AN AUTOMATED DESIGN STUDY OF THE ECONOMICS
OF EARTHQUAKE RESISTANT STEEL STRUCTURES

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SUMMARY

This paper presents an automated design approach to the study of the economics of earthquake resistant structures. An automated structural design program and a data base of uniform risk, pseudo spectral velocity (PSV) response spectra for regions of shallow seismicity, have been utilized in this study. Each selected structural system is subjected to more than 250 different response spectra obtained from the data base and automatically designed. The relations between the seismic environment, the designed structure and the cost of a given level of seismic resistance are studied.

INTRODUCTION

The earthquake resistant design of structures requires that the recurrance interval of earthquakes of given magnitude be estimated from the past seismic history of a given region. A widely used empirical relationship of this type is the one suggested by Gutenberg and Richter (Ref. 1). Once the seismicity of the region is determined, it is necessary to determine a design criteria for the lateral inertia forces which the structure must withstand. The most common form of this criteria is the pseudo static lateral loads which are specified in most building codes. A more accurate means of representing the seismic design criteria is the use of a smoothed design response spectrum which is representative of a large ensemble of recorded earthquake motions. An elastic design response spectrum (EDRS) can be used to represent elastic structural response or an inelastic design response spectrum (IDRS) can be used to consider inelastic structural response. In many regions of low to moderate seismic activity the lateral inertia forces due to earthquakes may be overshadowed by the lateral forces representing the equivalent static pressure of the wind acting on the face of the building. In this case the building will have a certain inherent resistance to earthquakes of different magnitudes and different return periods.

Another factor which must be considered in the development of a seismic design criteria is the amount of risk or uncertainty contained in the cri-

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teria. A smoothed design spectrum can be constructed which envelopes all spectra obtained from the recorded motions in the data base. This design criteria will have a low probability of exceedance. On the other hand a smoothed spectrum can be developed which has a high probability of exceedance. A median spectrum having a fifty percent probability of exceedance is often used for the design of ordinary building structures.

AUTOMATED DESIGN PROGRAM

The purpose of this study is to investigate the relationships between earthquake resistant design criteria, the seismic environment and the economics of seismic resistance. In order to accomplish this, it is necessary to design a limited number of structural systems for a large number of seismic environments. In the original study (Ref. 2) each of four structural systems was designed for 250 different seismic environments. Since the design process is an iterative process, several trial designs are required to reach a final design solution. This is particularly true in the case of earthquake resistant design because the seismic loads depend upon the dynamic properties of the structural system. Hence, in order to accomplish this task in a reasonable amount of time, it was essential to automate the design process.

The automated design program had to have a dynamic analysis capability for three dimensional structures, an ability to be cycled in an iterative mode and at the same time be economical to use. In order to meet these constraints the design programs were built around the analysis module and philosophy embodied in the ETABS (Ref. 3) program. Versions were developed for both steel frames and reinforced concrete frames (Ref. 2) although only the application for the steel frame is considered here. Steel structural systems which can be considered include the following: two and three dimensional moment frames, braced frames, framed tubes, eccentrically braced frames, trussed tubes and steel frames with infilled walls. The iterative design procedure is completely automatic and members are selected from a member property table in accordance with the strength design provisions of Part 2 of the AISC Specification (Ref. 4). Second order P-delta effects are considered and the program contains an option for increasing the member sizes to control story drift. Program variables permit the use of the strong column-weak girder design philosophy if required and members can be constrained to be the same size in order to reflect construction practice. Studies show that the program produces designs which are economical when compared to conventional designs.

EARTHQUAKE DESIGN SPECTRUM

Several different design spectra have been proposed for earthquake resistant design. One of the early spectra was the one developed by Housner (Ref. 5) which was based on the motions recorded during four major California earthquakes. More recently, the design spectrum suggested by Newmark and Hall (Ref. 6) has been widely used for seismic design of structures. This design spectrum has a standard shape and is scaled on base acceleration and structural damping.

The design spectrum used in this study is a uniform risk, pseudo spectral velocity spectra (Ref. 7). This spectrum is designed such that the probability of the spectrum being exceeded during any earthquake is independent of the frequency of the earthquake ground motion. Westermo et al (Ref. 8) developed a data base for these spectra based on regression equations between the PSV spectral amplitudes and the earthquake magnitude. The seismicity is modeled as a uniform, difuse circular zone of shallow earthquakes and the seismicity within the zone is defined by the Gutenberg and Richter equation

$$\log N = A - bM$$

where A and b are constants for a particular region and N is the number of earthquakes per year per 1000 square kilometers within the range of $M-0.25$ to $M+0.25$ in terms of Richter Magnitude. Tables of the seismic constants A and b for different regions of the world are available in the literature. To develop the design spectrum it is necessary to enter the data base with the seismicity constants (A,b), earthquake magnitude (M), percent of critical damping and the exceedance probability. A PSV uniform risk spectrum for a particular seismicity, having an exceedance probability of fifty percent, is compared with a Newmark-Hall spectrum in Figure 1.

PROGRAM OF INVESTIGATION AND RESULTS

In this study, a ten story steel moment frame is designed for different seismic environments and different levels of seismic risk. The seismic environments are represented by elastic design response spectra which have a uniform seismic risk at all ground motion frequencies. The possible design space for the steel frame using the EDRS is assumed to consist of all the rolled steel sections contained in the AISC manual. If the requirements of a particular design fall outside of this space, it is assumed that nonlinear aspects of the response will have to be considered. These might include the use of an IDRS for the design criteria or the use of a nonlinear time history analysis. The alternative of using built-up sections with the EDRS is discarded as being an uneconomical solution.

The geometry and static loading for the reference frame are shown in Figure 2. The frame is a typical interior frame of an office building in which the frames are spaced at twenty foot intervals. The designed frames are grouped into three seperate categories as follows:

Category S: Frames for which the design is controlled by combinations of gravity load and wind loads.

Category RS: Frames for which the design was controlled by combinations of gravity load and EDRS.

Category N: Frames which could not be designed economically using the EDRS. Consideration of nonlinear behavior is required.

Charts comparing the design method with the seismicity are shown in Figures 3 through 5. Here it can be seen that structural systems, even when not designed for earthquake resistance, have a substantial level of inherent earthquake resistance capacity as represented by the Category S region on the curves. Considering an earthquake of magnitude 5.5 (Figure 3) the importance of the exceedance probability can be seen. For exceedance probabilities of fifty percent or greater, almost the entire seismicity space can be accommodated without considering nonlinear behavior. However, at a ten percent exceedance probability the nonlinear region becomes significant. Considering the results shown in Figure 4 and 5, it can be seen that even for earthquake magnitudes of 6.5 and 7.5, the inherent seismic resistance of moment frames is adequate for a significant range of seismicities and risks. The figures also indicate that as the magnitudes increase and the exceedance probabilities decrease the range of economical application of the EDRS narrows considerably. This is accompanied by an increasingly wider range for the possible application of nonlinear methods.

Cost versus seismic risk charts for this type of frame are shown in Figures 6 through 8. The frame weight is used as an indicator of the cost. The vertical axis in these figures represents the normalized cost (ratio of frame weight to the weight for the frame designed for gravity and wind loads). These charts may be used as an aid in selecting economically acceptable exceedance probabilities. A review of these figures shows that with increasing seismicity (increasing A and decreasing b) the cost of the frame remains constant for an interval which conforms to region S. With further increase in seismicity the frame cost starts to increase gradually. This increase is almost linear for an interval and then starts to increase quite rapidly. This indicates that for these situations, neglecting the nonlinear behavior introduces increasingly high cost penalties on the designed frames.

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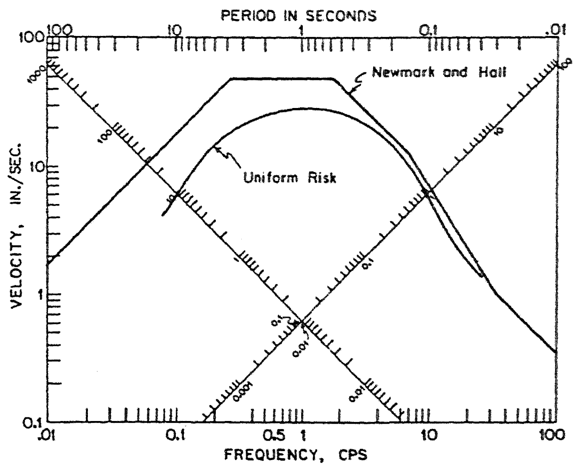


M = 7.5
A = 3.5
b = 1.0
Ex. P. = 50%
base accel. = .548 g
damping = 5%

Figure 1. - Comparison of Uniform Risk and Newmark-Hall Spectra

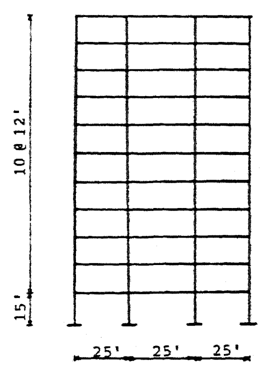
DEAD LOADS:

Roof	85 Psf
Typical Floor	100 Psf

LIVE LOADS:

Roof	20 Psf
Typical Floor	60 Psf

WIND LOADS: 20 Psf



H/D = 1.80

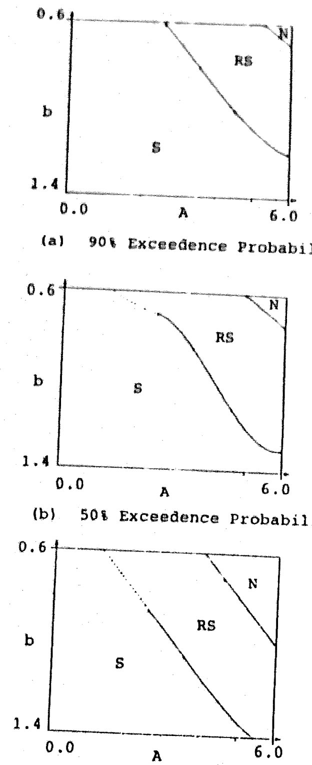
LOAD CASE COMBINATIONS:

1) 1.7(DL + LL)

2) 1.3(DL + LL ± W)

3) 1.3(DL + LL) ± EQ

Figure 2. - Geometry and Static Loading of the Ten Story Frame

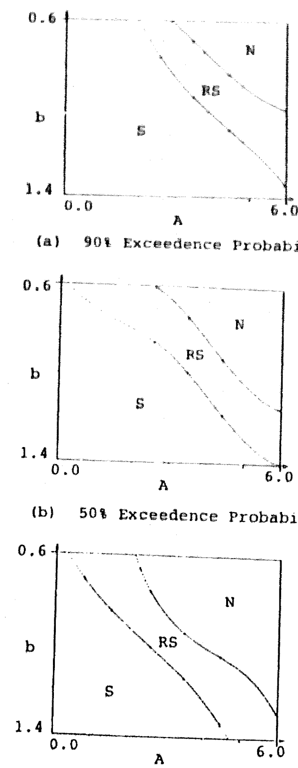


(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 3 - (M=5.5)

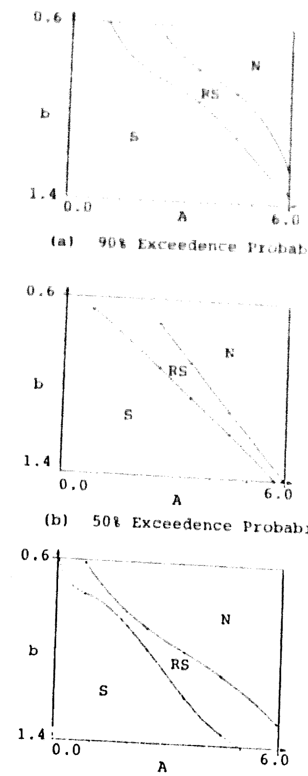


(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 4 - (M=6.5)

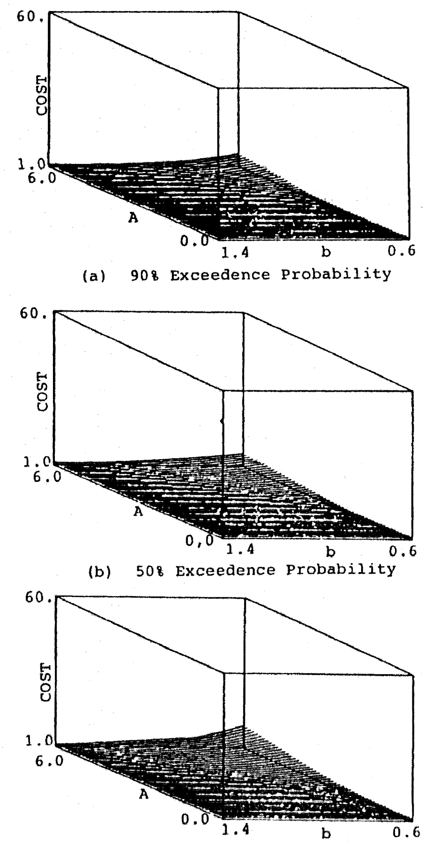


(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 5 - (M=7.5)

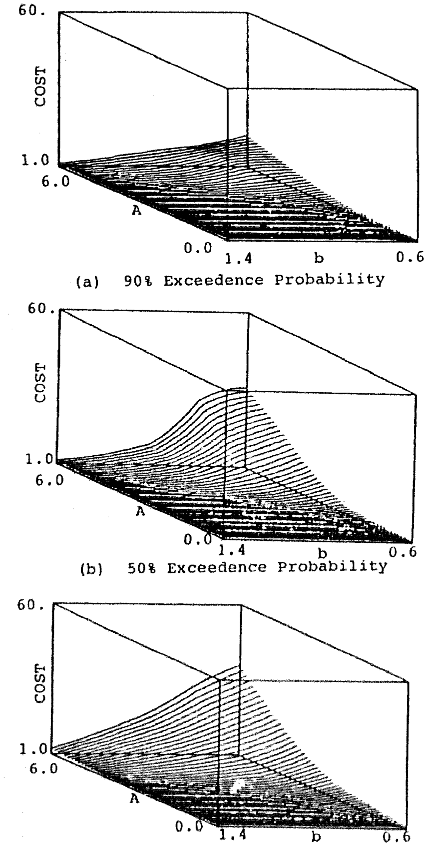


(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 6 - (M=5.5)

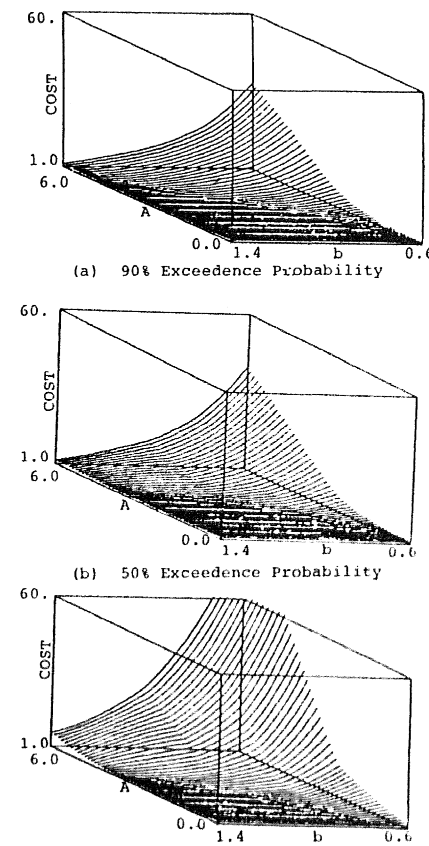


(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 7 - (M=6.5)



(a) 90% Exceedence Probability

(b) 50% Exceedence Probability

(c) 10% Exceedence Probability

Figure 8 - (M-7.5)

COST VERSUS SEISMIC RISK