CONSIDERATIONS IN PREDICTING EARTHQUAKE DAMAGE TO INDUSTRIAL FACILITIES

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SUMMARY

It is desirable to be able to estimate earthquake damage to structures, as well as to piping and equipment, without investing extensive time and effort into numerous and rigorous detailed dynamic analyses. This paper presents a seismic evaluation of a facility consisting mainly of steel framed structures, overhead cranes, heavy mechanical equipment, and numerous piping systems. The main purpose of the study was to provide a "realistic" (i.e., best estimate) assessment of the expected damage for various levels of earthquakes based on simplified analyses and the consideration of various factors. The evaluation results can be presented in a number of ways which can be useful and meaningful to the engineer, planner, and decision-maker.

INTRODUCTION

This paper discusses the seismic evaluation results of an industrial facility and the various factors considered in estimating the expected earthquake damage. Within the scope and budget, simplified analyses and selected dynamic analyses were performed to develop seismic scenarios and damage curves. Damage thresholds were developed for buildings, cranes, various related structures, mechanical systems, including heavy equipment and piping, electrical systems, and instrumentation systems. Major weak areas and common weaknesses among these types of structures were identified. The identification of uncertainties, the confidence level of the scenarios, and the usefulness of the results are also discussed.

DESCRIPTION OF FACILITY

The facility consists of numerous large process buildings, product handling buildings, main support and auxiliary buildings, and various miscellaneous buildings and structures. There are over 50 permanent buildings at the site. Most of the facility was constructed in the 1950s. The major buildings are typically two-story structures framed of structural steel with reinforced

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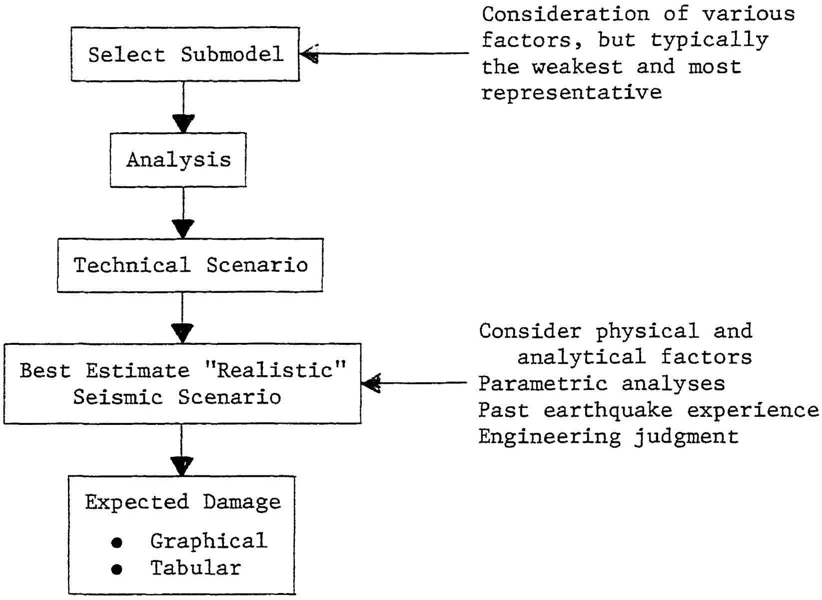
concrete floors and corrugated asbestos siding. Also, within the facility are numerous mechanical, electrical, and instrumentation systems, as well as various process and product handling equipment, and several smaller steel and concrete buildings and structures.

EVALUATION BASIS

Ground spectra were selected based on Refs. 1 and 2. Acceleration time histories were generated to match the spectra. Damping values selected were based on Ref. 3. The general evaluation procedure is outlined as follows:



The selection process was to completely lay out each building or system to be analyzed. Each building or system consisted of several structural frames or subsystems. The frames or subsystems were investigated and generally the weakest, critical frames or subsystems were selected for analysis. However, consideration was given to the following: (1) number of frame types, (2) relative frame stiffness, (3) strength of frame and connections, (4) representativeness for extrapolation of results, (5) period of frame, (6) representativeness for use in developing floor response spectra, (7) effect of live loads, (8) effect of connection strength and stiffness, and (9) engineering judgment. As an example, for one of the major buildings, forty-four various types of structural frames were investigated and only two frames were selected for analysis.

For the most critical safety-related structures and systems, linear elastic dynamic analyses were performed. Generally, the analyses were performed for a 0.05g ground acceleration earthquake level and these results were the basis for scaling and extrapolation to higher earthquake levels. The analytical models for the major buildings consisted of two-dimensional frame models; the analyses employed time history mode superposition technique. Floor response spectra (FRS) were generated at various locations for use in analyzing the associated piping and equipment.

For the critical mechanical piping systems, three-dimensional models (or submodels) were developed and analyzed for each particular system. The response spectrum analysis technique was used to compute the earthquake response of the piping systems. The analyses considered the effects of gravity, earthquake, temperature, and pressure, where applicable.

Parametric analyses of the building frames varying the effective mass and stiffness were performed. The results of these parametric analyses were used to determine the range of periods, variation in column base fixity, variation in floor response spectra, and the range of expected damage at various threshold levels. Friction and connection fixity were accounted for in several of the analyses. The column base capacities were determined using Ref. 4.

In developing the final seismic scenarios, the following factors were, at least qualitatively, considered: nonlinear behavior, multiple earthquake input excitation, actual earthquake motion, soil-structure interaction, seismic wave propagation, actual structural damping, variation in actual stiffness and loading for individual building frames, actual conditions of materials and connections and details, stress concentrations (at bends, tees, welds, etc.), fixity at connections, friction at supports, unknown strength of bellows and expansion joints, actual field conditions as compared to that shown on drawings, accuracy of floor response spectra used in the analyses, structural and material ductility, studies of past earthquake performance, and engineering judgment.

Table 1 summarizes some of the factors which may influence the thresholds and the development of the final seismic scenarios. The quantitative effect of these factors is difficult to determine without further work but the list is valuable in identifying some of the conservative, nonconservative, and unknown areas.

RESULTS

Damage scenarios and curves were developed for the structures and systems at the facility. Damage was expressed in terms of physical loss. One hundred percent damage was defined as total collapse or inability to repair and reuse the structure or system. Three levels of damage were defined as follows:

- Minor damage was defined as approximately 10% of total damage and can include concrete cracking, some member yielding, significant stresses, and noticeable displacements for flexible structures. Physically, one may hear such sounds as the creaking of the steel frame and loose joints, rocking movement of the building and hanging fixtures, and squeaking of the exterior wall siding. After such an earthquake, the structure or system is entirely usable, and only minor repairs would be required.

- Moderate damage was defined as approximately 40% of total damage from the damage curve, and can include concrete spalling, significant yielding and permanent deformations in members, initial cracking in piping, and local damage, but no overall collapse or

TABLE 1

FACTORS INFLUENCING THRESHOLDS

Factors	Effect on Damage Estimate Increase	Decrease	Vary	Unknown	Small Effect
Physical:					
1. Overhead Cranes			X		
2. Structural Redundancy		X			
3. Individual Frames			X		
4. Actual Live Loads			X		
5. Soil Structure Interaction					X
6. Seismic Wave Propagation		X			
7. Structural Damping		X			
8. Connection Fixity			X		
9. Bellows/Expansion Joints (pipes)	X				
10. Friction at Rollers, Supports, etc.		X			
11. Actual Condition of Material				X	
12. Actual Condition at Connections and Details			X		
13. Stress Concentrations				X	
14. Dynamic Strength of Material					X
15. Restraint due to Hammering (Bldg)		X			
16. Selection of Subsystem			X		
Analytical:					
1. Nonlinear Analysis		X			
2. Multiple Support Excitation		X			
3. Refined Modeling Assumptions		X			
4. 3-D Models for Buildings					X
5. Time Phasing of Peak Values of Response		X			
6. Refined Procedure to Compute FRS		X			
7. Time History Technique for Equipment and Piping		X			
8. Use of Multiple FRS		X			
9. Damping of FRS in Nonlinear Range		X			

failures. Physically, structural damage may range from a few cracked concrete beams or columns or buckled flanges on steel members to substantial structural damage requiring repair or replacement of some structural members. Cracking and falling of some exterior wall siding and sliding and overturning of unanchored equipment may result. After such an earthquake, most of the structures or systems are operable with some required local repair or replacement and clean-up. More complete repairs and/or strengthening can be performed later.

- Major damage was defined as 80% of total damage, and can include extensive yielding and permanent deformations in structural members, extensive nonstructural damage, major structural damage, local failures of structures and systems, and possible (but not likely) formation of incipient collapse mechanisms. Physically, substantial structural damage is expected but total collapse is not. After such an earthquake, the building is not usable or the system is inoperable, but most of the damage is structurally repairable.

Examples of damage curves are shown in Figure 1. A shallow or flat slope on the curve indicates good structural response with high material ductility. A steep slope indicates low ductility or brittle-type failures. The curve of an unanchored component will be steep near the point of overturning or sliding. Table 2 illustrates an example of a seismic scenario description of a building.

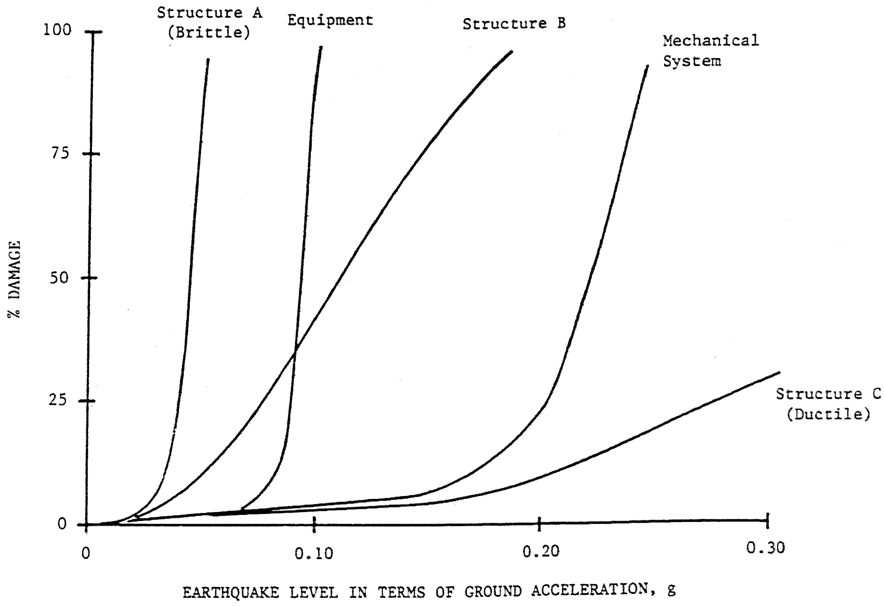


Figure 1: Typical Damage Curves

TABLE 2

SEISMIC SCENARIO OF SAMPLE BUILDING

Ground Acceleration (g)	Description/Remarks
0.05±	• The compression member of X-brace at column line G begins to buckle. No adverse conditions expected.
0.10±	• The compression member of X-brace loses stiffness, but tension member is adequate to carry overload. No significant structural damage is expected.
0.15±	• The K-brace at penthouse level at column line C begins to buckle. Some yielding in columns and at connections but no failures expected.
0.20±	• K-brace loses stiffness. Buckling of bracing members, significant yielding at connections, columns. Moderate damage but no gross failures expected.
	• The semi-gantry crane experiences minor damage due to building displacements.
0.25±	• Major structural damage. Incipient collapse mechanism for building is possible. The semi-gantry crane experiences considerable damage and may be derailed due to the large building displacements.

The major weak areas identified during the study are:

1. Flexible Structures - Flexible structures with large displacements will affect column stresses, diaphragm action, connection stresses, overhead crane structures, piping systems, and nonstructural elements.

2. Building Connections - The actual capacities of many of the building connections are difficult to estimate. The uncertainty of their strength and ductility capacities may very well affect the accuracy of the damage estimates.

3. Lateral Bracing - The capacities of some of the steel braces were determined to be fairly low. The K-type or single cross brace is generally more susceptible to compressive buckling than the X-type or double cross brace.

4. Expansion Joints in Piping - Seismic displacements at the expansion joints exceeded design values. The actual behavior of these joints will affect the damage estimates.

5. Flexible Piping - The piping systems with long lengths of laterally unsupported runs are susceptible to high stresses at connections, welds, elbows, and tees.

6. Unrestrained Equipment - Mechanical and electrical equipment that are not anchored are susceptible to overturning and sliding.

The objective was to predict the best estimate "realistic" damage at each g-level (maximum ground acceleration) without being overly or under-conservative. However, predicting damage becomes increasingly difficult as g-levels increase, particularly for flexible structures. Therefore, the range in the uncertainty of the predictions increases with increasing g-level. Hence, the level of confidence at each threshold is highest for low-level earthquakes and stronger structures and systems, and lowest for high-level earthquakes and weaker structures and systems. In general, the following can be stated:

- For low-level earthquakes (e.g., producing less than about 10% damage), the structures and systems will behave approximately in a linear manner and are thus reasonably well-represented by the linearly elastic models used in the evaluations. Therefore, a high level of confidence exists in the prediction of "realistic" seismic response in this range.

- For moderate level earthquakes (e.g., producing in the range of 10 to 40% damage), the responses of the structures and systems may be in the nonlinear range. The extrapolations of the linearly elastic analysis results to this range involve numerous approximations but were done with a satisfactory level of confidence.

- For higher level earthquakes (e.g., producing 50% damage or more), the responses of the structures and systems will generally be highly nonlinear. Extrapolation of linear results becomes very difficult. Effects of large deformations, stresses in connections, brittle-type failures, and similar factors become increasingly complex and thus difficult to predict without the benefit of additional investigations. Prediction of seismic response into this range is an estimate based mainly on engineering experience and judgment. For areas where there appear to be adequate ductility, possible failure was assumed to occur at 3 to 5 times the yield stress.

In summary, the methodology used in this study is based on simplified linear elastic analyses and consideration of a variety of factors, such as the type and quality of construction, analytical assumptions and techniques, physical factors, experience from past earthquakes, and engineering judgment. The evaluation results, presented in both graphical and scenario format, can be very useful and meaningful. The advantages and merit of this approach are: (1) provides for quick overview of a facility, (2) is a cost-effective method, (3) provides comparison of structures within a facility, (4) identifies the weak areas, (5) aids in facility planning, (6) is useful in determining accident scenarios and insurance needs, and (7) is useful in risk and hazard studies.

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