Seismic Capacities of Existing Nuclear Power Plant Structures

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Summary

The codes currently used for seismic design and construction of nuclear power plants, such as ACI and ASME codes and USNRC regulatory guides, impose a considerable amount of conservatism in a number of areas. Material strengths, structural damping, definition of seismic input, and extreme load combinations represent some of these areas. Studies have been performed to find the most likely seismic failure capacity of nuclear power structures by identifying the areas of conservatism and then, by using median-centered values instead of design values, establishing a factor of safety for each area. When these factors are then combined, the overall structural median factor of safety is established. Variabilities on these factors are also calculated to take into account incomplete knowledge and natural randomness.

This paper presents a discussion of the more important conservatisms and some of the results obtained when this methodology has been applied to various nuclear plants. Results are shown for both BWR and PWR plants, on both rock and soil sites, and for plants and soil sites, and for plants that were designed in the late 1960s to plants that have yet to load fuel. Safe shutdown earthquake design levels of 0.1g to 0.25g were used for these plants. Overall median structural factors of safety for the lowest significant seismic failure capacity at each plant ranged from 3.5 to 8.5. The lowest containment-related failure capacity at each plant ranged from 4.6 to 31. The types of failure coresponding to each safety factor are also tabulated.

1. Introduction

Nuclear power plant structures are currently designed and constructed to well-defined codes and standards. Among these are the ACI and ASME codes, and the USNRC standard review plan and regulatory guides. These or similar standards are used in most other countries throughout the world. These codes impose a considerable level of conservatism on the designer in a number of areas including the definition of seismic input, structure response analysis criteria, extreme load combinations, and allowable material strengths. More conservatism is introduced in some areas than others, depending to some extent on the uncertainties in the parameters. However, in general, the conservatism introduced in each stage of the design and analysis is compounded and propagated through to the final factor of safety for the structure. Even for older plants where the design standards were not as well defined, seismic failure capacity levels significantly above the design values exist. This paper summarizes the factors of safety against seismically-induced failures calculated for a number of existing nuclear power plant structures. Both PWR and BWR facilities are included. These structures were designed in the time period from the mid 1960's to the present, and include plants located on both soil and rock sites. The evaluations were conducted using median-centered properties for all parameters rather than the normally more conservative design values in order to obtain realistic values for the seismic capacities.

2. Definition of Failure

With the exception of the pressure retention function of containment buildings, the only requirement of nuclear power plant structures for the safe shutdown of the reactors is to maintain the integrity of the essential mechanical and electrical systems supported by these structures. Seismic capacity of structures is, therefore, defined as the level of seismic excitation required to cause inelastic deformations sufficient to potentially interfere with the operability of safety-related equipment attached to the structure. For the containment buildings, breach of the liner system is also considered as failure of the structure. For many potential modes of failure, considerably greater margins of safety may exist against structural collapse.

The level of seismic excitation required to cause failure is reported in terms of the effective peak ground acceleration rather than the peak instrumental acceleration. The peak effective acceleration is typically described as 1.23 times the peak of the third highest acceleration cycle and is considered to be a more valid descriptor of seismic damage of structures. Where site specific ground response spectra were not available, median-centered broadband spectra consistent with the expected earthquake magnitudes and site foundation characteristics were assumed (Newmark [1]).

3. Sources of Design and Construction Conservatism

Conservatism is introduced from a number of sources imposed by the design criteria. These sources can be conveniently separated into considerations of strength, dissipation of inelastic energy, and the seismic response of the structure.

Design codes, whether for steel or concrete structures, normally impose some conservatism when considering the ultimate seismic capacity. Material design strengths are usually specified to be less than the actual mean or median-centered properties for both structural and reinforcing steel. Concrete strengths are normally specified to exceed some minimum design value at some specific time from mixing (for example, 28 days or 90 days), and compliance with this requirement is verified by laboratory testing. Two major factors justify the selection of median values of concrete strength above the design strength. The contractor normally creates a mix which has an "average" strength above the design strength because there are so many factors that affect concrete strength (some of which are beyond the contractor's control), and it is essential that the actual strength be at least equal to the design strength. Also, as concrete ages, its strength increases. Not only do the design codes normally impose conservative treatment of the material strengths but also for allowed analytical approaches through requirements for capacity reduction (ϕ) factors or similar design factors. For instance, experimental studies have shown that the shear strength of low-rise concrete shear walls is significantly underpredicted by current design codes (Barda et. al. [2], Shiga et. al. [3]). Coupled with consideration of the actual strength of the reinforcing steel, a significant factor of safety can be expected for reinforced concrete structural elements. Similar factors of safety exist for structural steel construction. The inherent conservatism in the codes is often further compounded by conservative assumptions made by the individual designer.

In addition to the strength capacity, a much more accurate assessment of the seismic capacity of a structure can be obtained if the inelastic energy absorption of the structure is considered. The most rigorous method of accounting for this energy dissipation would be to perform a number of nonlinear time history analyses of the structure. This is expensive and time consuming, however. One tractable method involves the use of ductility modified response spectra to determine the deamplification effects (Riddel et. al. [4]). For single-degree-of-freedom systems, the deamplification factor is primarily a function of the ductility ratio, μ, defined as the ratio of maximum displacement to displacement at yield. Damping has been shown to have some effect, but the shape of the resistance function as characterized by elastic-perfectly plastic, bilinear, or stiffness degrading models is not particularly important. However, the system ductility can vary significantly from the ductility of a single structural element, and care must be taken to utilize suitable system ductility ratios when using the ductility modified response spectra approach for multi-degree-of-freedom structures.

In the seismic design process, a number of additional parameters are involved which effect the response of a structure. Many of these response parameters are treated conservatively in addition to the strength and inelastic energy considerations. For instance, structure damping at response levels near failure is expected to be considerably higher than most values specified for design. Design damping values are typically taken from USNRC Regulatory Guide 1.61 [5]. Damping values considered to be more realistic at higher stress levels are found in Newmark et. al. [6]. Design ground response spectra are normally mean or median plus one standard deviation, and often are very broadband spectra which have been developed from many recording locations rather than site-specific characteristics. Actual earthquake excitation for most sites is expected to be closer to the median-centered characteristics, and often, actual earthquakes do not have sufficient energy content or duration to fully excite the structures to their ultimate capacity levels. Methods of combining modes, combination of earthquake directional components, and soil-structure interaction analysis techniques may also introduce various levels of conservatism in the design process. Finally, design load combinations are usually conservatively defined. As an example, the probability of peak seismic loads occurring simultaneously with those from a loss of coolant accident (LOCA) is considered to be very low. Thus, containment structures typically exhibit very high seismic capacities when the earthquake loads are not combined with those from a LOCA.

All the sources of conservatism discussed above have some degree of variability associated with them. In many cases, this variability could be reduced, sometimes significantly, by further analysis or test. On the other hand, given the current state of knowledge, some variability should be expected which cannot be substantially reduced. These latter sources are, for the most part, associated with the dynamic characteristics of the earthquake itself. In many cases, the statistical distribution of the variability of the various parameters is not known. For most structural materials and for the response characteristics of the earthquakes, the lognormal distribution fits the data as well as or better than other commonly used distributions (Freudenthal et. al. [7], Kennedy [8]), so long as one is not primarily concerned with the extreme tails of the distribution. However, for a parameter such as structural damping near failure levels, the actual distribution is unknown. The lognormal distribution is mathematically tractable and for these reasons, the lognormal distribution is used, and the median capacities of the structures are presented rather than the mean or some other parameter of central tendency.

4. Structure Seismic Capacities

In order to indicate the overall level of conservatism of nuclear power plants structures to withstand seismic excitation, failure capacities for nine typical U.S. plants are discussed. The plants include both PWR and BWR facilities and include both soil and rock sites. Safe Shutdown Earthquake (SSE) design levels range from 0.1g to 0.25g and plants designed and constructed in the mid-to-late 1960's through plants which have yet to load fuel are included. Table I shows site characteristics and seismic design values for the plants.

In addition to the containment structures for the plants investigated, evaluations were also conducted for other safety-related buildings such as diesel generator buildings, auxiliary buildings, and service water pump structures. Non-safety related buildings such as turbine buildings were evaluated only to the extent their failure could cause damage to safety-related equipment or strutures. In general, the lowest seismic capacities were identified for the structures other than the containment buildings. When this was not the case, the mode of failure often was impact between the containment building and an adjacent structure. Table II shows the type of failure expected for the lowest capacity major structural failures for the various plants. Factors of safety from approximately 3.5 to 8 are indicated with median seismic capacities from 0.5g to 2.1g for the 0.1g to 0.25g design basis structures. Also, shown in Table II is the overall or composite lognormal standard deviation associated with the median capacity. This variability includes both the contributions from inherent randomness in the earthquake characteristics as well as uncertainty resulting from analytical modeling and other lack of knowledge.

Most of the potential failure modes presented in Table II could be expected to result in failure of one or more safety-related systems, but are not expected to result in breach of the containment liner system. Table III shows the lowest containment related structural failures expected for the nine plants. For the PWR plants, two of the containment related failures involve impact with adjacent structures. The remaining three have very high factors of safety for structural failures of the containment alone. These capacities would be reduced by including simultaneous LOCA loads, however. The internal structures for the PWR containment structures investigated possess even greater seismic capacities. For the BWR systems, the lowest containment related seismic capacities are related to the internal structures. For the Mk II drywells, median seismic capacities in excess of 2g are expected before loss of containment occurs.

5. Conclusions

The results presented here show significant factors of safety for seismic excitation for all plants investigated. These factors of safety result from conservatism introduced by the design codes and standards as well as by the design engineers for a number of steps in the design and construction process. In particular, the containment structures possess very large amounts of reserve capacity to withstand earthquakes.

References

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TABLE I

Plant Design Criteria

Plant/Type	Foundation	SSE Design Acceleration(g)	Seismic Design Spectra	Design Time Period
A. PWR	Soil	0.17	Modified Housner	Late 1960s
B. PWR	Rock	0.15	Housner	Late 1960s
C. PWR	Soil	0.12	Housner	Late 1960s Early 1970s
D. PWR	Rock	0.10	Modified Housner	Late 1960s Early 1970s
E. PWR	Rock	0.25	USNRC 1.60	Late 1970s Early 1980s
F. BWR	Rock	0.20	Housner	Late 1960s
G. BWR	Soil	0.20	Newmark	Early 1970s
H. BWR	Rock	0.10	USNRC 1.60	Mid 1970s
I. BWR	Rock	0.15	Newmark	Late 1960s Early 1970s

TABLE II

Lowest Major Seismic Failure Capacities

Plant/Type	SSE Design Acceleration(g)	Factor of Safety (Lowest Capacity Failure Mode)	Median Failure Acceleration(g)	Logarithmic Standard Deviation	Type of Failure
A. PWR	0.17	4.4	0.73	0.44	Aux. Bldg. shear wall
B. PWR	0.15	8.3	1.2	0.28	Control Bldg. shear wall
C. PWR	0.12	5.2	0.7	0.39	Reactor Bldg./Aux. Bldg. impact
D. PWR	0.10	7.4	0.74	0.33	Aux. Bldg. shear wall
E. PWR	0.25	8.5	2.1	0.33	Pump house shear wall
F. BWR	0.20	4.2	0.84	0.35	Reactor Bldg. floor diaphragm
G. BWR	0.20	4.4	0.88	0.40	Diesel Generator Bldg. roof diaphragm
H. BWR	0.10	5.0	0.5	0.35	Pump house roof diaphragm
I. BWR	0.15	3.5	0.53	0.38	Reactor Bldg. shear wall

TABLE III

Lowest Containment-Related Failure Capacities

Plant/Type	SSE Design Acceleration(g)	Factor of Safety (Lowest Capacity Failure Mode)	Median Failure Acceleration(g)	Logarithmic Standard Deviation	Type of Failure
A. PWR	0.17	4.6	0.78	0.50	Impact with Auxiliary Building
B. PWR	0.15	16.0	2.4	0.47	Shear above base mat
C. PWR	0.12	5.2	0.7	0.39	Impact with Auxiliary Building
D. PWR	0.10	20.0	2.0	0.39	Shear above base mat
E. PWR	0.25	31.0	7.6	0.44	Flexure above base mat
F. BWR	0.20	4.6	0.92	0.37	Sacrificial shield wall anchor
G. BWR	0.20	6.7	1.3	0.45	Reactor vessel pedestal
H. BWR	0.10	11.0	1.1	0.38	Sacrificial shield wall flexure
I. BWR	0.15	7.5	1.1	0.36	Sacrificial shield wall flexure