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Fragility Assessment for Seismic PRA Studies

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Abstract

This paper discusses the fragility assessment for seismic PRA studies. First, the current methods for fragility evaluation proposed by utilities and research groups are briefly reviewed. Then, the areas which affect the fragility results, e.g., the failure modes, tail problem, etc., are discussed. Suggestions for improving the fragility evaluation are also presented.

1. Introduction

Seismic probabilistic risk assessment (PRA) studies have been performed on a number of nuclear power plants by utilities and research groups in the United States[1-3]. The PRA utilizes a systematical process which intends to take all possible randomness and uncertainties into consideration. Thus, PRA studies may provide insights to the performance of a nuclear power plant and may be used by the regulatory agencies and utility owners to improve safety as well as operational reliability of nuclear power plants.

The major steps in performing a PRA study are as follows: (1) hazard analysis, (2) fragility assessment, (3) accident sequence analysis, and (4) consequence evaluation. It is recognized that all of the above steps involve large uncertainties in modeling assumptions and analysis techniques. In addition, pertinent fragility data are scarce. Thus, the absolute risk estimate can not be made precisely and the conclusions must be drawn carefully in the face of uncertainties.

This paper discusses the fragility assessment for seismic PRA studies. First, the current methods for fragility evaluation proposed by utilities and research groups are briefly reviewed. Then, the areas which affect the fragility results, e.g., the failure modes, tail problem, etc., are discussed. Suggestions for improving the fragility evaluation are also presented.

2. Current Methods for Fragility Assessment

The fragility of a structure, a secondary system or an equipment (refered as a component hereafter) is defined as the conditional frequency of failure for a given value of a parameter. The parameter may be chosen to be a local response, such as stress, moment and acceleration at a specific location or it may be chosen to be a peak ground acceleration. If the peak ground acceleration is used as the parameter, the response analysis is included in the fragility evaluation. On the other hand, unless a local parameter is chosen so that it can define the component fragility directly, some degree of response analysis may still be necessary. Hence, in this paper, the fragility evaluation will include the response analysis.

In the United States, several methods have been proposed for fragility evaluation[3-6]. However, these methods vary from that based on subjective judgements and design drawings to that based on the probabilistic structural mechanics. Some of these methods are discussed briefly below.

2.1 Zion Method

The Zion method[4] was developed and applied to many industrial PRA studies such as Zion and Indian Point PRA studies. In the Zion method, the fragility of a component is defined as the conditional frequency of failure for a given peak ground acceleration. The main features of the method are: (1) the component fragility is assumed to be a product of several factors representing quantities such as capacity, ductility, and structural response, etc., (2) each factor is assumed to be lognormally distributed. The median and two logarithmic standard deviation values (one for randomness and the other for uncertainties), which define a lognormal distribution, are primarily determined by subjective judgement. Therefore, (3) the component fragility itself is also lognormally distributed with the median evaluated by a multiplication scheme as the product of the medians of the pertinent factors. The Zion method is characterized by using engineering judgement to the largest extent. Thus, it usually does not require detailed response and capacity analyses. This method may be useful for a first-cut approach if performed by experienced engineers on an unbiased basis. However, the use of lognormal distributions for all variables is purely for mathematical expedience. Furthermore, the subjective inputs and multiplication scheme do not appear to be a good combination. As a result, the fragility curve is very sensitive to the subjective judgement. An example given in Ref. 7 indicated that the substantial change of fragility curve can occur due to an increase of the median value of the fragility.

2.2 SSMRP Method

The SSMRP method[3] was developed under the NRC-funded Seismic Safety Margins Research Program (SSMRP). In this method, the fragiliy of a component is defined as the conditional frequency of failure given a value of a local response (e.g., moment, stress, acceleration, etc.). The main features of this method are that the response of a component is evaluated through a detailed modelling, linear time history analysis and simulation techniques while the capacity is estimated based on subjective judgement, lognormal distribution assumptions and limited test data. The SSMRP method makes a great effort to utilize the current techniques for response analyses. However, the use of time history analysis and Latin hypercube simulation technique made the response analysis expensive. It is reported that a simplified version of the SSMRP method is being developed, however, no details are available yet. It is noticed that the choice of a local response as a parameter may be difficult since the failure mode may depend on a combination of different factors. For example, column failure depends on the combination of axial force and bending moments. Therefore, it is difficult to choose either one as a parameter.

2.3 BNL Method

In addition to the Zion and SSMRP methods, other research groups also try to develop methods for fragility evaluation. One such method is developing at Brookhaven National Laboratory (BNL)[5]. In this method, the fragility is defined as the conditional frequency of failure for a given peak ground acceleration. This definition is the same as that used by the Zion method. The main features of this method are: (1) an earthquake is represented by a Gaussian process with zero mean and an appropriate power spectral density function, (2) the distribution of the maximum response is established using modal analysis, random vibration theory and extreme value theory, (3) each failure mode (limit state) is analytically defined and then the conditional frequency of failure is computed by a reliability analysis technique. Thus, using this method, the fragility curve for a component is analytically generated. At present, this method is only applied to structures and it needs further development. Given additional resources, we expect to extend the method to include additional failure modes and probabilistic non-linear response analysis.

3. Comments on Fragility Assessment

As mentioned above, current methods proposed for fragility assessment vary from that based on subjective estimation to that based on analytical evaluation. The fragility evaluations must be made so that consistency and quality of fragility results are ensured. In this regard, the following comments are presented.

3.1 Failure Modes

For PRA studies, the failure modes may be defined by component capacity or functional requirements. A component usually has many possible failure modes. For example, a structure may fail due to cracking, yielding, crushing, buckling and drifting, etc. Since the fragility assessment of a component is to predict how and where a component will fail with what kinds of chances, it is essential to clearly specify the failure modes for each component. Unless failure mode is clearly defined, it is impossible to determine the capacity of a component, to choose a method for response analysis and to compare the results from different analyses of the same component. Identification of failure modes is also very important for collection of experimental data. If failure modes are not well identified, we may use irrelevant data for fragility evaluation resulting in erroneous conclusions. Unfortunately, in some of the fragility studies, definitions of the failure modes are only described in a broad general term. As a result, it is difficult to evaluate and compare the results.

3.2 Most Probable Failure Mode

A realistic assessment of the component fragility requires the identification of the most probable failure mode of the component. Otherwise, the strength of a component probably will be over-estimated. However, a component is often structurally very complicated and has many possible failure modes, and therefore, without understanding the details of a component and its true behavior under a seismic event, it may be difficult to identify the most probable failure mode. For example, one may suppose that the most probable mode is that associated with the location where most severe load effects (forces; moment, etc.) will occur. However, this may not necessarily be true, since an experienced designer may recognize it and provide much larger resisting capacity at that location. Consequently, the failure location will be shifted elsewhere with less capacity to resist the load effects. As an additional example, the code committee may recognize some failure modes are critical and thus, specify very conservative design criteria. As a result, these failure modes will be well protected but other failure modes will become more vulnerable.

3.3 Tail Problem

Components in nuclear power plants are usually designed with highly conservative criteria. Thus, the chance of their failure is quite small even under extremely severe earthquakes. Thus, the lower tail of the fragility curve is most important in view of a realistic seismic hazard. In this respect, it is important to recognize that the tail part of a fragility curve is very sensitive to the assumptions of input variables. For example, the relative shapes of commonly-used probability distribution functions are quite different in the tail region. This made it critical to assume a particular distribution function for fragility evaluation.

3.4 Effort for Fragility Analysis

It is sometimes asserted that component fragility curves need not be determined with precision in view of the large variations associated with the seismic hazard estimation. If this were true, the current effort, with aid of highly sophisticated analysis, experiments and field tests, to predict the response behavior of the components under seismic condition could be dismissed as cost-ineffective at best and totally useless at worst. The assertion could also imply that the current design criteria are unrealistically conservative. It appears to be true that the variation in component fragility may be smaller than that in seismic hazard. However, fragility estimation of different groups of engineers may also vary considerably, especially in the lower tail region. Hence, the author believe that it is important to perform a realistic evaluation of component fragility and, the effort of such an evaluation may focus on a mean composite curve, which is obtained by combining the randomness and uncertainties. A realistically estimated mean fragility curve is enough to represent the component fragility, if the variations with component fragility are indeed much smaller than those associated with seismic hazard.

The mean composite curve concept is contrary to the current practice of separating variability into randomness and uncertainty. This separation is to create bounds for fragility. However, in practice, the distinction of randomness and uncertainty become blurred. In addition, the estimation of uncertainty on median value is made on subjective judgements which itself creates large uncertainties. Furthermore, the uncertainties in the lognormal assumption are not included in the estimation of bounds. Thus, the validity of the bounds is questionable and the separation of randomness and uncertainty may be only an ideal concept.

3.5 Response Analysis

In the current fragility evaluation methods, the treatment of response analysis vary from almost no analysis to detailed finite element analyses. It is often heard that there are thousands of components in a nuclear power plant and thus, detailed response analysis are prohibitively expensive. On the other hand, in view of the delicate nature of fragility evaluation, certain degree of response analysis is necessary in order to realistically evaluate the component fragility. Taken both viewpoints into consideration, a simplified response analysis method seems appropriate for the purpose of fragility evaluation. This simplified method should be based on a relatively simple model which captures the major feature of the component behavior such as non-linear characteristics, and should use less cumbersome analytical schemes to predict its responses to earthquakes.

4. Concluding Remarks

This paper discusses component fragility assessment for seismic PRA studies. The components used in nuclear power plants are conservatively designed. As a result, the frequency of failure is extremely small and sensitive to various assumptions. It is the author's belief that the fragility assessment should be performed by experienced engineers and the approach employed should be verifiable. In addition, sensitivity analysis should be performed to provide numerical insights to the fragility evaluation.

In order to perform realistic fragility evaluation, identification of failure modes and response analysis need special attention. Failure mode should be clearly defined and the most probable failure mode should be identified so that it can be used to estimate the component capacity. On the other hand, a simplified response analysis method should be employed to realistically predict the component behavior. In this regard, the understanding of non-linear behavior of components under severe earthquakes and analytical methods (probabilistic and deterministic) to predict non-linear behavior need to be improved. In addition, an effort should be made to summarize the results from various research and thus, it may provide useful information for fragility evaluation.

The fragility evaluation is not completed without the verification with the actual fragility data. At present, the component fragility data is very scarce and obviously it is necessary to collect all pertinent data including proof-testing data that can be made available. In the United States, the Nuclear Regulatory Commission (NRC) is currently sponsoring a component fragility program. Under this program, existing data for equipment will be collected and new tests for fragility data may be performed. It is hoped that such an effort will be extended to other components such as those of structures and piping system so that a more reliable data base for component fragility will be established.

5. References

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NOTICE

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