these older buildings. Structures designed in accordance with minimum seismic code requirements received only architectural damage where the MGA was less than 0.2g. There was minor to appreciable damage to these buildings when subjected to ground motions in the 0.2 to 0.3g range. The estimated strong motion duration ($\geq$ 0.05g) for the earthquake is about 10 seconds. Had the duration of the shaking been much longer, the observed damage would have been much more severe, and more modern structures might have collapsed. The San Fernando earthquake confirmed that buildings designed according to building code provisions can have markedly different responses because of different architectural layout, structural type, quality of workmanship, and engineering judgment.

*These percentages are expressed in terms of the total current replacement cost of the building.

COMPARISON OF HISTORIC DAMAGE WITH ESTIMATED DAMAGE

In this section, the average damage functions from the rapid seismic analysis (RSA) are compared with the corresponding historic damage functions. The comparisons are made at maximum ground accelerations between 0.2 and 0.4g, where most of the damage is anticipated to occur. The percent difference in damage used in the comparisons is in terms of the current total replacement cost of the building.

A comparison of the damage functions for steel buildings is shown in Figure 6. The RSA damages are between 8 and 20% larger than the historic damages for steel frame buildings without seismic design. The RSA damages are between 31 and 36 larger than the historic damages for steel frame buildings with seismic design. Finally, the RSA damages are between 20 and 28% larger than the average historic damages for steel frame buildings with and without seismic design.

A comparison of the RSA damage functions for 1.0, 1.2, and 1.5 times the computed base shear capacities of steel buildings with the historic damage functions is presented in Figure 7. Because of the reason given earlier, it is felt that the RSA damage function for 1.2 times the base shear capacities is more representative of the actual response of the steel buildings analyzed.

The primary cause of the difference between the RSA damage function and the historic function for steel buildings is the presence of long-span structures, such as industrial shops, warehouses, and aircraft hangars. Such long-span structures are expected to experience greater earthquake damage than short-span steel structures, such as office buildings, because of the greater seismically induced inertia forces in the vertical lateral force-resisting elements of the long-span structures.

A comparison of the earthquake damage functions for reinforced concrete buildings is given in Figure 8. The RSA damages are between 7 and 39% smaller than the historic damages for reinforced concrete frame buildings without seismic design. The RSA damages are between 4 and 6% larger than the historic damages for reinforced concrete frame buildings with seismic design. The RSA damages are between 17 and 20% larger than the historic damages for reinforced concrete shear wall buildings with seismic design. None of the RSA concrete buildings were designed to resist the seismic forces by frame action or shear wall action alone. These buildings are generally designed to resist the seismic forces by a combination of concrete frame (without seismic design) and shear wall action. The RSA damages generally are within about ±6% of the average of the historic damage functions for reinforced concrete frame buildings without seismic design and reinforced concrete shear wall buildings with seismic design.

A comparison of the damage functions for reinforced masonry buildings is shown in Figure 9. The RSA damages are between 7% smaller and 3% larger than those for medium-quality reinforced masonry buildings without seismic design. The RSA damages are between 15 and 29% larger than those for high-quality reinforced masonry buildings with seismic design. Finally, the RSA damages are about 10% larger than the average of the historic damage functions for medium-quality reinforced masonry buildings without seismic design and high-quality reinforced masonry buildings with seismic design.

Table 3. Sensitivity of RSA-Estimated Damage to Increases in Base Shear Capacities and Natural Periods for Steel Buildings

Condition[a]	Average Estimated Damage (%) at Maximum Ground Acceleration of--									
	0.05g	0.10g	0.15g	0.20g	0.25g	0.30g	0.35g	0.40g	0.45g	0.50g
Unmodified	3.9	13.6	27.0	38.8	48.0	55.2	60.9	65.9	69.7	72.9
1.2 times base shear capacities	2.6	9.9	20.1	31.4	40.5	48.0	54.1	59.1	63.5	67.3
1.5 times base shear capacities	1.6	6.8	13.6	22.3	31.4	38.8	45.2	50.5	55.2	59.1
1.2 times natural periods	3.3	12.1	25.1	36.4	45.1	52.4	58.5	63.4	67.3	70.6
1.5 times natural periods	2.6	10.6	22.4	32.5	40.9	48.0	54.2	59.0	63.0	66.4

[a]At yield and ultimate levels.

Table 4. Sensitivity of RSA-Estimated Damage to Increases in Base Shear Capacities and Natural Periods for Wooden Buildings

Condition[a]	Average Estimated Damage (%) at Maximum Ground Acceleration of--									
	0.05g	0.10g	0.15g	0.20g	0.25g	0.30g	0.35g	0.40g	0.45g	0.50g
Unmodified	7.9	26.4	41.6	53.1	61.6	68.2	73.4	77.5	80.9	83.6
1.2 times base shear capacities	4.9	20.6	34.4	45.8	54.7	61.6	67.2	71.8	75.5	78.7
1.5 times base shear capacities	2.4	14.4	26.4	36.9	45.8	53.1	59 0	63.9	68.2	71.8
1.2 times natural periods	7.5	25.1	40.4	51.9	60.5	67.4	72.6	76.8	80.2	83.1
1.5 times natural periods	7.0	22.9	37.9	49.3	58.0	64.8	70.3	74.6	78.2	81.2

[a]At yield and ultimate levels.

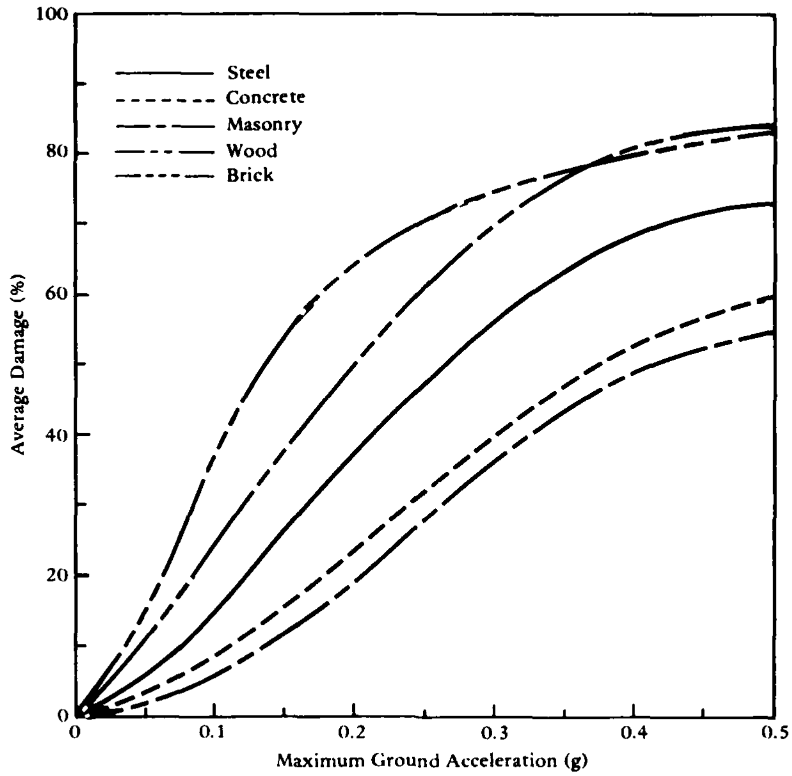

Figure 5. Rapid seismic analysis estimated damage functions for buildings.

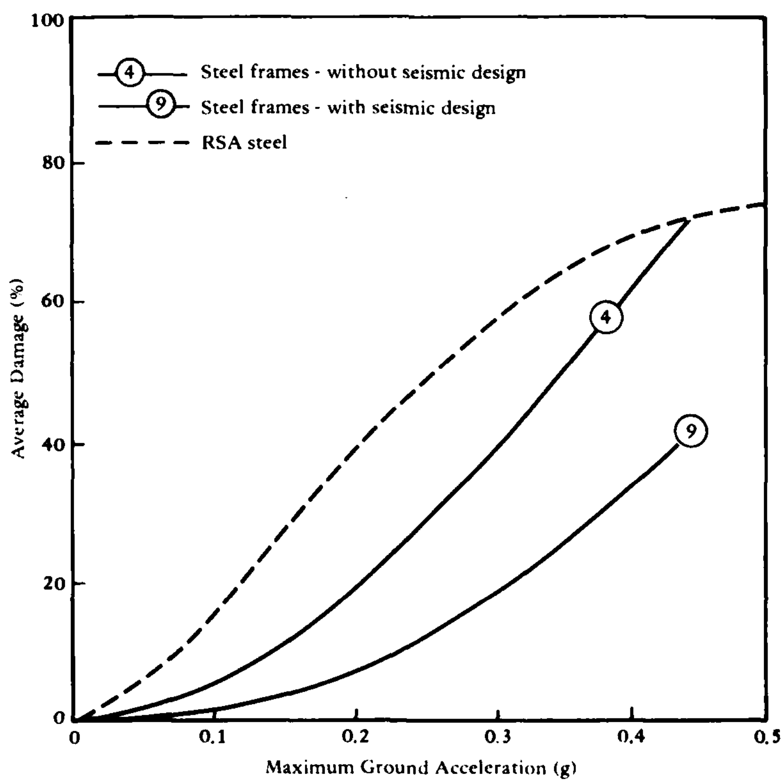

Figure 6. Comparison of historic earthquake damage functions with the rapid seismic analysis (RSA) estimated damage function for steel buildings.

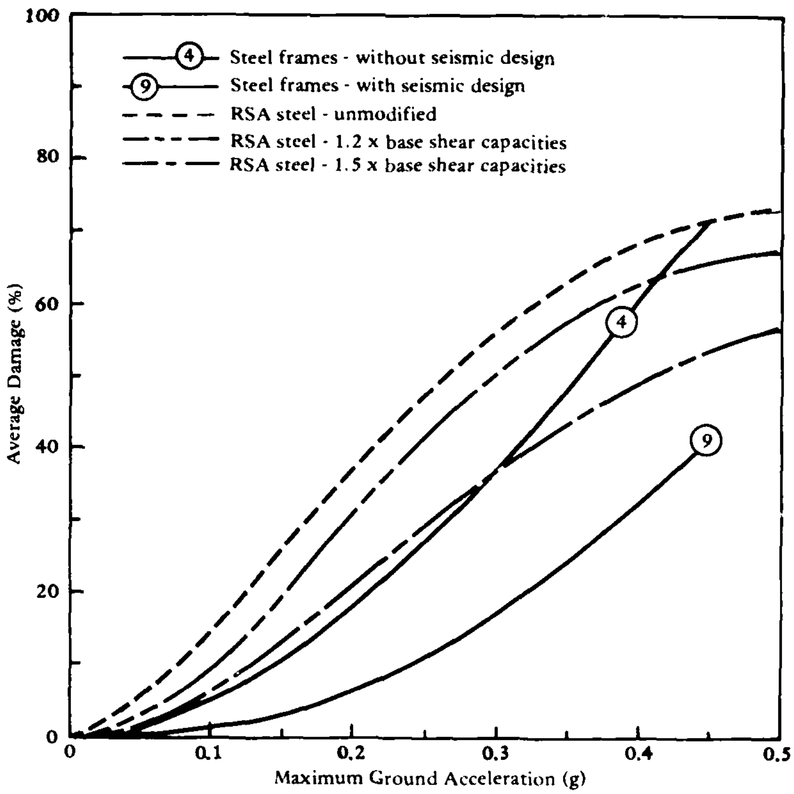

Figure 7. Comparison of historic earthquake damage functions with those estimated by the rapid seismic analysis (RSA) procedure for steel buildings with and without modified base shear capacities.

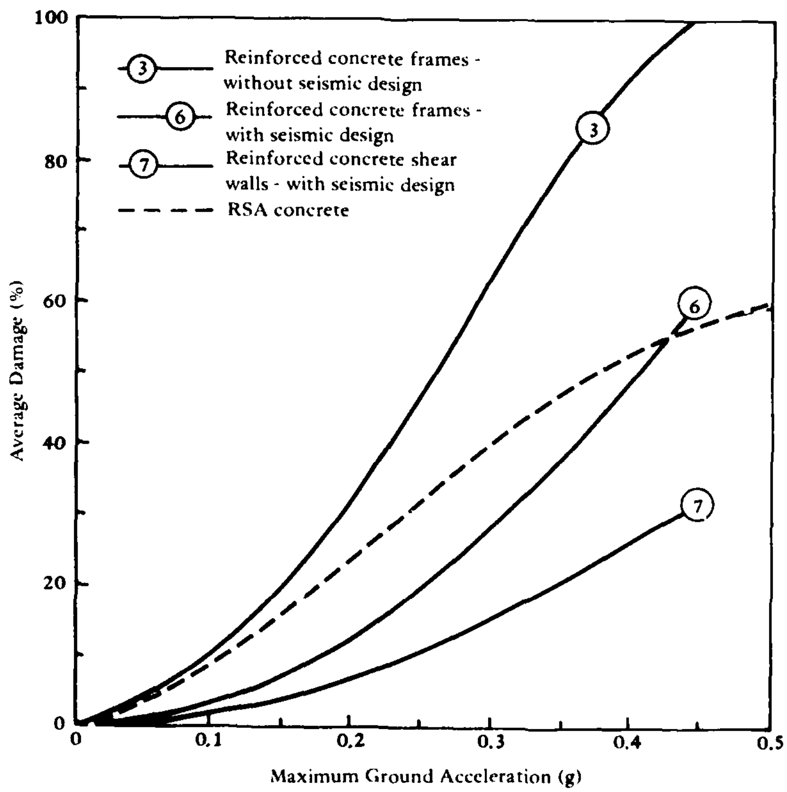

Figure 8. Comparison of historic earthquake damage functions with the rapid seismic analysis (RSA) estimated damage function for concrete buildings.

A comparison of the RSA damage functions for wooden buildings with the corresponding historic damage functions for steel frame buildings with and without seismic design and wooden frame dwellings is given in Figure 10. Theoretically, historic damage for steel frame buildings and wooden frame dwellings is not directly comparable with the RSA damage for wooden structures. The RSA wooden structures generally consist of relatively long-span structures, such as theaters, gymnasiums, warehouses, and industrial shops. The smaller wooden frame dwellings or similar short-span wooden structures have virtually been eliminated from the RSA by the selection criteria. Understandably, the seismic performance of steel frame buildings is not directly comparable with the seismic performance of wooden buildings because of the difference in material behavior. However, the spans of steel buildings (typically between 20- and 30-foot spacing between bays) are closer to the spans of RSA wooden buildings than typical wooden frame dwellings with numerous interior partitions. The historic damage functions for the steel buildings are used as references for assessing the validity of the RSA damage estimates for wooden buildings. Furthermore, the author hypothesizes that the RSA-estimated damages for wooden buildings should be closer to the historic damage for steel frame buildings without seismic design, with the RSA damages somewhat larger than the historic damages for steel buildings. This is because the strengths, ductilities, energy absorption, and dissipation capacities of the steel structural members and connections are larger than those for wooden structural members and their connections.

From the damage functions shown in Figure 10, the RSA damages for wooden buildings are between 44 and 62% larger than the historic damages for wooden frame dwellings. The RSA damages are between 43 and 48% larger than historic damages for steel frame buildings with seismic design. Finally, the RSA damages are between 21 and 33% larger than historic damage for steel frame buildings without seismic design.

In the few cases where the RSA was performed on small wooden buildings similar to wooden residential dwellings, the estimated damages are generally within about ±20% of the historic damages for wooden frame dwellings.

The effects of increasing the base shear capacities for RSA wooden buildings by 20 and 50% on the damage function are shown in Figure 11. Again, the estimated damages are compared with the historic damages for steel frame buildings and wooden frame dwellings.

A comparison of the RSA damage function for brick buildings with the historic damage function for low-quality unreinforced masonry buildings is given in Figure 12. At MGAs less than about 0.3g, the RSA damages are greater than the historic damages. By contrast, the RSA damages are less than the historic damages at MGAs greater than about 0.3g. The RSA-estimated damages are within ±25% of the historic damages for low-quality unreinforced masonry buildings.

In short, the average RSA-estimated damages are generally within between 5 and 25% of the average historic damages for the corresponding types of buildings. The RSA-estimated damages for reinforced concrete and masonry buildings are generally within 5 and 10% of the average historic damages for reinforced concrete and reinforced masonry buildings, respectively. The RSA-estimated damages for steel buildings and unreinforced brick buildings are generally within 25% of the historic damages for the corresponding types of buildings. Moreover, it is hypothesized that the RSA-estimated damages for wooden buildings are generally within about 25% of the historic damages for such buildings.

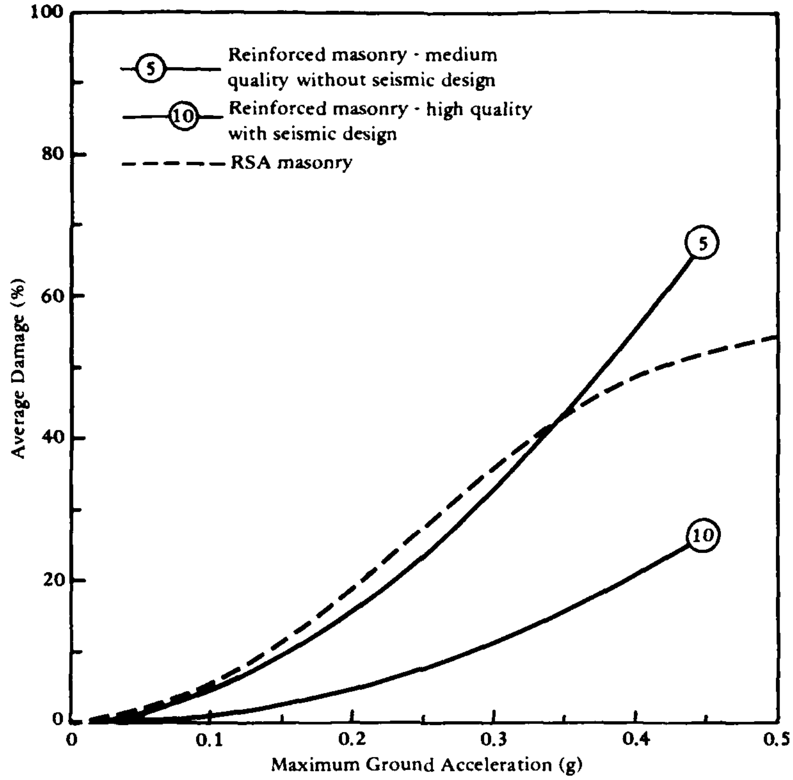

Figure 9. Comparison of historic earthquake damage functions with the rapid seismic analysis (RSA) estimated damage function for masonry buildings.

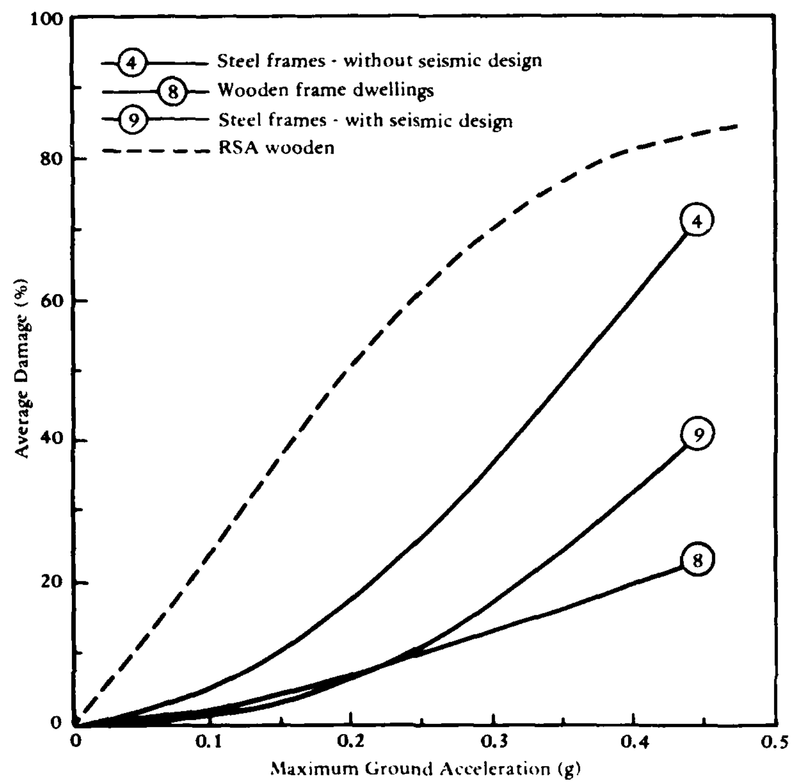

Figure 10. Comparison of historic earthquake damage functions with the rapid seismic analysis (RSA) estimated damage function for wooden buildings.

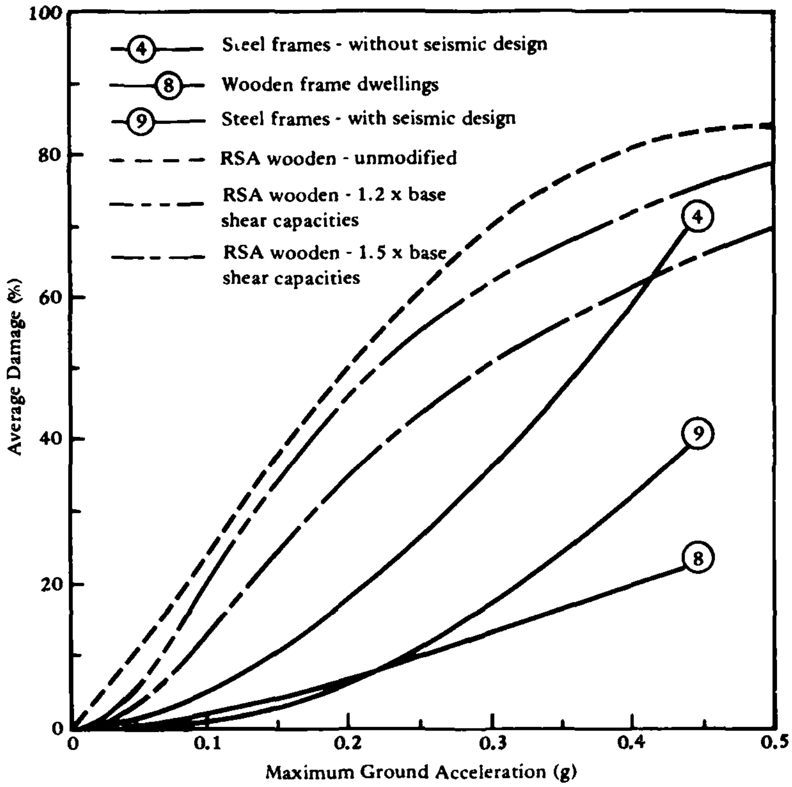

Figure 11. Comparison of historic earthquake damage functions with those estimated by the rapid seismic analysis (RSA) for wooden buildings with and without modified base shear capacities.

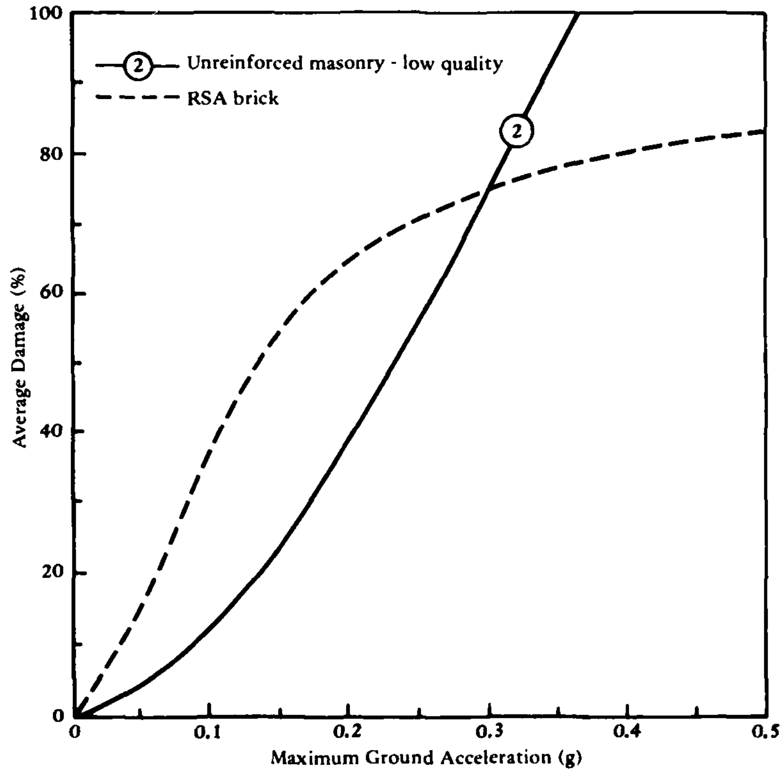

Figure 12. Comparison of historic earthquake damage function with the rapid seismic analysis (RSA) estimated damage function for brick buildings.

CONCLUSIONS

1. Assuming that the RSA building data represent a random sampling of the Navy buildings in seismic zones 3 and 4, the average building damage functions for steel, concrete, masonry, wood, and brick buildings obtained in the study will generally be within ±6.9, ±6.9, ±9.9, ±8.0, and 15.4%, respectively, of the values had all the Navy buildings within the two seismic zones been included.*

2. Comparisons of the RSA damage functions with the historic damage functions at between 0.2 and 0.4g maximum ground accelerations indicate that:

- The RSA damage function for steel buildings is between 20 and 28% larger than the average of the historic damage functions for steel frame buildings with and without seismic design.

- The RSA damage function for reinforced concrete buildings is generally within ±6% of the average of the historic damage functions for reinforced concrete frame buildings without seismic design and that for reinforced concrete shear wall buildings with seismic design.

- The RSA damage function for reinforced masonry buildings is about 10% larger than the average of the historic damage functions for medium-quality reinforced masonry buildings without seismic design and that for high-quality reinforced masonry buildings with seismic seismic design.

- The RSA damage function for mostly long-span wooden buildings is between 44 and 62% larger than the historic damage functions for relatively short-span wooden frame dwellings. The RSA damage function for wooden buildings is between 21 and 33% larger than the historic damage functions for steel frame buildings without seismic design.

- The RSA damage function for unreinforced brick buildings is within ±25% of the historic damage function for low-quality unreinforced masonry buildings.

3. The RSA building damage functions and the historic building damage functions can be used for estimating earthquake damage to buildings not analyzed by the RSAP. However, the inherent limitations of these functions given in the text must be considered.

RECOMMENDATION

Seismically inadequate buildings that pose hazards to life or impact the mission reliability of the activity should either be strengthened, have their functions transferred to seismically resistant structures, or be scheduled for demolition and replacement.

*These percentages and subsequent ones are expressed in terms of the total current replacement cost of the building.

ACKNOWLEDGMENT

This investigation was authorized by the Naval Facilities Engineering Command (NAVFAC) under Project Order N000258WR1052W of 19 Oct 1983.

The continual support by Mr. J.V. Tyrrell (NAVFAC Code 04BA) is appreciated.

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