Using Reliability Techniques to Investigate Pipe Breaks Caused by Seismically-Induced Support Failures

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1.0 INTRODUCTION

Based on the origin of failure, the study of piping reliability during an earthquake has been divided into two parts: the direct and the indirect pipe failures (either a leak or a double-ended guillotine break (DEGB)). Direct pipe failure is defined as pipe failure caused by the growth and instability of existing cracks in the piping system. Cracks grow during the lifetime of a piping system and may become unstable due to seismically-induced stresses. Indirect pipe failure is failure due to all causes other than crack growth and instability. Indirect pipe failure is due to failure of other structures or components, which in turn cause the pipe to fail. One major indirect source is earthquake-generated missiles, such as falling objects. The other major source of indirect pipe failure is the failure of pipe and component supports. That is, an earthquake can cause the supports to fail first, and this failure breaks the pipe. In reality, direct and indirect pipe failure can be closely related because the pipe can fail due to crack growth and instability (direct source) induced by the stress conditions caused by missile and/or support failure (indirect source). A comprehensive probabilistic analysis of the seismically-induced pipe failure should follow the formulation:

$$P[PF] = P[PF|\text{no } SF] * P[\text{no } SF] + P[PF|SF] * P[SF] \qquad (1)$$

In this equation, the conditional pipe failure (PF) probabilities, P[PF|SF] and P[PF|no SF], include failure due to both direct and indirect sources. P[SF] is the probability of failure in at least one of the supports in the system and P[no SF] is the probability of no support failure at all. In addition, P[PF|SF] and P[PF|no SF] should also consider both the without-existing-crack case and the with-existing-crack case as follows:

$$P[PF|\text{no } SF] = P[PF|\text{no } SF,\text{cracks}] * P[\text{cracks}] + P[PF|\text{no } SF,\text{no crack}] * P[\text{no crack}] \qquad (2)$$

and,

$$P[PF|SF] = P[PF|SF,\text{cracks}] * P[\text{cracks}] + P[PF|SF,\text{no crack}] * P[\text{no crack}] \qquad (3)$$

2.0 PRIMARY COOLANT SYSTEMS OF PRESURIZED WATER REACTORS (PWR)

In practice, it is not always easy to consider all four parameters on the right-hand side of Eq. 1 and to include both the with-crack and without-crack cases in Eqs. 2 & 3. In our earlier piping reliability assessment of primary coolant

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systems of PWRs, the work was divided into direct and indirect pipe failure studies. This separation was possible because of the following simplifications:

1. In the direct pipe failure analysis, the supports were assumed not to fail during an earthquake and pipe failure was assumed to be the result of growth and instability of existing cracks.
2. the effect of existing cracks in the weld joints and their growth and possible instability was neglected in the indirect pipe failure analysis.

The probability of pipe failure due to an indirect source was found to be small if no support failure was involved. That is, only an indirect source involving support failure was considered. Therefore, the first term on the right-hand side of Eq. 1 represents only the direct pipe failure. Corresponding to P[PF|no SF] of the first term, P[PF|SF] of the second term included only the indirect pipe failure in the analyses of RCLs of the PWR plants because the pipe was assumed to have no existing cracks in the study of support failure.

As a matter of fact, Eq. 1 was simplified even further in the analysis of PWR plants by assuming that the value of P[no SF] and P[PF|SF] were equal to 1.0. The system failure probability became the sum of P[PF|no SF], which represents failure due to a direct source, and P[SF], which represents failure due to an indirect source. For the PWR reactor coolant loops (RCLs), these were valid assumptions for the following reasons:

1. The components of the RCLs are very heavy, and the pipes are short and are supported by the loop components. There are no intermediate pipe supports, or supports between two in-line components. Once the support of a component fails, the integrity of the piping to which these components are attached would not necessarily be assured, regardless of whether or not there is an existing crack. Consequently, it is reasonable to assume that failure of a heavy component support would always result in an indirect pipe failure (or the conditional probability of pipe failure, P[PF|SF], equals 1.0).

2. The component supports are generally very strong, and the probability of failure of these supports is very small. In this situation, the value of P[no SF] is close to 1.0 even for a high intensity earthquake.

As a result of the simplifications, the probability of pipe failure is a direct sum of P[PF|no SF] and P[SF], which were the focus of the direct and indirect pipe failure studies in our work on the PWR primary coolant systems.

3.0 PRIMARY COOLANT SYSTEMS OF BOILING WATER REACTORS (BWR)

The above stated simplifications for the PWR primary coolant systems are not necessarily applicable to the major pipings of BWR primary coolant systems, the recirculation loops, since these pipes are longer and less stiff, and no major components are connected to the loop piping except the reactor pressure vessel. The recirculation pumps are light compared to the coolant components of the PWR plants. Unlike the reactor coolant loops, the BWR pipes of interest have intermediate supports, either pipe hangers or snubbers, between two in-line components. The impact of the failure of these intermediate supports is expected to be much less than the failure of RCL component supports. It might be grossly conservative if the conditional pipe failure probabilities, P[PF|SF], were assumed to be 1.0.

A comprehensive demonstration analysis considering all terms in Eqs. 1, 2, and 3 was performed and was documented in detail in a report for the U.S. Nuclear Regulatory Commission (Lo 1987). This analysis considers the recirculation system of a BWR plant, the Brunswick Steam Electric Plant, to gain some valuable insight into the failure of intermediate supports. Section 4 briefly describes this demonstration analysis.

4.0 SEISMICALLY-INDUCED FAILURE OF INTERMEDIATE SUPPORTS

4.1 Methodology

In the BWR plants, the major piping of the primary coolant system (the recirculation loops) is inside the drywell containment, which is much smaller and contains less equipment and fewer structures than the PWR plant containments. It is unlikely that sources other than support failure would play a significant role in the indirect part of the pipe failure analysis. Therefore, the study of indirect pipe failure can again be limited to support failure. There are two essentially identical recirculation loops in the Brunswick Plant - Loop A and Loop B. Loop B was randomly chosen in this study.

Incorporating the effect of support failure on pipe failure probability involves two major difficulties: the timing and sequence of support failure and the stress redistribution as supports fail. In the study of RCLs of PWR plants, there is no need to face such difficulties because the piping system is considered failed once a support failure occurs. The following assumptions are made to simplify this demonstration study.

1. All support failures occur at the same time and the piping system experiences the full duration of the earthquake for any given combination of support failures. Thus, the timing and sequence of support failures in an earthquake are again not considered.
2. The supports experience the same stress distribution as if no support failure occurred during an earthquake. This assumption is actually the result of the previous assumption. This assumption allows the regular fragility development method to be applied to each support for all levels of earthquake intensity. It also allows one single set of in-structure response spectra or one single set of floor time-histories to be used in all seismic analyses.
3. The failure events of the supports are statistically independent of each other. The probability that certain supports will fail together in an earthquake is the product of their individual failure probabilities.

The second term on the right-hand side of Eq. 1 can be expressed as the combination of all support failure scenarios. Thus,

$$P[PF] = P[PF|\text{no SF}] * P[\text{no SF}] + \sum_{i=1}^{N}\{P[PF|SFi] * P[SFi]\} \tag{4}$$

where N represents the total number of support failure combinations, and SFi represents the "i"th combination of support failure. For example, a piping system with four supports will have a total of fifteen support failure combinations; that is, four cases of one-SF scenarios, six cases of two-SF, four cases of three-SF, and one case of four-SF. To describe the general methodology as represented by Eq. 4, a flow chart is shown in Fig. 1. The analysis can be summarized in four major tasks.

1. Estimate support fragilities.
2. Calculate structural responses for all support failure combinations.
3. Estimate the conditional pipe failure probabilities at weld joints for all support conditions.
4. Perform system failure analyses for all support failure combinations.

The following subsections describe these tasks.

4.2 Support Fragility

The purpose of the support fragility calculation is to estimate P[no SF|a] and

P[SFi|a] for a given earthquake peak ground acceleration, a. For each earthquake intensity, P[SFi|a] is simply the product of individual support failure probabilities of the combination scenario number i as stated in assumption 3. P[no SF] is equal to 1.0 minus the sum of all cases of support failure probabilities.

Three kinds of pipe support were used in the the recirculation loops of the Brunswick Plant: rigid supports (or anchors), spring hangers, and hydraulic snubbers. The hangers and the snubbers are supported by structural members, which are generally much stronger than the hangers and the snubbers. Therefore, there is no need to examine the failure mode of the supports due to failure of these structural members in estimating overall support fragility.

The reactor pressure vessel provides a rigid support for the recirculation loops since the reactor vessel is massive. Failure of reactor vessel supports would most likely induce the recirculation loop to fail. The conditional pipe failure probability can be assumed to be 1.0. This scenario is the same as for the PWR reactor coolant loops. Therefore, the failure of reactor pressure vessel supports can be addressed in the same fashion as the earlier indirect pipe failure analysis. In this study, we will focus our attention only on the cases for which the conditional pipe failure probability is not equal to 1.0.

Spring hangers are used to support the dead weight of the piping system. The stiffness of the spring hangers is much less than the stiffness of the piping and the snubbers during an earthquake. The increase in load in the hangers is expected to be insignificant compared to the snubbers. On the other hand, the load in snubbers is zero at all times except during a seismic event, during which the load can be very high depending on the earthquake intensity. Thus, it is reasonable to neglect hanger failure during an earthquake in this study.

There are nine snubbers in four natural groups of the Loop B of the Brunswick recirculation system. Each group, as a unit, provides support for a specific part of the piping system. It is natural to assume that if one in the group fails, the other snubbers in the same group would also lose their function. This conservative assumption simplifies the problem and makes it easier to handle than considering all nine snubbers as individual supports. The fragilities of the four support groups were calculated based on the assumption that the support (or the snubber) failure events are statistically independent.

4.3 Seismic Responses Given Support Failure

In cases of support failure, the seismic responses of a piping system are different from those of the system without support failure. The structural responses for each case should be estimated separately depending upon the specific support failure combination. The regular seismic analysis process can be used starting with preparing the seismic analysis model, followed by either response spectrum or time history analysis, and ending with the calculated seismic stresses at each weld joint. Sixteen cases of seismic analysis of the recirculation Loop B were performed and the corresponding pipe stresses were obtained using the response spectrum approach (Lo 1987).

4.4 Probabilistic Fracture Mechanics Analysis

Once the seismic stresses are calculated, a probabilistic fracture mechanics analysis is then performed for each case of support failure combination and for the case without support failure, to account for stress redistribution caused by the failure of intermediate supports. This analysis yields the conditional failure probabilities at weld joints conditioned on the occurrence of an earthquake of specific intensity and the occurrence of a specific support failure scenario.

The probabilistic fracture mechanics methodology described in several LLNL reports (LLNL 1981, Woo 1984, and Lo 1984) is a rather complicated procedure and this demonstration analysis does not warrant that level of sophistication. To minimize computational effort, a simplified procedure was developed (Lo 1987) to estimate the values of P[PF|no SF] and P[PF|SFi].

For the four support groups identified in our study, sixteen separate PRAISE runs were required to cover all possible combinations and permutations of support failure (including the case of no failure). The most time-consuming part of the probabilistic fracture mechanics analysis is the Monte Carlo simulation, in which thousands of crack samples are monitored for growth and instability for all transients during the lifetime of the plant. In the simplified approach, the sampling scheme was replaced by a deterministic estimate of the transition zone on a sampling space (Lo 1984, Appendix A).

The sampling space includes two variables: the initial crack depth and the initial crack aspect ratio. The transition zone is shown schematically on Figure 2a. On one side of the transition zone, the cracks have no chance of causing pipe failure. On the other side, the reverse is true. As the name implies, some of the crack samples within the transition zone may and some others may not lead to pipe failure. If crack growth is not a major contributing factor to the pipe failure probability, the transition zone will be quite narrow. In a limiting situation, the transition zone can be represented by a line. The transition line can be found by using only one or two hundred selected crack-size samples and following the existing probabilistic fracture mechanics approach. The search follows the route as depicted by the alphabetical order shown in Fig. 2b. If a crack is found to result in failure, a point on the transition line is found, and another crack with the same depth but slightly smaller aspect ratio, can be tested. If this newly selected crack does not result in failure, a slightly deeper crack is tried next until the selected crack depth results in failure. This process is continued until the other end of the transition line is reached.

The total pipe failure probability is the sum of the probabilities within each long and slender rectangular region shown in Fig. 2b. The probability of each failure region is the product of the marginal distributions of the crack depth and the marginal crack aspect ratio, which are assumed to be statistically independent.

4.5 System Failure Analyses

A system failure analysis (Lo 1984; Lo 1987), the last task in Fig. 1, can be performed to fold in the various results, such as the P[PF|SFi,a], P[SFi|a], and the seismic hazard curves to calculate the probability of failure of a piping system for each support failure scenario. The probability of overall system failure, including all support failure scenarios, can therefore be obtained as simply the sum of the system failure probabilities of the cases according to Eq. 4. The method of system failure analysis is documented in detail in the report on Combustion Engineering RCLs (Lo 1984).

5.0 SUMMARY AND CONCLUSIONS

A comprehensive piping reliability analysis method was discussed. The simplifications made in dividing the assessment of the PWR coolant systems into direct and indirect pipe failure analyses were described and validated. For the recirculation loops of BWR systems, the effects of the failure of intermediate pipe supports need to be included in the reliability assessment. An analysis method of including these effects was introduced and demonstrated in the analysis of the Brunswick recirculation loops.

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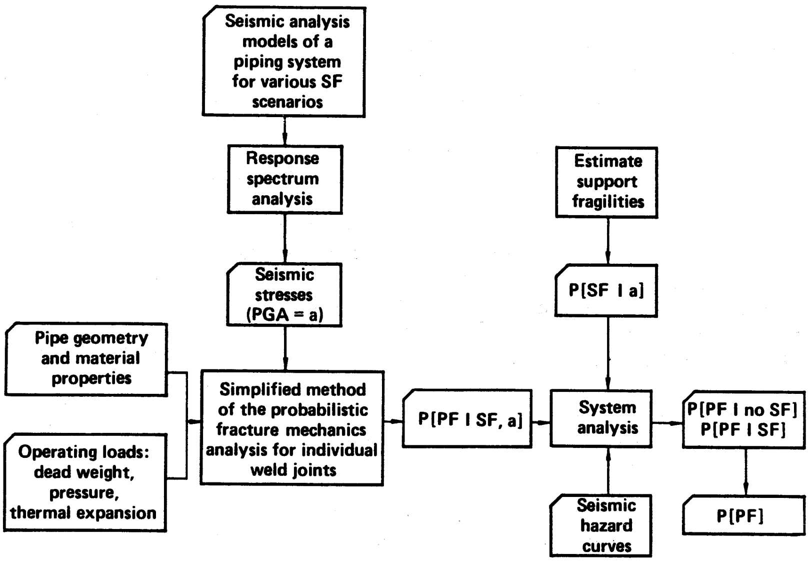

Fig. 1. Piping reliability study considering seismically-induced support failure.

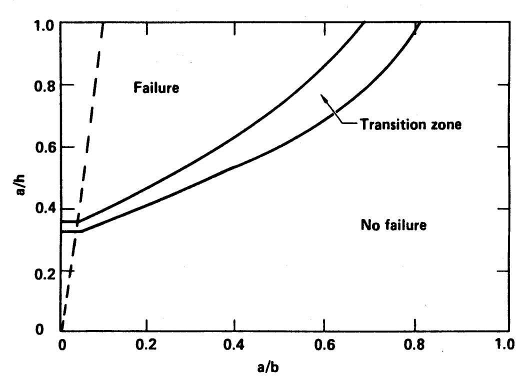

Fig. 2a Sampling space and zones of failure.

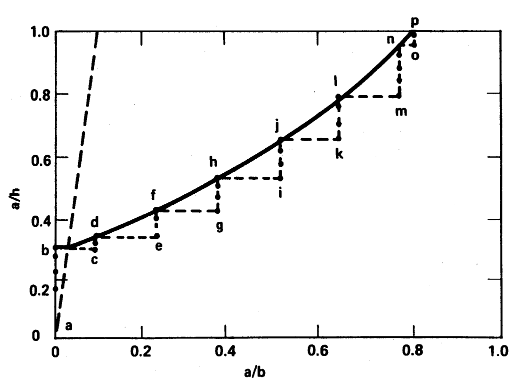

Fig. 2b Finding the boundary between failure and no-failure zones.