DIRECTIONS FOR NEW SEISMIC CODES AND DESIGN PROCEDURES

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ABSTRACT

Present seismic provisions of building codes attempt to provide the additional capacity required for major earthquakes by means of ductile detailing requirements, avoidance of irregularity, and limits on susceptible types of structural systems. The designer is not required to investigate the overall lateral resistance capacity of the building for forces that exceed the minimum code requirements. Therefore, there is a great uncertainty on how most buildings will actually perform during a major earthquake. This paper reviews recent developments that can lead to a more rational procedure to design buildings to resist seismic forces. The procedure is generally referred to as a two-level approach. The building is designed to resist a prescribed level of earthquake forces within the elastic limits of the structural materials. It is then analyzed for its ability to resist a higher level earthquake inelastically. Approximate procedures are described that can be practicably applied by the design engineer. This type of approach to seismic design can give the practicing engineer more confidence in the design of structures and can reduce the risk of catastrophic damage in the event of a major earthquake.

INTRODUCTION

Seismic provisions of our current building codes (1,2,3) prescribe lateral forces that are substantially less than the equivalent forces that will result from the response of buildings to major earthquakes. Building codes attempt to provide the additional capacity required for major earthquakes by means of ductile detailing requirements, restrictions on irregular structures, and higher load coefficients on susceptible types of structural systems. However, the designer is not required to evaluate the structure for its overall lateral resistance capacity to resist major earthquake motion. It is generally assumed that code-designed buildings will perform as follows (4,5,6):

1. Respond to minor earthquakes within the elastic limits of the structural elements and without damage.

2. Withstand moderate earthquakes with damage to nonstructural elements, but little or no damage to the structural elements.

3. Survive a major earthquake without collapse, but with the possibility of substantial nonstructural and structural damage.

The terms minor, moderate, and major earthquakes represent relative values. Their magnitudes or intensities will be dependent on the general seismicity of the region in which they are located.

The code forces are applied to capacities based on working stress criteria or on strength design with load factors. Therefore, there is some reserve capacity available prior to first yielding of structural elements. The amount of the pre-yielding reserve capacity will be dependent on the effects of gravity loads (dead and live loads), as well as lateral seismic forces. In other words, the ratio of yield limit to code forces will not simply be equal to the seismic load factors or the ratio of yield stress to working stress, but will be dependent on various load combinations affecting each structural element.

Additional capacity is generally available after the first structural elements begin to yield due to redundancy, redistribution of forces, and reserve energy of the inelastic action of ductile materials. The additional capacity is not all in terms of increased force capacity. A great amount of the building's ability to resist large earthquakes can be attributed to the lengthening of the building period due to stiffness reduction and the effective increase of damping due to energy absorption.

When buildings are subjected to actual earthquake ground motion, their performance is not always consistent with the assumptions made during the lateral force design. Some buildings designed in accordance with modern earthquake lateral force criteria have been substantially damaged during moderate earthquakes. Other buildings that were built with little or no seismic consideraton withstood the same earthquake ground motions with little or no damage.

Buildings damaged by earthquakes have been analyzed to determine the causes of the damage. The damage can usually be attributed to one or more of the following: structural discontinuities, torsional irregularities, load reversals, inadequate details, unanticipated participation of nonstructural elements, lack of redundancy, or nonductile behavior. If these buildings had been evaluated for the effects of excess lateral loads prior to construction, in many cases, the potential deficiencies could have been detected and corrected.

Buildings that survive earthquakes without apparent damage are seldom evaluated. In order to obtain some data on undamaged buildings, the United States Geological Survey funded a research project in 1981 to investigate the correlation between earthquake ground motion and building performance. The report was prepared by Applied Technology Council as project ATC-10 (7). In this project, six representative buildings were evaluated to approximate their ultimate or limit capacities relative to their design capacities. The results of the study indicated that many buildings relatively uniform and regular in size and shape can undergo seismic motions considerably in excess of those represented by the coefficients used in building design with little or no damage.

On the basis of post-earthquake evaluations of damaged buildings and on the results of the ATC-10 project, it seems apparent a design procedure can be developed that will give a better insight on the seismic performance of buildings than is resulting from current building code procedures. Currently available alternatives to the commonly used static code procedures include the dynamic analysis provisions of the National Building Code of Canada (8), the Applied Technology Council Publication ATC 3-06 (5), and the Veterans Administration Handbook H-08-8 (9). Each of these seismic design procedures provide a design response spectrum that is used to determine the forces and displacements of the structure. However, to avoid an inelastic analysis, each of these procedures provides for a force reduction factor. The Canadian code modifies the spectrum by use of ductility factors (10), the ATC 3-06 uses a response modification factor R, and the Veterans Administration uses a coefficient "alpha" that considers both ductility and damping. A disadvantage of these procedures is that the design is essentially an elastic design. The designer does not evaluate the potential inelastic performance of the structure, but relies on the validity of the spectrum modification factors. The Canadian code recognizes the potential for high and nonuniform ductility demands in cautionary notes in Paragraphs 37 and 38 of Commentary K (8).

A project is now underway to develop seismic design guidelines for critical buildings for the U. S. Army Corps of Engineers as a supplement to the Tri-Services seismic design manual (6). The procedure presents a two-level approach to seismic design that attempts to evaluate the inelastic performance of structures.

TWO-LEVEL APPROACH TO SEISMIC DESIGN

A two-level approach to seismic design is proposed to provide a rational procedure to design buildings to resist seismic forces. First, the building is designed to resist the lower level of earthquake motion, E-Q-I, by elastic behavior. Then the building is evaluated for its ability to resist the higher level earthquake, E-Q-II, with allowances for inelastic behavior.

First Level Earthquake

A response spectrum is used to represent E-Q-I ground motion that has 50 percent probability of being exceeded in 50 years. This is considered to be the maximum ground motion that is likely to occur at the site during the life of the structure. The structure is to be designed to resist the forces of E-Q-I within the elastic range of the capacity of the lateral force resisting system. The general procedure requires a trial and error process because the magnitude and distribution of seismic forces depend on the weight, periods of vibration and mode shapes of the structure. Thus, an approximation of the building characteristics is required before the design forces can be calculated. The selection of trial structural member sizes can be made in a manner similar to that of conventional static design procedures. Structural member forces are calculated by means of a modal analysis using the E-Q-I response spectrum with the prescribed damping. The member forces are compared to the elastic capacities of the structural elements. All building components are designed to provide yield strength capacities sufficient to resist the combined effects of the seismic forces and applicable gravity loads. A load factor of 1.2 is placed on the dead load to account for possible vertical components of seismic force. Live and seismic loads are given a load factor of 1.0. Some slight flexural yielding of a limited number of structural components may be acceptable on the condition that the elastic-linear behavior of the overall structure is not substantially altered. Upon completion of the first level seismic design, the structure is evaluated for the second level earthquake.

Second Level Earthquake

The response spectrum with a low probability of being exceeded during the life of the structure is used to represent E-Q-II. The structure that was designed to resist the forces of E-Q-I elastically is now evaluated to determine its performance characteristics when subjected to the demands of E-Q-II. Two acceptable procedures are presented. One is an elastic analysis procedure that evaluates overstress ratios and the other is an approximate inelastic analysis procedure that evaluates lateral distortion limits. Load factors for the second level earthquake are equal to unity and live loads may be reduced to realistic actual conditions, which can be as low as 25 percent of the design live load.

Elastic Analysis Procedure: The elastic analysis procedure is acceptable when the equivalent forces of E-Q-II are not too much greater than the equivalent forces of E-Q-I and when the distribution of overstresses is fairly uniform. The structural member forces are calculated by means of a modal analysis using the E-Q-II response spectrum with the prescribed damping. The damping value for the E-Q-II spectrum is generally higher than the damping value used with E-Q-I. Also, the mathematical model of the structure may be revised to account for some inelastic distortions associated with E-Q-II, thus resulting in longer natural periods of vibration. The calculated elastic structural member forces (demand) are compared to yield capacities of the structural members. Inelastic demand ratios, a ratio of the demand forces to the yield capacity, are calculated for all structural elements of the lateral force resisting system. The inelastic demand ratios are evaluated for the following conditions: exceeding prescribed maximum values, unsymmetrical yielding on a horizontal plane, forming column mechanisms, discontinuity in vertical elements that cause instability, and unusual distributions. If all the conditions are within prescribed limits, the structure is considered to satisfy the provisions of the seismic design criteria. If the conditions are not met, structural modifications are required or the approximate inelastic analysis procedure must be used.

Approximate Inelastic Analysis Procedure: A step-by-step approach is used to approximate the inelastic capacity of the structure. First, the structure is analyzed to determine the lateral force level that is required to cause first major yielding of the structure. Next, the stiffness characteristics of all structural elements that are within 10 percent of their yield capacities are revised to represent plastic hinges. Then, additional lateral forces are applied to the structure until an additional group of structural elements reaches their yield capacities. The process is repeated until the combined results reach an ultimate limit governed by a mechanism, instability or excessive distortion. The results are converted to a capacity curve based on the periods and spectral acceleratons for the fundamental mode of vibration. A graphical solution is used to compare the demand of E-Q-II with the capacity of the structure. This procedure was first developed for an evaluation of the Naval Facilities at Bremerton, Washington (11). Examples of how the procedure is implemented are available in References 7 and 12.

CONCLUSIONS

As seismic design codes presently stand, the designer is unaware of how the structure will perform if subjected to severe earthquake type motion. A two-level approach to seismic design will force the designer to evaluate the building performance characteristics and discover possible weak spots that are susceptible to severe damage. The approximate procedures described can be practicably applied by design engineers. This type of approach to seismic design can give the practicing engineer more confidence in the design of structures and can reduce the risk of catastrophic damage in the event of a major earthquake.

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