Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Correlation between recorded building data and non-structural damage during the Loma Prieta earthquake of October 17, 1989 – Selected case studies

S.S. Rihal
California Polytechnic State University, San Luis Obispo, Calif., USA

ABSTRACT: Results of a study of the correlation between recorded response data and non-structural damage observed in the Santa Clara County Government Center, San Jose, during the Loma Prieta Earthquake of 1989 are presented. The main objective of this seismic case-study was to investigate the relationship between seismic response parameters, e.g., peak response acceleration levels, frequency content and inter-story drift levels and corresponding non-structural damage observed during the Loma Prieta earthquake. The project documents the techniques used in realistic modeling of the as-built building systems for carying out seismic (dynamic) analysis using state-of-the-art computer software. Results of seismic analyses include mode-shapes and frequencies and dynamic displacements; inter-story drift levels using the earthquake spectrum from CSMIP data recorded at the base of this case-study building. In conclusion some suggestions are presented to establish threshhold levels of seismic response parameters that relate to non-structural component damage observed in buildings during earthquakes.

1 INTRODUCTION

A unique and important aspect of the Loma Prieta, California, earthquake of October 17, 1989 was the widespread non-structural component damage observed and reported in a broad class of buildings distributed over the San Francisco Bay Area, including cities of Oakland, San Francisco, and San Jose. Based on observed performance and behavior of building components during this earthquake, it is clear that the major consequences of the non-structural component damage were the significant losses caused by such damage including disruption of building functions, as well as possible life-hazards in some cases. A valuable and unique opportunity was provided by recorded data obtained from instrumented buildings, especially those that suffered non-structural damage during the Loma Prieta earthquake.

2 SCOPE AND OBJECTIVES

The main objective of this study is to analyze recorded SMIP data and study the correlation between available recorded data and non-structural component damage in instrumented buildings during the Loma Prieta earthquake of October 17, 1989. Further objectives are (1) to study the seismic performance and behavior of an instrumented case-study building which suffered non-structural component damage and make a comparison with its performance and behavior during the 1984 Morgan Hill and the 1986 Mt. Lewis earthquakes, and (2) to develop a methodology for assessing the performance and behavior of non-structural building components during earthquakes.

3 INSTRUMENTED BUILDING CASE-STUDY SANTA CLARA COUNTY GOVERNMENT CENTER - SAN JOSE

After an initial survey it was decided to focus on the a case-study of the Santa Clara County Government Center located at 70 West Hedding Street in downtown San Jose. This building has been the source of recorded data from two previous earthquakes in 1984 and 1986, and has been the subject of studies by other investigators (Mahin (1989), Naaseh (1985).

4 DESCRIPTION OF BUILDING STRUCTURAL SYSTEM

This thirteen story building is essentially square in plan configuration. The structural system consists of moment-resisting frames at 26 ft. spacing in both directions. Wings along the west and south sides of the building are used primarily for circulation, e.g., elevators and stairs as well as for mechanical systems. These wings are offset in plan and that is the only plan irregularity in the layout of the primary structural system. Furthermore, these wings extend one floor above the roof which is the main vertical irregularity in the building structural system as shown in Figure 1.

5 OBSERVED NON-STRUCTURAL DAMAGE

5.1 *Loma-Prieta Earthquake of October 17, 1989*

Non-structural building components are classified to include partitions, suspended ceilings, curtain walls, facades and cladding, and contents, e.g., filing cabinets, book shelves, computer equipment, office furniture, etc.

The non-structural damage observed in the Santa Clara County Government Center falls mainly in the category of contents damage including damage to interior space-enclosure partial-height partitions. In general, valuable non-structural damage data gets lost soon after an earthquake due to the necessity to quickly repair such damage to bring building facilities back into normal operation. For this case-study, the Santa Clara County Government Center, a video tape documenting nonstructural damage observed soon after the Loma Prieta earthquake, was obtained from Van Osdol (1991), for study and analysis. A review of the video tape of observed non-structural damage shows that there was substantial damage to contents in this building facility, mainly at the 7th, 9th, 10th and 11th floor levels. According to Van Osdol(1991), the extent of non-structural component damage during the 1989 Loma Prieta earthquake was much greater than that during the 1984 Morgan Hill and 1986 Mt. Lewis earthquakes. The floor motions experienced were strong enough to cause extensive damage to lateral file cabinets and similar non-structural components. It appears that whole rows of such filing cabinets bolted end-to-end and not back-to-back overturned, creating very hazardous conditions for safe evacuation of building occupants, immediately after the Loma Prieta earthquake.

It appears that non-structural components such as lateral file cabinets were subjected to rocking action due to the floor motions produced by the earthquake. One major factor that contributed to the overturning failure of lateral file cabinet systems was the sudden opening of upper drawers which caused these components to overturn due to the adverse P-Δ effects.

A systematic classification of non-structural components, corresponding observed damage as well as its distribution across the height of the building was developed and is presented elsewhere by Rihal (1992).

Typical and representative non-structural component damage at 7th and 11th floor level is graphically presented in Figure 2.

6 ANALYSIS OF RECORDED MOTIONS

These were a total of twenty-two CSMIP recording sensors located at lower, second, seventh, twelveth and roof levels of this building as shown in Figure 1. Complete details of sensor location and orientation are presented elsewhere by Shakal (1989) and Rihal (1992).

The typical CSMIP recorded and processed time-history data obtained from the strong motion instruments in the Santa Clara County Government Center, during the 1989 Loma Prieta earthquake as provided by Shakal (1985, 1991), is shown in Figure 3. Representative floor acceleration response spectra obtained from each of the instrumented floors are presented in Figure 4. These acceleration spectra graphs are based on Volume 3 data provided by CSMIP. A summary of the peak floor accelerations and peak floor displacements recorded during the 1989 Loma Prieta, earthquake is presented in Table I. An approximate analysis of recorded acceleration time-history data for channel 14 (7th floor) and channel 10 (12th floor) was made and resulting estimated building periods are presented in Table II.

TABLE I
Santa Clara County Government Center - San Jose
Maximum Recorded Floor Accelerations and Displacements

Loma Prieta Earthquake, 17 October 1989

Location Level	Corner	Direction	Channel #	Max. Acceleration (g)	Max. Deflection (in.)
Lower	NW	Up	1	0.104	1.59
Lower	SW	Up	2	0.087	1.62
Lower	SE	Up	3	0.104	1.61
Roof	NW	East	4	0.337	14.49
Roof	SW	East	5	0.309	16.38
Roof	SW	North	6	-0.338	-17.44
Roof	SE	North	7	-0.325	-14.80
12th	NW	East	8	0.266	13.27
12th	SW	East	9	0.256	15.20
12th	SW	North	10	-0.294	-16.97
12th	SE	North	11	-0.259	-14.06
7th	NW	East	12	0.257	10.12
7th	SW	North	13	-0.251	11.18
7th	SW	North	14	0.222	-10.91
7th	SE	North	15	0.144	-7.20
2nd	NW	East	16	0.134	-6.10
2nd	SW	East	17	0.131	-5.12
2nd	SW	North	18	-0.106	-4.37
2nd	SE	North	19	-0.098	-4.53
Lower	NW	East	20	-0.087	-3.75
Lower	SW	East	21	0.084	-3.60
Lower	SW	North	22	-0.098	-2.79

TABLE II
Santa Clara County Government Center - San Jose
Building Periods - Estimated from Recorded Acceleration Data

Floor Level	Sensor Channel #	Direction	1989 Loma Prieta Earthquake (seconds)	1986 Mt. Lewis Earthquake (seconds)	1984 Morgan Hill Earthquake (seconds)
7th	14	N-S	2.27	2.19	2.08
12th	10	N-S	2.27	2.16	2.16

7 CORRELATION BETWEEN RECORDED DATA AND OBSERVED NON-STRUCTURAL DAMAGE

Non-structural component damage in buildings is characterized by both acceleration as well as inter-story drift effects. A study of the observed non-structural damage data recorded on video tape showed that in general, there was no damage observed below the fifth floor level. The majority of the non-structural component damage is concentrated at the 7th and 11th floor levels, with lesser damage observed at the 8th, 9th and 10th floor levels. There was no observed damage to the mechanical and electrical equipment located at the 12th floor and roof levels.

Through consultation with Reitherman (1991) it is suggested that characteristics of recorded floor motions that contribute to non-structural component damage are as follows:

1. Peak recorded amplitudes of floor accelerations, as well as displacements.
2. Frequency content of floor response accelerations.
3. Number of cycles of floor response accelerations with peak acceleration levels ≥ 0.05g.
4. Duration of recorded floor accelerations/velocities/displacements.

7.1 *Non-Structural Component Damage Index:*

It is suggested that non-structural component damage expressed as percent of non-structural components damaged at any given floor level could be used as one crude type of non-structural component damage index, as presented in Table III (Reitherman 1991). The next step is to develop a composite non-structural damage index taking into account the characteristics of recorded floor response motions outlined above. Summaries of peak responses recorded at instrumented floor levels in the Santa Clara County Government Center, during the 1989 Loma Prieta, California earthquake are presented in Table IV.

TABLE III
Santa Clara County Government Center - San Jose
Non-Structural Damage Index (expressed as % of Components Damaged)

7th Floor		Type of Damage			
Non-structural Component	Number Counted	Over-Turned	Broken	Spilled	Moved
Computers	13	23%			
Bookcases	4	50%			
Filing cabinets	54	22%		26%	9%
Desks	32	3%		56%	6%
Plants	1		100%		
Bookshelves	1			100%	
Microfiche	4	25%		75%	
Partitions		4 fell			
Tall Cabinets	22	5%		41%	

TABLE IV
Santa Clara County Government Center - San Jose
Summary of Peak Recorded Motions/Damage Data by Levels - 1989 Loma Prieta Earthquake

East-West Component

Level	Channel #	Peak Acceleration (g)	Peak Displacement (in)	Peak Spectral Response @ T (seconds)	# of Cycles ≥0.05g
Lower	20	-0.087	-3.75	2.4	5
2	16	0.134	-6.10	2.4	10
7	12	0.257	10.12	2.4	35
12	8	0.266	13.26	2.2	40
Roof	4	0.337	14.49	2.2	43

North-South Component

Level	Channel #	Peak Acceleration (g)	Peak Displacement (in)	Peak Spectral Response @ T (seconds)	# of Cycles ≥0.05g
Lower	22	-0.098	-2.79	2.4	8
2	18	-0.106	-4.37	2.4	10
7	14	0.220	-10.90	2.4	38
12	10	-0.294	-16.97	2.4	41
Roof	6	-0.338	-17.40	2.4	48

8 EVALUATION OF SEISMIC BEHAVIOR OF BUILDING SYSTEM

A siesmic analysis of the Santa Clara County Government Center was carried out using the computer program ETABS (Computer & Structures, 1991). Details of ETABS Seismic Analysis model are presented elsewhere by Rihal (1992).

Input ground motion used for this seismic analysis was the earthquake response spectrum recorded at the lower level of this case-study building as shown in Figure 5.

The first three modal periods and frequencies obtained are presented in Table V.

A comparison of response displacements, as well as inter-story drift ratios, obtained from ETABS Seismic Analysis using CQC spectrum loading, 1988 UBC loading as well as those obtained from recorded data are presented in a detailed report by Rihal (1992).

TABLE V
Santa Clara County Government Center - San Jose
Modal Time Periods and Frequencies

Mode #	Period (second)	Frequency (cycles/second)	(translation) X	(translation) Y	(rotation) Z
1	2.14547	0.46610	•		
2	2.10116	0.47593		•	
3	1.58903	0.62931			•

9 OBSERVATIONS/PRELIMINARY CONCLUSIONS

9.1 *Analysis of Observed Non-Structural Damage and Recorded Response Data*

A comparison of peak recorded motions at different levels in theSanta Clara County Government Center during the 1989 Loma Prieta earthquake and the 1986 Mt. Lewis and 1984 Morgan Hill earthquakes is graphically presented in Figures 6-7.

Significant non-structural damage was observed to have occurred particularly at the 7th floor level especially during the 1989 Loma Prieta earthquake. At this floor the recorded peak accelerations and displacements during the 1989 Loma Prieta earthquake were approximately 2-3 times those recorded during the 1986 Mt. Lewis and 1984 Morgan Hill earthquakes.

Another important factor contributing to the extensive non-structural damage during the 1989 Loma Prieta earthquake, may be the relatively large number of floor acceleration cycles with aplitudes ≥0.05g, as shown in Table IV. These results show that typical number of floor acceleration cycles (≥0.05g) were 38 (1989), 22 (1984), and 17 (1986).

In an attempt to further determine threshhold levels of non-structural damage, recorded floor acceleration response spectra for the 7th floor and 12th floor (in E-W and N-S directions) were superimposed as shown in Figure 8. It is suggested that if the fundamental dynamic properties, e.g., period etc., of the non-structural components can be estimated, then the responses of non-structural components to floor response spectra could be evaluated and correlated with observed non-structural component damage.

9.2 *Discussion of Results and Conclusions*

In view of the fact that only five floor levels were instrumented, recorded inter-story drift levels were not readily available. A study of the inter-story drifts obtained from seismic analysis using ETABS and CQC spectrum loading shows that analytically predicted inter-story drift index was of the order of 0.007. A study of observed component damage shows that despite the large displacements experienced by this case-study building, none of the observed non-structural component damage was caused by inter-story drift effects. It appears that the exterior glass curtain-wall system survived the 1989 Loma Prieta earthquake without any visible damage. None of the open office areas had any full-height non-structural partitions that could have been prone to earthquake damage due to the inter-story drift levels experienced by this building.

In conclusion, the important issues of correlation between recorded response data and non-structural component damage observed in the Santa Clara County Government Center are as follows:

- Threshholds of response motions that produce non-structural component damage.
  At the 7th floor level peak recorded acceleration was 0.257g and peak recorded displacement was 10.12 inches in the E-W direction. Significant non-structural component damage occurred at this floor level, especially during the 1989 Loma Prieta earthquake.
  The number of cycles of recorded floor accelerations (≥0.05g):
  Non-structural components @ 7th floor level experienced 35 cycles of floor accelerations with amplitudes ≥0.05g. This may be one significant reason for the extensive nonstructural damage observed during the 1989 Loma Prieta earthquake.

- Non-Structural Component Damage Index
  A crude non-structural component damage index expressed as a percentage of components damaged and based on a review of the video-tape of the observed non-structural damage was attempted in consultation with Reitherman (1991) as presented in Table III. Such an index, when improved by taking into account additional factors outlined above, could provide a means of characterizing observed non-structural component damage.

ACKNOWLEDGEMENTS

This study is supported by a research grant from the Strong Motion Instrumentation Program of the California Department of Conservation. This support is gratefully acknowledged. The author would like to thank Dr. Moh Huang and Dr. Tony Shakal of the CSMIP for their support. The valuable assistance of Mr. Wes Van Osdol of the County of Santa Clara, General Services Agency during this study is gratefully acknowledged. The author acknowledges the valuable assistance and contributions of Robert Reitherman during the course of this investigation. The author acknowledges the valuable assistance of project research assistants Evelyn Pratt, John LaPorta, Paul Philbaum, Mat Melcher and Tonya Emerson during the course of this research project.

REFERENCES

Arnold, Chris, Occupant Behavior Related to Seismic Performance in a High-Rise Office Building.

Benuska, L., Editor, "Loma Prieta Earthquake Reconnaissance Report," Earthquake Spectrum, Supplement to Vol. 6., Earthquake Engineering Research Institute, 1990.

ETABS, Computers and Structures, Inc., Berkeley, California, 1991.

Mahin, S.A., Boroschek, R., and Zeris, C., Engineering Interpretation of the Responses of Three Instrumented Buildings in San Jose, SMIP 89 Seminar, California Department of Conservation, Division of Mines and Geology, Sacramento, California, May, 1989.

Naaseh, Simin., "The Morgan Hill Earthquake of April 24, 1984 - Performance of Three Engineered Structurs," Earthquake Spectra, Vol. 1, No. 3, Earthquake Engineering Research Institute, May 1985.

Reitherman, Robert, Personal Communication, 1991.

Rihal, Satwant S., Correlation Between Recorded Building Dta and Non-Structural Damage During the Loma Prieta Earthquake of October 1989, Draft Report submitted to the California Division of Mines and Geology, Office of Strong Motion Studies; Research Report EQRU-01-91, Cal Poly State University, San Luis Obispo, California 93407, January, 1992.

Shakal, A., Huang, M., et al., "CSMIP Strong-Motion Records and Processed Data from the 1984 Morgan Hill Earthquake," California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, OSMS 85-05.

Shakal, A., Huang, M., et al., "CSMIP Processed Strong-Motion Data from the Loma Prieta Earthquake of 17 October 1989," California Department of Conservation, Division of Mines and Geology, Office of Strong Motion Studies, Report No. OSMS 91-07, 1991.

UBC, 1988 and 1991 Editions, International Conference of Building Officials, Whittier, California.

Van Osdol, Wes., Video-Tape of Non-Structural Damage and Personal Communication, 1991.

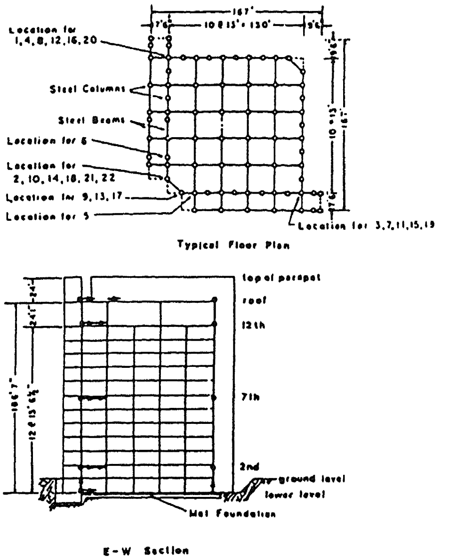


Figure 1 Santa Clara County Government Center - San Jose
Plan and Section - Source: Shakal (1985)

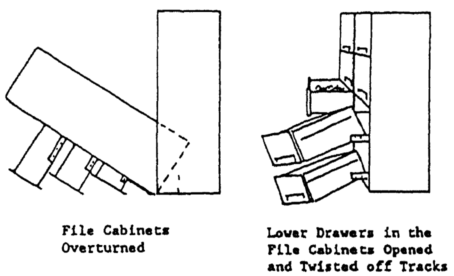
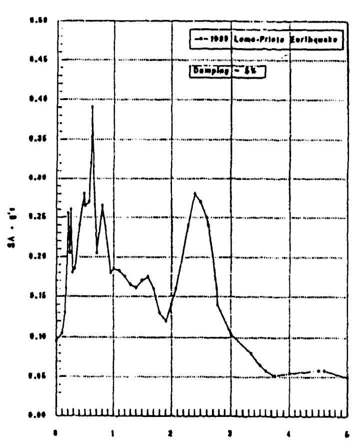
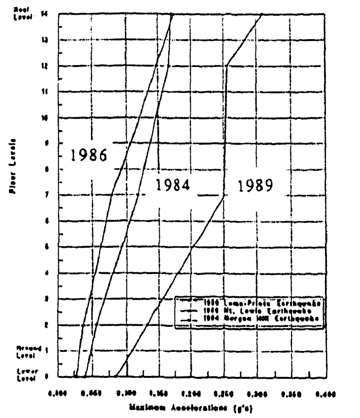


Figure 2 Representative Non-Structural Component Damage
7th Floor (left) and 11th Floor (right)



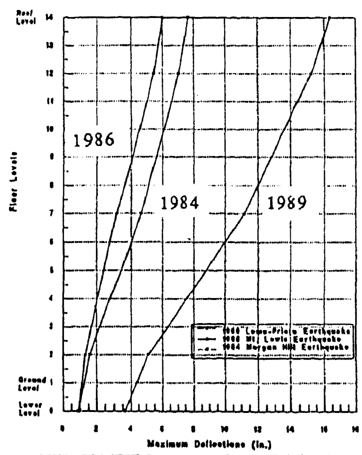
CSMIP PROJECT Santa Clara County Building - Case Study
Earthquake Response Spectrum Lower Level - Chan No. 22
SW Corner in N-S Direction

Figure 5 Input Acceleration Response Spectrum - Seismic Analysis



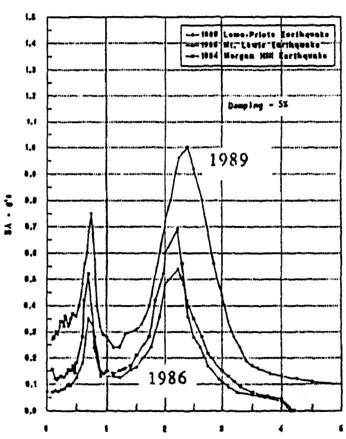
CSMIP PROJECT Santa Clara County Building Case Study
Maximum Recorded Accelerations vs Floor Levels
SW Corner of Building in East-West Direction

Figure 6



CSMIP PROJECT Santa Clara County Building Case Study
Maximum Recorded Deflections vs Floor Levels
SW Corner of Building in E-W Direction

Figure 7



CSMIP PROJECT Santa Clara County Building - Case Study
Earthquake Response Spectra - 7th Floor, E-W Direction
CSMIP Chan No. 13

Figure 8

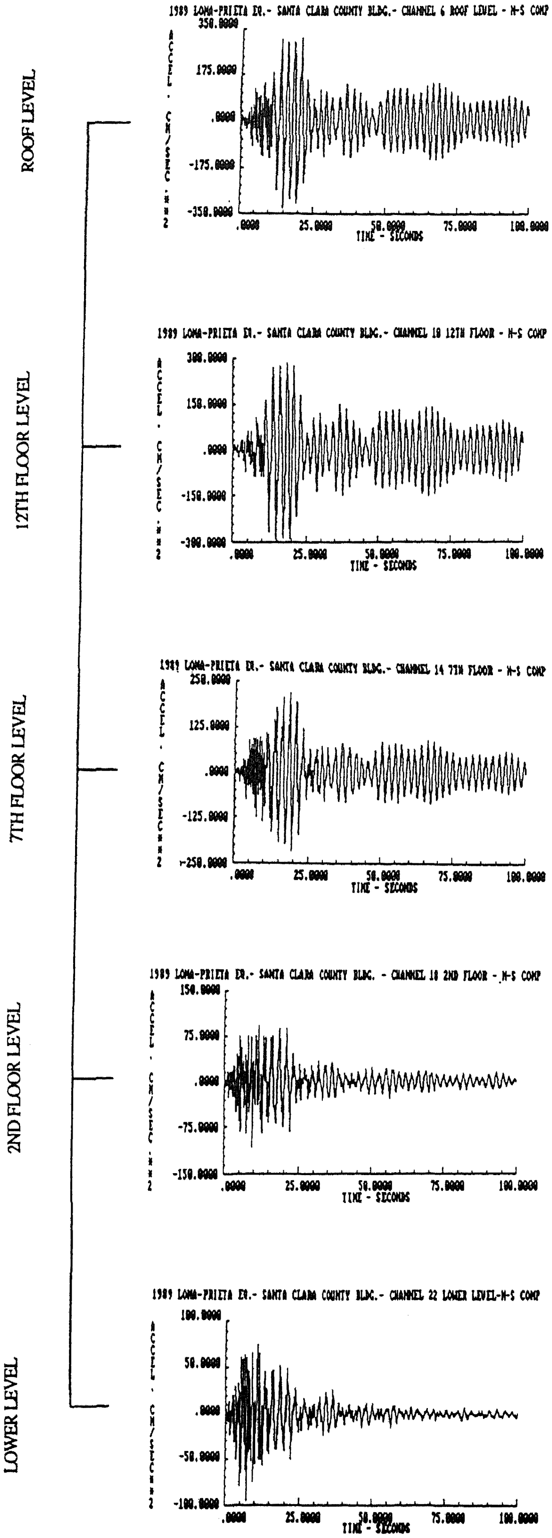


Figure 3 Recorded Acceleration Time-History Data

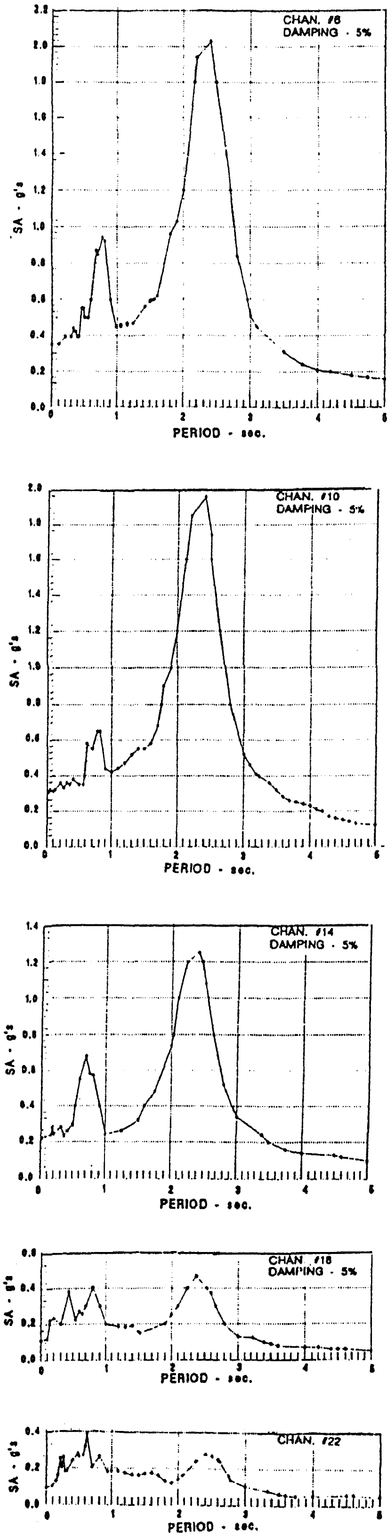


Figure 4 Recorded Acceleration Response Spectra