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SUBJECT: RESEARCH SUMMARY ON
DISPLACEMENT BASED SEISMIC DESIGN METHODS

Background

The design of structures subjected to seismic loadings has been traditionally performed using elastic methods. This approach was a natural outgrowth of the use of elastic analysis methods to evaluate structural performance under working loads. The acceptance criteria for load combinations on structures, including seismic effects, have been based on ultimate strength provisions. Seismic loads have often been reduced in this process by dividing the loads by ductility factors to account for the fact that ductile structures can withstand dynamic loads larger than the elastic limit load.

The NRC has recently updated its requirements for earthquake engineering design of nuclear power plants. The regulation governing seismic criteria and design, Appendix A to 10 CFR Part 100, was revised in December 1996. Since that time, studies of the effects of the Northridge (1994) and Kobe (1995) earthquakes have been performed. The results of these studies have inspired some reassessment in the technical community about certain aspects of design practice for conventional structures. In particular, questions have arisen about the effectiveness of basing earthquake resistant designs on resistance to seismic forces and then evaluating the structure's ability to tolerate the expected displacements.

The traditional approach to reassessing the seismic capability of an existing building, for either an increase in perceived seismic hazard or degradation of the structure, has been to recalculate the capacity using the original design calculations with actual, as built, material properties and dimensions. This reliance on elastic analytical methods has been changing over the past few years as a result of the growing interest in reducing the potential effects of earthquakes on the nation's building inventory. Under the National Earthquake Hazards Reduction Program (NEHRP), all federal agencies are required to evaluate the seismic capacities of their building inventory, to develop retrofits that reduce the seismic risk, and to prioritize the repairs based on cost benefit criteria. As agencies began to implement this requirement, it soon became apparent that budgetary constraints emphasize the importance of prioritization. Useful cost

benefit criteria require that the seismic response used to evaluate the buildings be as realistic as possible. Elastic analysis methods (even with the use of ductility factors) are not adequate for this purpose. Rather, the analytical methods must focus on inelastic methods which rationally account for the effect of ductile behavior on the seismic capability of the building. FEMA 273 [1] sets the basic criteria to be used in implementing NEHRP. Inelastic analysis methods are proposed which focus on predicting the maximum seismic displacement rather than the seismic load that a structure can withstand. It is expected that meeting the NEHRP requirements will acquaint the profession with the use and benefits of inelastic deformation seismic analyses.

Therefore, a research effort was undertaken to determine the need for any changes to NRC's seismic regulatory practice to reflect the move, in the earthquake engineering community, toward using expected displacement rather than force (or stress) as the basis for assessing design adequacy.

Summary of the Research

A literature survey was conducted on the recent changes in seismic design codes and standards, on-going activities of code-writing organizations and published documents by researchers on the displacement-based design methods. The detailed results of the literature survey are reported in Appendix A to NUREG/CR-6719 [2]. A summary of this survey was presented in SMiRT-15 [3]. Based on the survey, it was observed that the transition to displacement based seismic design is a rather slow process due to inertia invariably encountered in the engineering community. Changes in one element of a design tend to be counterbalanced by changes in another element. Uniform nationwide acceptance is expected to come slowly. Thus, it did not appear that there would be a major "ground swell" of demand to change NRC criteria for new plants.

In the area of rehabilitation of existing buildings, however, it was noted that a need for change has been accepted. Researchers and practitioners tend to test and implement new ideas first in the areas of repair or rehabilitation. Thus, it was concluded that if the nuclear industry proposed to utilize some of the recent developments, it would at first be most likely applied to seismic reevaluation or seismic margin and PRA studies.

Traditionally, nonlinear analyses of nuclear power station structures have been used for margin studies where it is desirable to account for ductility effects in a rigorous manner. Seismic margin studies relate demand loads to a prediction of ultimate capacity. The ultimate capacity for ductile structures subjected to dynamic loading is tied to a deformation criteria, such as a number of yield deflections, for estimating failure. Elastic analysis is not suited to this task as it focuses on load and says nothing about structural behavior post yield. A nonlinear dynamic analysis is required, but is difficult and time consuming to perform. Hence attempts have been made to apply factors (ductility) to elastic analysis to account for acceptable structural response into the post yield range.

The FEMA 273 methodology is an alternate approach that accounts for performance into the post yield range. It requires the performance of a nonlinear static analysis of the structure with the loading monotonically increased (pushover analysis). Criteria are then given for the maximum displacement that the structure must withstand; this displacement is related to the level of the earthquake and the dynamic characteristics of the structure. The distribution of

loads and displacements throughout the elements of the structure at this displacement are then investigated by comparing the element deformations with acceptance limits. The acceptance limits are set to values typically suitable for margin studies.

Our research explored the extent to which FEMA 273 methodology could be useful for reviewing nuclear power stations. The FEMA 273 methodology has the very desirable characteristic that the same analysis can be used for evaluating the facility at the design level earthquake and at larger magnitude earthquakes associated with margin studies. It is also directly applicable to graded criteria where more important facilities would be subjected to more stringent acceptance limits than less important facilities.

Two structures common to nuclear power plants were chosen to compare the results of the analysis models used. The first structure is a four-story frame structure with shear walls providing the primary lateral load system, referred herein as the shear wall model. The second structure is the turbine building of the Diablo Canyon nuclear power plant. The models were analyzed using both the displacement based (pushover) analysis and nonlinear dynamic analysis. In addition, for the shear wall model an elastic analysis with ductility factors applied was also performed. The objectives of the work were to compare the results between the analyses, and to develop insights regarding the work that would be needed before the displacement based analysis methodology could be considered applicable to facilities licensed by the NRC.

Results of the Research

The research was completed in the Fall of 2000 and fully documented in Reference 2. A condensed version of the final report was also presented [4] at the SMiRT16 Conference held in Rosslyn, VA, in August 2001. A summary of the research results is presented below.

1. Shear Wall Model

The shear wall model is a four-story reinforced concrete building with shear walls. This building was previously used as a sample problem for the IDARC program [5]. IDARC is a Fortran program developed and maintained by the National Center for Earthquake Engineering Research (NCEER) at the State University of New York at Buffalo. The code was designed to perform Inelastic Damage Analysis for Reinforced Concrete structures; thus it was named IDARC. Since the code has been used to perform nonlinear static (pushover) analysis for commercial buildings, it was selected for this study to perform both the time history analyses and the FEMA analyses.

The following conclusions were found from the comparisons:

1. The displacement based method gives results comparable to the nonlinear time history analysis for the shear wall building where there are only material nonlinearities.

2. The use of ductility factors with a linear response spectrum analysis gives results which are comparable to those obtained from either the nonlinear time history analysis or the displacement based method.

2. Diablo Canyon Turbine Building

The Diablo Canyon turbine building was selected for the second case study comparing results obtained using the nonlinear time history and displacement based methods. This building was selected because it is a nuclear power plant structure for which complete nonlinear time history analyses are available. These analyses are available for two different seismic input levels such as would be required for a seismic margin study. It is also of interest since the nonlinear effects include both material nonlinearity and geometric nonlinearity (gaps).

A probabilistic evaluation of the Diablo Canyon turbine building was performed [6] during the plant licensing reviews. A simple model of the building was developed that characterized its performance through displacements that were likely to cause collapse. The objective of that evaluation was to determine the probability of failure for several levels of severe earthquake inputs.

A displacement based method using a FEMA 273 approach does not give results which are comparable to the more complete nonlinear time history analysis for the Diablo Canyon turbine building where both material and geometric nonlinearities (gaps) were included. This result is probably due to the strong effect of the gaps on the system response.

The differences are probably due to four factors:

1) Since the turbine is so massive, the dynamic characteristics of the building change dramatically when the gaps close. The basic idea behind the displacement-based approach is that an “equivalent” static analysis can be performed to represent the dynamic response. It is unlikely that a single static model could adequately model the response of a system that changes so dramatically as the gaps close and open.

2) The load path changes from the turbine pedestal supporting the building to the building supporting the turbine pedestal as the operating floor diaphragm and then the turbine pedestal reach their respective yield loads. It is also unlikely that this could be modeled with a single equivalent static model.

3) The displacement-based methodology was developed for cases where the building has softening stiffness characteristics. Some elements of the turbine building problem have the opposite characteristic. After the operating floor diaphragm yields, it is partially supported from the turbine pedestal. This support results in a nonlinear increase in building stiffness.

4) The turbine pedestal and shear wall structure behave as uncoupled systems during a large part of the response.

<u>Regulatory Implications</u>

1. It was concluded that there is no need to revise nuclear power plant acceptance criteria for seismic design of new plants to address displacement based methods. The displacement based approach is not likely to be used for the design of nuclear power facilities since the current acceptance criteria are force based and all responses are required to remain in the linear elastic range. While a displacement based approach could be developed for plants similar to the existing LWR designs, it would offer no advantages over the force based methodologies currently in use for evaluating design adequacy.

2. If new plant designs have different controlling accident scenarios than the current generation and are more tolerant of inelastic deformation, then displacement based methods would seem to have potential application. The same observation also applies to fuel cycle facilities.

3. Seismic margin studies for existing nuclear facilities are based on displacement acceptance criteria (usually inelastic deformation limits corresponding to a given probability of failure). The displacement based analysis is directly applicable to problems where only material nonlinearity occurs. The displacement based methods offer two advantages over nonlinear time history analysis. First, the displacement based approach (or pushover analysis) is much simpler and less time consuming to use than the time history analysis. Second, this simplification is likely to reduce the potential for erroneous results and to increase the number of engineers that have the background required to perform the analysis.

4. Additional studies need to be performed before nuclear power plant structures with both material and geometric nonlinearities can be treated with the current displacement based methods that presume only material nonlinearity.

5. If the displacement based methods of FEMA 273 are to be applied on a wide scale to nuclear facilities, efforts must be undertaken to develop appropriate coefficients and displacement limits that are consistent with the importance of the structure. Alternative forms of displacement based methods are also possible. The primary steps in any displacement based method are to predict the expected displacement of the structure to earthquakes of interest accounting for nonlinear characteristics of the structure, and to evaluate the details of the structure to determine whether sufficient ductility is available to accommodate the displacement pattern with adequate margin. A method, similar to FEMA 273, could be developed specifically for nuclear structures.

Followup Actions for RES

In anticipation of the use of the displacement based approach by licensees for seismic margin/fragility analysis and in order to gain experience and learn of any potential problem areas, a modest research effort will be considered through the PBPM process. The research scope would be limited to situations involving only material nonlinearity. The main focus of the research would be on the use of displacement based methods on representative plant structures including the choice of displacement limits. The use of displacement based methods can be expected to increase as fragility analyses are introduced for risk information purposes. The method greatly reduces the effort required to produce structural fragility curves from that which is required using time history analyses. A single static nonlinear analysis is required to produce the pushover curve. Solutions for different probabilities of failure are then obtained by evaluating the criteria earthquake required for the structural displacement to reach the acceptance criteria associated with the probability of failure. Since many nonlinear time history analyses would be required to generate the fragility curve, a displacement based approach has potential for cost savings and is likely to become popular. We will keep you informed of our activities in this area.

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