

A NONLINEAR SEISMIC DESIGN PROCEDURE FOR NUCLEAR FACILITIES

by

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SYNOPSIS

A procedure is presented for an efficient, economic, and reliable earthquake resistant design for nuclear facilities. The main emphasis is on frame type structures, such as auxiliary or turbine buildings of a nuclear power plant complex. Reactor containment structures are also discussed. The design procedure for frame type structures consists of a step-by-step nonlinear, inelastic, optimum design approach, including proposed preliminary and final design techniques. Probabilistic methods for determining the reliability of designs so obtained are also reviewed.

INTRODUCTION

Safety and economy have become the primary considerations in the design of nuclear facilities. Different safety requirements may, however, apply to different structures and components in a nuclear power plant complex, depending upon the importance of the structure and the contained equipment, and the consequences of potential accidents related to that structure. In this context, the reactor containment structure (and the contained emergency cooling piping systems) are the most important and require special treatment in their analysis and design. Other structures, such as auxiliary buildings and turbine buildings, are relatively less important than containment structures from a safety point of view.

For the seismic design of a containment structure, it is therefore necessary that under a safety level earthquake, there should be no (or minimum) damage. The stresses should therefore remain well within the allowable limits, though it might result in uneconomical designs. For auxiliary, turbine, and other structures of a nuclear power plant complex, however, it is desirable to go into the nonlinear range so that a rational, economical, as well as reliable, design can be obtained. A seismic design procedure is presented here in view of the above overall considerations.

In general, the main objective of any designer is to obtain a design which should be economical, reliable, and serviceable. Recent advances in computer technology have lead to the development of sophisticated analysis procedures for complex structural systems. However, use of a sophisticated analysis procedure does not necessarily guarantee a design which would satisfy the necessary criteria of safety and serviceability. There are several other factors involved which would determine what kind of design is finally obtained. One of them is the desirability of a good and

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efficient preliminary design. If the preliminary design of a structure is "poor," repeated analyses of such a design, regardless of how sophisticated the analysis procedure may be, would usually lead to an improved "poor" design. Another factor on which obtaining a good and efficient design would depend is the design concept used. These two factors would generally determine how the strengths and the stiffnesses of members are distributed through the whole structure, which in turn would determine the lateral story force (inertial force) distribution transmitted from bottom to top when the structure is subjected to a strong ground motion.

In addition, it is important that some kind of optimization procedure is used to be able to obtain the most economical design practically possible, which would at the same time satisfy all the desired design criteria. An approximate and informal optimization procedure may be used based on the judgment of the designer. On the other hand, if the designer is not very experienced, it may be desirable to use a formal optimization procedure such as Linear or Nonlinear Programming.

Finally, for a realistic estimation of the reliability of a design, it is desirable to use a combination of deterministic and probabilistic techniques. Simplified probabilistic approaches such as second-moment format may be employed for this purpose.

PROPOSED DESIGN PROCEDURE

The proposed design procedure is divided into two different parts, depending on the importance and the safety category of the structure and the structural system used. For auxiliary and turbine buildings, which are generally steel or concrete frame type structures, a nonlinear, inelastic, optimum design procedure is proposed, along with a simplified probabilistic approach to estimate the structural reliability of the final design. For the reactor containment structure, which usually consists of concrete shell or shear-wall systems, a linear, elastic design procedure is proposed, along with a simplified probabilistic approach to estimate the structural reliability.

FRAME TYPE AUXILIARY AND TURBINE STRUCTURES

A detailed description of a similar basic procedure developed by the authors, along with an example, was presented in References 1, 2, and 3. A very brief description of this procedure will therefore be presented here due to a shortage of space with details of the latest modifications only, where applicable.

In developing this proposed design method, an attempt is made to obtain the most economical (minimum weight) design practically possible. To this end, Linear Programming technique is utilized. Economic considerations also require that for a major dynamic loading (e.g., a major earthquake), the structure should be able to absorb and dissipate large amounts of energy through inelastic deformations. An inelastic model is therefore used here, so that the design is based on the limit state that actually controls it. A strong column-weak girder design concept is utilized so that all the large inelastic deformations are confined to girders only. This ensures that there would be no column failures resulting in disastrous structural failure, and also that there would be a more reasonable story load distribution through the height of the structure. In the absence of such a design concept, if a certain story yields under the action of a strong ground

motion, the story shear transmitted above that story would be equal to the capacity of that particular story and therefore the design of that story would govern the design of stories above it.

The proposed design procedure consists of a step-by-step computer-aided procedure which is basically carried out in the following major steps: (1) Preliminary Analysis; (2) Preliminary Design; (3) Analysis of Preliminary Design; (4) Final Optimum Design; (5) Analysis of Final Optimum Design; and (6) Determination of the Reliability of Final Optimum Design.

In the first step, after careful analysis of the data, serviceability and safety requirements are established and the corresponding design spectra from USNRC Regulatory Guide 1.60 are utilized. These linear elastic response spectra are then reduced to take into account the inelastic behavior corresponding to a properly selected pattern of values of ductility. Based on values of periods and mode shapes selected from tabulated values obtained from experimental and analytical investigations already carried out on similar frames, preliminary story shear forces are obtained using a mode superposition procedure. A step-by-step iterative procedure is used to achieve a proper combination of the values for the fundamental period, drift, damping, ductility, story shear forces, and seismic coefficient. When this is achieved, the values so obtained for the story shear forces are the ones used for the subsequent preliminary design of the structural members.

The preliminary design consists of a story-wise strong column-weak girder limit design using optimization to obtain first the sizes of the girders and then the sizes of the columns. The columns are designed with a larger factor of safety than the girders. This is done to account for the greater uncertainties involved in the design of columns, the probable effects of biaxial shear and bending, and possible increase in axial forces due to the other horizontal component as well as the vertical component of ground shaking. The girders are designed so that the weaknesses are uniform at each floor level as well as throughout the height of the building. This is required to avoid early yielding at one particular "critical region" of a girder, and, therefore, to reduce the possibility of a considerably higher rotation ductility demand in this region. Furthermore, in order for the application of modal superposition procedure and the use of a reduced response spectrum to provide satisfactory results, it is desirable that critical regions of the entire structure yield simultaneously. This preliminary design can be carried out by hand computations or through the use of a computer program developed for this purpose, and is based on elasto-plastic analysis using a single story subassemblage and including the $P-\Delta$ effects. Working load drift limitations can be imposed and an approximate cost minimization technique using linear programming can be applied (Ref. 1, 2, and 3).

The static response of the preliminary designed subassemblages and of the whole structure, and then the dynamic response of the whole structure are obtained using two nonlinear computer programs (Ref. 1, 2, and 3) based on an elasto-plastic moment-curvature relationship with linear strain-hardening. The inelastic rotations, which are assumed to take place at localized plastic hinges, are computed to provide a measure of the plastic rotation demand on the critical regions of the structure. The $P-\Delta$ effects and the influence of axial force on column yielding strength and flexural stiffness are also taken into account. Application of a nonlinear dynamic analysis program permits the evaluation of the response of the preliminary designed structure to different earthquake motion time-histories compatible with the design spectra.

From the outputs of the above two programs, maximum values as well as time-histories of the curvature, rotation, and displacement ductilities are obtained. If these ductility values and their variations agree closely with those preselected, and if the pattern of maximum shear forces obtained from the dynamic analysis as well as that of the shear capacities of each story obtained from the static analysis is close enough to the pattern of story shears used in the preliminary design, the values of this last set of shears are adjusted in accordance with those found from the two analyses, and they are then used for the final optimum design of the frame. If the agreement of one or more of the above parameters is poor, the results obtained in the preliminary analysis and design must be reviewed and modified until satisfactory agreement is achieved.

The final optimum design procedure is similar to that used for the preliminary design except that it is completely automated and uses more sophisticated story subassemblages and more formal linear programming technique.

Analyses of the structure to several different earthquake time-histories compatible with the NRC design response spectrum are then carried out using the nonlinear dynamic analysis computer program MULTY, developed by the senior author (Ref. 1 and 2). Dynamic response analyses of the designed structure to a set of different ground motion time-histories, covering as many characteristics as possible which can be critical to the behavior of the structure, are necessary because of the uncertainties involved in predicting the future earthquakes. Artificial time-histories compatible with the design spectra are generated using the computer program, SEQGEN, developed by the senior author and colleagues.

Finally, the reliability of the final optimum design is estimated by using simplified probabilistic methods. Probability of failure of each story is determined by considering it as a "parallel" or "fail-safe" type of system, and using the governing strong column-weak girder failure mechanism with the actual story shear applied at that story, already determined from the deterministic analysis above. Failure of the structure is assumed to result if any single story fails and the whole structure is therefore considered to be similar to a "series" or "weakest-link" type of system. An alternate procedure where a combined deterministic-cum-probabilistic approach is used is also being developed (Ref. 7). In this procedure, the deterministic and probabilistic techniques are used side-by-side when performing the nonlinear dynamic time-history analyses. Markov processes are used for the probabilistic part of the analyses.

The different steps of the basic methodology of this procedure are discussed in detail in References 1, 2, and 3. The procedure was applied to a 10-story, 3-bay unbraced frame (Ref. 1 and 2).

REACTOR CONTAINMENT STRUCTURE

The design of reactor containment structure is based on a linear, elastic approach. The preliminary design is usually already established on the basis of considerations other than seismic, such as radiation shielding requirements, protection against missile impact, etc. A linear dynamic seismic analysis is then performed using axi-symmetric or three-dimensional finite-elements. Because the structural design of the containment is already established prior to seismic analysis, as mentioned above, and the seismic forces may not generally govern the design, it is not necessary to use any optimization procedure. The main objective is to check the adequacy of the structure for the

design seismic loading to determine if the seismic stresses are within the allowable limits. The reliability of the containment structure can then be estimated using probabilistic approaches, as described briefly in the next section.

RELIABILITY OF DESIGN

Reliability of a structure is not a physical, directly quantifiable property. The conventional way of measuring structural reliability is through the use of a "factor of safety." This can be useful to some extent for comparing the reliability of two very similar structural systems behaving in a very similar way under the action of very similar loads. However, for an absolute measure of reliability, this concept loses its usefulness. Probabilistic methods need to be used for this purpose.

Application of probabilistic methods in estimating the probability of failure of complex structural systems, such as frame type auxiliary and turbine buildings and reactor containment structures, becomes very difficult mainly because of the presence of a large number of possible failure modes as well as a large number of random variables, many of them dependent. Simplified approaches can be used to obtain an estimate of the reliability of a structural system, e. g., use of second-moment theory.

If L and R respectively denote the load and the corresponding structural resistance, the probability of structural failure can be written as

$$P_f = P(R \leq L)$$

The evaluation of such a probability requires the knowledge of probability distribution functions of R and L , which may sometimes become impractical and difficult to obtain. Second-moment theory can therefore be used to get a reasonable estimate of the probability of structural failure.

For the frame type structures, probability of failure of each story may be determined by considering it as a "parallel" or "fail-safe" type of subsystem and using the governing failure mechanism with the actual story shear applied at that story level, already determined from the deterministic analyses. Failure of the structure is assumed to result if any single story fails, and the complete structural system is considered to be similar to a "series" or "weakest link" type of system.

A containment structure can fail in a number of different modes and at different critical locations, e. g., cylinder (or hemisphere) in longitudinal direction at spring line, cylinder in hoop direction, and cylinder at base in longitudinal direction (possible yielding of reinforcing bars), etc., for a cylindrical containment structure with a hemispherical top. The structural resistances to failure at the same locations are also obtained. The failure of containment under seismic loading is then expressed as $P(F_{ST}/A) P(A)$, where F_{ST} indicates the structural failure due to the combination of overload and containment understrength, and A denotes the combined occurrence of gravity and semipermanent loads and a safety level earthquake. If the containment structure can fail in a number of different modes, F_{ST1}, F_{ST2}, \dots , these failure modes not necessarily being mutually exclusive, $P(F_{ST}/A) = \sum_M P(F_{SM}/A)$. The probability, $P(A)$, can be developed assuming, for example, that the occurrence of failure follows the law of Poisson arrivals. The value of $P(F_{ST}/A)$ can be developed mainly from structural considerations, using the possible failure modes.

An alternate and perhaps more sophisticated approach to determine the system reliability, e. g., of a frame type structure for auxiliary or turbine buildings, and at the same time determine the probabilistic-cum-deterministic response of the system, is to use the combined deterministic-cum-probabilistic approach proposed by the senior author in Reference 7. Along with the step-by-step deterministic time history dynamic analyses, Markov transition probability matrices are determined for each member at each time step, depending on the "condition" of that member at that instant. The "most probable stiffness matrix" is then determined and the procedure is continued for all the remaining time (load) steps, until the entire loading time history is applied to the structural system.

CONCLUSIONS

A seismic design procedure is described for nuclear facilities. For frame type auxiliary and turbine buildings, a nonlinear, inelastic, optimum design procedure is proposed, which consists of several steps including preliminary design, analysis of the preliminary design, final design with optimization, and the determination of the reliability of the final design using probabilistic methods. Most of the important factors affecting the design, viz. fundamental period, ductility factor, damping coefficient, seismic coefficient, story drift, etc. are included — thereby enabling the design procedure to exert far greater control over the seismic design than the conventional design procedures. References 1, 2, and 3 describe this procedure in considerable detail. The use of probabilistic methods provides a reasonable estimate of the reliability of the structural system for the design safety level earthquake. For the containment structure, it is proposed that the design be carried out in the linear, elastic range, and the reliability of the design is again estimated using probabilistic methods.

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