E-Journal of Advanced Maintenance Vol.17 (2025) No.1
Japan Society of Maintenology

Development of performance loss function for the importance analysis of inspection in terms of risk of safety performance of a piping system

Akihiro MANO[1,*], Takuya SATO[1], Masakazu ICHIMIYA[1] and Naoto KASAHARA[1]

[1] *The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8654, Japan*

ABSTRACT

The inspection focusing on high-risk significant parts of a piping system is known as one of effective inspection methodologies. In nuclear power plants, the risk is defined for its safety performance that is protection from the harmful effect of radiation. On the other hand, investigation into another risk concept is performed in the field of structural integrity. The risk concept is defined for safety performance of a passive component, such as the boundary performance and cooling performance, as the failure consequence. However, the failure consequence on the safety performance is not sufficiently considered in analyses on the risk in the structural integrity field. The failure consequence is assumed to lose the safety performance completely or assumed to be negligible. In this research, we applied the concept of performance loss function that considers both of occurrence probability and failure consequence to the risk analysis for the effective inspections for a piping system. Its quantitative evaluation method for the piping system was developed. As an example of the risk analysis for inspection, the effect of inspection was quantified for a piping system using the developed evaluation methodology. The effectiveness of inspections based on the performance loss function was demonstrated.

KEYWORDS

Inspection, Piping system, Core cooling performance degradation, failure consequence

ARTICLE INFORMATION

Article history:
Received 16 July 2024
Accepted 14 May 2025

1. Introduction

Risk informed in-service inspection (RI-ISI) for a piping system of nuclear power plants is utilized as an effective inspection methodology in the several countries. The inspection is planned in accordance with RI-ISI methodologies, such as those developed by Electric Power Research Institute [1, 2] and Westinghouse Owners Group [3]. In the RI-ISI, a piping system is divided into several parts. The risk significance for the parts is evaluated. The inspections to detect cracks are carried out focusing on the parts of piping system of risk significant. In contrast, the inspections are not required for the parts of low significance. The risk significance is determined by considering both occurrence probability of a failure of a part of piping system caused by a crack and failure consequence on the safety performance of nuclear power plants. Here, the definition of failure is either break or leak in the piping system. The safety performance of nuclear power plants is protection from the harmful effect of radiation. The failure consequence on the safety performance is quantified using numerical indicators, such as conditional core damage probability and large early release probability, through the probabilistic risk assessment. It should be noted in the assessment that the failure is assumed to disable completely the safety performance of the piping system, such as the boundary performance or core cooling performance composing a part of the safety performance of nuclear power plants.

In the structural integrity field, the investigation is carried out for another definition of the risk which focuses on the safety performance of a passive component including the piping system [4, 5]. As is obvious in a tiny leak from a piping system, failure does not always disable the safety performance of a passive component (e.g., boundary performance and cooling performance of piping system), but it degrades the safety performance by a certain level. Considering this degradation as “consequence” caused by a failure, the risk on safety performance of a passive component is defined by the product of

*Corresponding author, E-mail: mano-akihiro313@g.ecc.u-tokyo.ac.jp

occurrence probability of a component failure caused by a loading event and failure consequence on degradation of the safety performance of the component. Minimizing this kind of risk contributes to reduce the risk of nuclear power plants regarding the protection from radiation. An important feature of the risk is the necessity of consideration for possible failure modes of the component. Each failure mode has unique occurrence condition. In addition, failure behavior of the component depends on the modes. Therefore, the failure consequence on the degradation of safety performance of the component differs by the failure modes. Specifically in a piping system, each of a leak and break may occur with different probability. Moreover, break of piping disables its safety performance whereas a leak can degrade the performance by a variety levels. This risk concept is utilized for the design of passive components [4-6] and is also considered useful for the inspection for piping system. Since a crack increases the risk on the safety performance of the piping system, inspections focusing on significant parts in terms of this kind of risk concept is an effective approach as in the case of RI-ISI described in the first paragraph.

However, the analysis has not been sufficiently performed on the risk regarding safety performance of a passive component including piping system. Specifically, the failure consequence is assumed to lose the safety performance completely or assumed to be negligible [3, 7]. As a result, the risk is simply represented by the occurrence probability of failure mode, or fragility curve as the function of the scale of loading event. Thus, regarding the inspection for piping system, the risk significant parts identified based on the risk analysis can be different from the actual risk significant parts. For example, buckling does not always disable the boundary performance of a component whereas the risk may be evaluated high by the assumption to lose the performance completely. For this problem, we previously proposed a new concept for the risk analysis on the safety performance of a passive component "the concept of performance-based fragility" based on the concept of fragility curve [8]. The proposed concept represents multiplication of the occurrence probability and the consequence on the safety performance regarding failure modes. Later, the concept is renamed as performance loss function concept in terms of more appropriate naming.

In this research, for the risk analysis on the safety performance of a piping system used for effective inspections, the previously proposed general concept of performance loss function is applied to piping system, and its quantitative evaluation method is developed. One of the methods to measure the risk significance of the parts is magnitude of the effect of inspection. Thus, as an example, the effect of inspection is evaluated for piping system using the developed method of the performance loss function. The effectiveness of inspections based on the performance loss function is demonstrated.

2. Concept of Performance Loss Function

The concept of performance loss function for a component [8] is represented by the product of the occurrence probability of failure "P" due to a loading event by the failure consequence "C", namely $P \times C$, as the function of scale of the event. As described in the introduction, a component has a variety of failure modes. Both the occurrence probability and the failure consequence on the safety performance differ by the failure modes. Therefore, they are firstly multiplied for each failure mode, and performance loss function must be obtained for each failure mode as shown in Eq. (1). Then, the set of performance loss functions for all failure modes is combined to be the performance loss function of a component expressed by Eq. (2).

Performance loss function for failure mode i: $f_i(a) = P_i(a) \times C_i$ (1)

Performance loss function for a component: $F(a) = \sum_i f_i(a)$ (2)

Here, $P_i(a)$ is occurrence probability of failure mode i due to a loading event of scale a. This corresponds to the conventional fragility curve for failure mode i. The consequence by failure mode i on the safety performance of the component (e.g., boundary performance or cooling performance) is represented by the factor C_i. The factor of failure consequence may include uncertainty. In such case, the mean value of the factor is used for the calculation of the performance loss function.

The factor is defined as degraded level from the originally expected performance level for the component normalized by the originally expected performance level. Therefore, the factor can take a value from zero to one. The factor of zero means no impact on the safety performance and the factor of one means complete loss of the safety performance. The reason why the normalized factor is employed to express the failure consequence is described below. Components in nuclear power plants have a variety types and levels of safety performance (e.g., difference in flow rate by piping systems). In addition, a variety of indices can be employed to measure the performance level. To unify the scale of failure consequence for the differences in types and levels of the performance and the employed index, the degraded performance level is normalized by the performance level originally expected for the component.

It should be noted for some failure modes that the factor of consequence C_i varies by the scale of the event a. For example, the leak rate and its consequence in piping system may become large as the scale of event becomes large. For such failure modes, the performance loss function is defined as described below instead of Eq. (1). Suppose that the factor of failure consequence C is divided into several categories that represent the consequence from tiny to severe levels. When k categories are defined, each of these categories has a unique value c of the factor of failure consequence in the order of $c_1 < c_2 < \cdots < c_{k-1} < c_k$. Since C can take a value from zero to one, $c_1 = 0$ and $c_k = 1$. Let $p_j(a)$ denotes the probability that a value of a factor of failure consequence C is included in j-th category when scale of event is a. Uncertainty included in C and variation by the scale of the event a are expressed by the values of $p_j(a), (j = 1, 2, \ldots, k)$. In case that the scale of the event becomes large, the value of $p_1(a)$ and $p_2(a)$ may decrease whereas $p_{k-1}(a)$ and $p_k(a)$ may decrease. Thereby the performance loss function of the failure mode is obtained as Eq. (3).

$$f_i(a) = \sum_j \left(p_j(a) \times c_j\right) \tag{3}$$

It is noted that the factor of failure consequence is essentially continuous, but not discrete values of $c_1, c_2, \ldots, c_k$. Therefore, Eq. (3) is rewritten in the integration form.

$$f_i(a) = \int_0^1 p_{ic}(a, c)\mathrm{d}c \tag{4}$$

Here, $p_{ic}(a, c)$ denotes the occurrence probability of the factor of failure consequence c due to failure mode i under the condition that scale of event is a. $f_i(a)$ in Eq. (2) is calculated by Eq. (1) or (4).

The image of performance loss function is illustrated in Fig. 1. The factors of failure consequence are multiplied with the occurrence probabilities of three types of failure modes, and the performance loss functions are obtained for the failure modes. The dashed line, dotted line and dashed line with dots indicate the performance loss function when the factors for failure modes A, B, and C are assumed 0.2 (small impact), 0.4 (middle impact), and 1.0 (large impact), respectively. The characteristic of the function appears well in the failure mode A. When a failure mode with small impact occurs, the function takes also small value. The performance loss function of the component (i.e., the summed value of the functions of the failure modes) is drawn by the bold line. The failure occurrence probability of a component is illustrated by a thin line as the conventional fragility. Since the failure consequence is assumed to lose safety performance completely in the fragility, the factor of failure consequence is set as 1.0. Comparing the fragility and the performance loss function, the influence of consideration of failure consequence in performance loss function is quite clear. It should be noted that occurrence probability and consequence are assumed to be independent by failure modes in the performance loss function expressed by Eq. (2). An analyst can incorporate the dependencies as needed. Due to the assumption, the summed value can exceed one. This means the complete loss of safety performance of the component. Therefore, the maximum value of the performance loss function is limited to one.

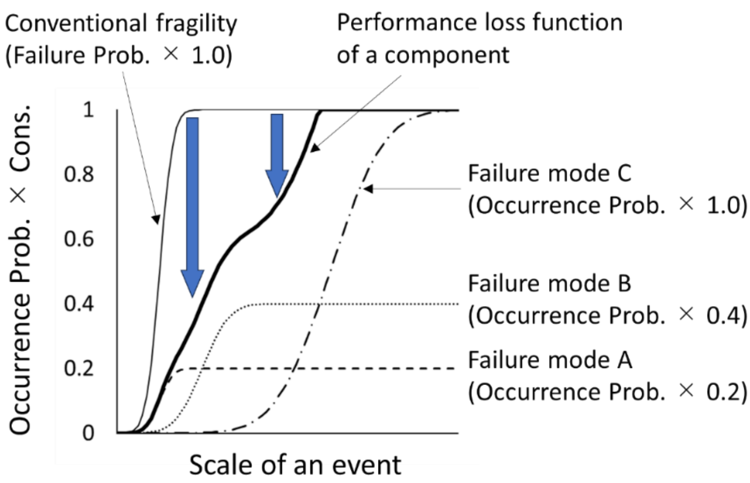


Fig. 1 Concept of performance loss function

3. Performance Loss Function for Piping System

The concept of performance loss function described in section 2 was applied to piping system. As the loading event to cause its failure, the earthquake was selected. Earthquake is an event with high risk for the safety performance of a piping system because its loading can be dominant compared with other types of loading. In addition, safety performance was defined as the core cooling performance that is a typical type of performance of a piping system in nuclear power plants.

3.1 Failure mode in Piping System

To evaluate the performance loss function for a piping system, it is important to identify the failure modes to be considered. According to RI-ISI [1-3] described in introduction, leak and break are the important failure modes from the viewpoint of inspection for crack detection. In addition, these failure modes are known to occur in a cracked piping system during earthquake [9-12]. Specifically, a crack can propagate due to fatigue caused by cyclic strain. This can result in the leak when a crack penetrates wall thickness of the piping system. In addition, break is a failure mode which leads to unstable fracture by an existing crack and excessive load. Large leak occurs at the break point. The risk of these failure modes can be reduced by inspection to detect and remove the crack. These failure modes are illustrated in Fig. 2 schematically.

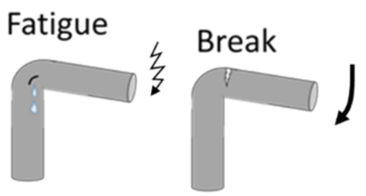


Fig. 2 Failure modes caused by a crack

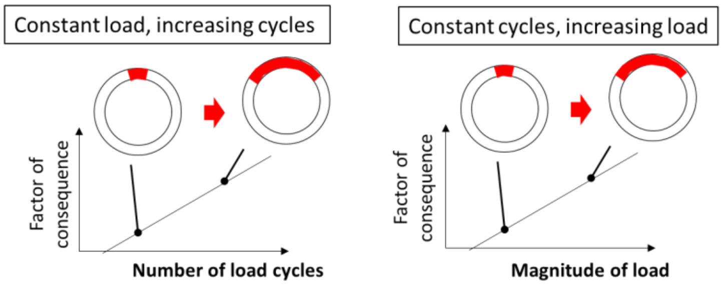
3.2 Concept for Performance Loss Function for Failure modes Caused by Crack

In accordance with the description in section 2, the concept of the performance loss function for leak and break were defined.

3.2.1 Leak (fatigue)

Leak during the earthquake can be caused by fatigue. Fatigue has the characteristics that state of failure progresses with number of loading cycles in the forms of the crack propagation. When a crack penetrates the wall thickness, the leak occurs. The occurrence probability of leak can be represented shown as the conventional fragility in Fig. 1.

Moreover, as the crack propagates, the level of safety performance is degraded. A value of the factor of failure consequence in the performance loss function increases. Namely, the factor does not take a unique value as in the example of Fig. 1. Figure 3 illustrates the characteristics of leak due to fatigue regarding the factor of failure consequence. The factor increases with number of loading cycles and magnitude of the cyclic loading, respectively. Thus, the performance loss function for leak is expressed by the form of Eq. (4). The description below focuses on the increase of the factor with magnitude of the cyclic loading assuming constant number of cycles shown in Fig. 3(b).



(a) Constant load, increasing cycles (b) Constant cycles, increasing load
Fig. 3 Characteristics of leak regarding the factor of failure consequence

3.2.2 Break

Break of a cracked piping system occurs as the result of unstable crack extension or plastic collapse of the piping system. For the occurrence of break, the crack size is the important factor in addition to loading condition. As the crack size becomes large, crack extension force increases and structure strength decreases due to reduction of ligament. It is noted about the break during earthquake that the crack size becomes large due to fatigue crack propagation explained above. Thus, occurrence probability of break in the performance loss function needs to be evaluated considering the influence of crack propagation during earthquake. Break is the most severe failure mode for a piping system. Thus, the factor of failure consequence is anticipated to take a certain high value. The performance loss function is expressed by the form of Eq. (1).

4. Evaluation methodology

4.1 Leak

Firstly, we discuss how leak occurs and the core cooling performance is degraded. As explained in 3.2.1, fatigue crack propagation occurs during earthquake which results in a local boundary failure to leak. The leak flow passes through a crack. Crack opening area (COA) is an important factor for leak rate. COA largely depends on the crack size. Once COA is determined, leak rate is determined by the pressure loss in the flow path and pressure differential, and so on. The above discussion is almost the same as leak before break evaluation [13]. The leak reduces the flow rate of main flow path for the core cooling. As a result, the cooling performance is degraded. In accordance with the causal relationship, the evaluation methodology is described below.

4.1.1 Crack growth analysis

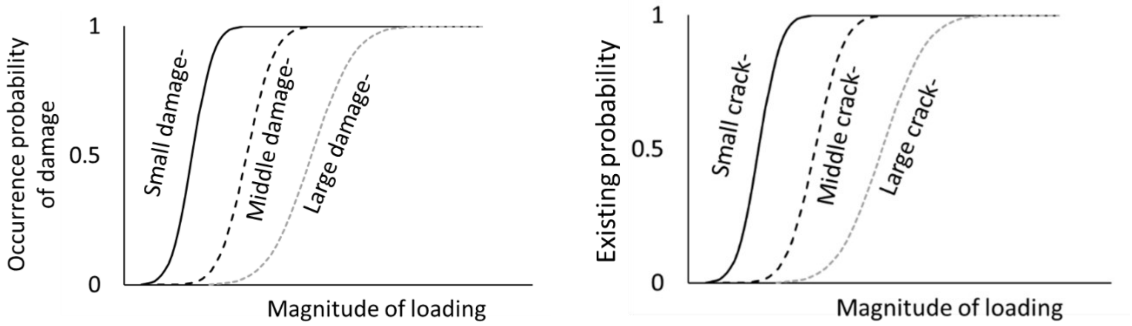
Firstly, a certain size of crack is postulated. Fatigue crack growth analysis is performed for the crack. Based on the analysis result, the occurrence of leak and crack size after the earthquake are determined. By considering the relevant uncertainties, occurrence probability is obtained in the form of the conventional fragility shown in Fig.1. In addition, data on the size of through-wall cracks are obtained with uncertainties. The data on size of through-wall cracks are represented by relationship between crack size and its existing probability. The procedure to develop the relationship is described below.

Firstly, the concept of the fragility analysis in the civil and architecture field [14] is described as a reference information. Building subjected to earthquake is damaged by a variety of magnitudes, such as peeling, cracking, and collapse. The damage of the building is divided into categories from small damage to large damage. Giving occurrence conditions to the damage categories, fragility is estimated as schematically illustrated in Fig. 4 (a) considering relevant uncertainties. In the figure, "small damage

-" means that damage category larger than and equal to "small".

Considering the similarity between the damage categories of building and the size of through-wall crack, by dividing the crack size into categories, existing probability can be evaluated per crack size category. As an example, three kinds of categories (i.e., crack size categories small, middle, and large) are defined. In this case, the probability to satisfy the condition of each category is evaluated like the result shown in Fig.4 (b). In the figure, "small crack -" means that existing probability of crack with size larger than and equal to "small". Namely, the category of "small crack -" includes middle crack and large crack redundantly in addition to small crack.

Next, the probabilities in Fig.4(b) are converted to the existing probabilities corresponding to the categories as shown in Fig.5 by excluding the redundancy. Since the crack size becomes large as increase in loading, the existing probability of small crack category increases at small loading. When the loading further increases, the category proceeds from small to middle crack. Thereby, the existing probability of middle crack category increases whereas that of small crack category decreases. That is, existing probability of a certain category can present decremental tendency. It should be noted that the actual data on crack size with uncertainty is not discrete as in the examples, but continuous. In the case of tiny division of crack size, the relationship between the crack size and its existing probability can be estimated.



(a)Occurrence probability for damage of building (b)Existing probability for crack size

Fig.4 Occurrence probability for damage category

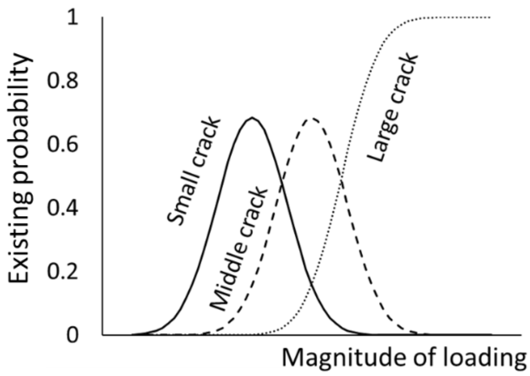
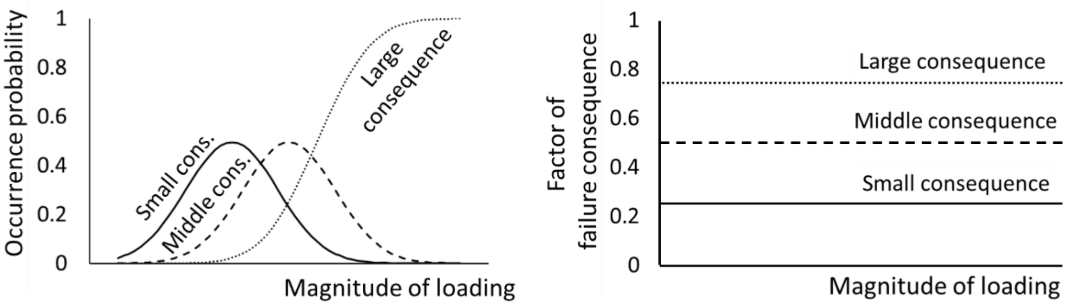


Fig. 5 Existing probability of each crack size category

4.1.2 Safety performance degradation and factor of failure consequence

The factor of failure consequence on the core cooling performance for a certain crack size is evaluated by utilizing the approach for the well-known leak-before-break analysis [13]. Firstly, considering the crack size, COA should be evaluated based on the load conditions and material strength. Considering the COA, the leak rate is evaluated. Considering the leak rate, the main flow rate after the failure occurrence is calculated. The flow rate reduction is normalized by the expected flow rate. The normalized flow rate reduction is the factor of failure consequence.

As described in 4.1.1, crack size includes uncertainty and is represented by the relationship between crack size and its existing probability. Thus, the factor of failure consequence also contained uncertainty. By the same approach as the case of crack size, the relationship between values of the factor and its occurrence probability can be evaluated. That is, the factor of failure consequence can be divided into number of categories. Assuming three kinds of categories small, middle, and large for failure consequence as an example, occurrence probability for each category can be evaluated as schematically shown in Fig.6 (a) using the approach of the first paragraph based on the crack size shown in Fig.5. In addition, the representative value of the factor can be given for each category independent of magnitude of loading shown in the example of Fig.6 (b). It should be noted again that the actual failure consequence is essentially continuous. By dividing into infinitesimal categories, the relationship between the factor of failure consequence and its occurrence probability can be estimated.



(a)Occurrence probability **(b)Factor of failure consequence**

Fig. 6 Occurrence probability and factor of failure consequence for each category

4.1.3 Performance loss function

Performance loss function of leak $f_L(L,N)$ is calculated by Eq. (5) in accordance with the definition of Eq. (3).

$$f_{\mathrm{L}}(L,N) = \sum_j \left(p_{Lj}(L,N) \times c_j\right) \tag{5}$$

Here, j means the name of category defined for the factor of failure consequence. c_j is the representative value of factor of failure consequence for category j. $p_j(L,N)$ is the occurrence probability of category *j* under the condition of loading *L* and number of loading cycles *N*. Considering the case of Fig. 6, the performance loss function is evaluated as shown in Fig.7. The increase in the factor of failure consequence against magnitude of loading is expressed by increase in occurrence probability of category with higher consequence. As described above, the value of factor of failure consequence is continuous. Thus, Eq. (5) is converted to continuous form expressed by Eq. (6).

$$f_{\mathrm{L}}(L,N) = \int_0^1 p_{\mathrm{Lc}}(L,N,c)\,\mathrm{d}c \tag{6}$$

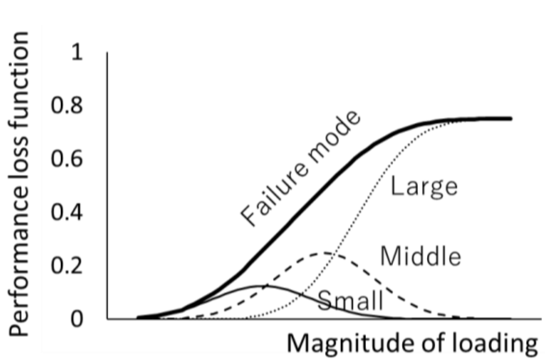


Fig. 7 Performance loss function

4.2 Break

Break is regarded as a catastrophic failure mode because of its unstable crack extension behavior and large boundary failure. Thus, the factor of failure consequence can be set as high value, such as 1.0.

Performance loss function of break $f_{\mathrm{B}}(L)$ is calculated by using occurrence probability of break P_{B} as follows.

$$f_{\mathrm{B}}(L) = P_{\mathrm{B}}(L) \times 1.0 \tag{7}$$

4.3 Performance loss function for a cracked piping

Based on Eqs. (6) and (7), the performance loss function for a cracked piping is finally obtained as Eq. (8).

$$\text{Performance loss function: } F(L, N) = \int_0^1 p_{\mathrm{Lc}}(L, N, c)\,\mathrm{d}c + P_{\mathrm{B}}(L) \tag{8}$$

5. Example Analysis of the Effect of Inspection

Using the developed performance loss function, the effect of inspection was quantified. Regarding the types of inspection, the post-earthquake inspection [15] explained below was focused.

When an excessive earthquake occurs, a piping system can fail via the modes, such as leak or break due to fatigue described above. Even if failure does not occur, a crack due to fatigue can occur. The crack increases the risk of core cooling performance in subsequent operation. Therefore, after the occurrence of an excessive earthquake, parts of a piping system, such as elbows, are inspected to detect the crack. If cracks are detected, countermeasures such as repair and replacement are performed as necessary.

5.1 Analysis Target

The analysis target of a piping system is shown in Fig. 8. The piping system consisted of straight pipes and elbows. The geometry and performance level were specified by referring to those of high-pressure injection system of PWR. The elbow to be evaluated was rounded in red. The outer diameter and thickness were 114.3 mm and 14 mm, respectively. Curvature radius was 150 mm. The length of straight pipes was written in Fig.8. The unit of the length was mm. 15 MPa of internal pressure was considered. The material was stainless steel.

To apply in-plane bending moment due to dead weight at the elbow, the additional mass of 1000 kg was set at the position apart from the straight pipe. In addition, seismic acceleration was considered in the direction so that in-plane bending moment was applied to the elbow. The direction of shaking the piping system was also illustrated in Fig. 8. The seismic acceleration consisted of constant amplitude sine waves with 300 cycles. Consequently, bending moment from dead weight and seismic acceleration was applied to the elbow. The amplitude of acceleration was varied for the evaluation of occurrence probability and factor of failure consequence of the failure modes.

The flow rate to represent the cooling performance expected for the piping system was set as 150 m^3/h. Reduction of flow rate from this value was considered at the calculation of the factor of the failure consequence.

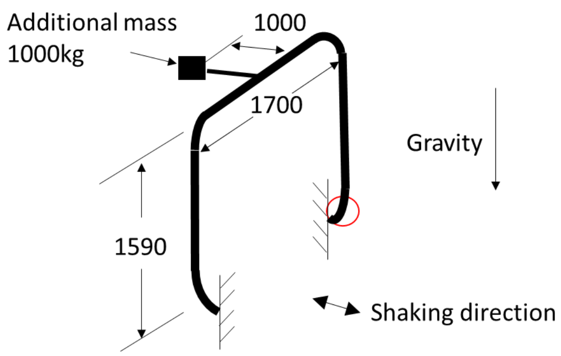


Fig. 8 Piping system for the analysis

5.2 Consideration of Inspection

The effect of the post-earthquake inspection was analyzed by comparing the performance loss functions assuming the existence of cracks with different size. One of the assumed cracks had 13.9 mm depth, just before leak occurs. If a crack penetrates wall thickness and leak occurs, the leak would be detected. The part is repaired or replaced. Thus, this is the maximum crack size that can remain in the pipe after an earthquake. The other crack had 3 mm depth. It was specified based on the crack depth which is difficult to detect with the probability of 100% [16]. This is the maximum crack size that can remain after the inspection. The half-length of these cracks was set so that aspect ratio became 0.4 [13]. Therefore, the half-length was set to 34.6 mm for the former crack and 7.5 mm for the latter crack. These cracks had the longitudinal orientation. The location of these cracks was assumed to be the side of the elbow, which is typical location of a fatigue crack.

5.3 Analysis Method

The performance loss function was evaluated using the methodology developed in section 4 based on Monte Carlo method considering the uncertainties included in the analysis conditions. Leak and break were considered as the failure modes caused by the cracks at the elbow of the piping system.

The evaluation consisted of the three steps: (i) crack growth analysis, (ii) evaluation of COA, and (iii) calculation of leak rate passing through the crack. The detailed methods for the evaluation were described below.

The crack growth analysis due to fatigue was performed to determine the occurrence of leak and the crack length after the earthquake. Crack growth rate for excessive cyclic load was calculated by the following equations using J-integral [17]. Eq. (9) represents the crack growth rate for fatigue. Eq. (10) represents the ductile crack extension.

$$\frac{\mathrm{d}a}{\mathrm{d}N} = 5 \times 10^{2} \times C'^{\Delta J^{1.5}} \tag{9}$$

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \left(\frac{J_{\max}}{3.36}\right)^{\frac{1}{0.32}} - \left(\frac{J_{\max-1}}{3.36}\right)^{\frac{1}{0.32}} \tag{10}$$

Here, $\frac{da}{dN}$ is crack growth rate in mm/cycle at a loading cycle. C' is random variable expressed by the lognormal distribution. Logarithmic mean value was set as -29.45. Logarithmic standard deviation was set as 0.25. ΔJ is the J-integral range at the loading cycle. $J_{\max}$ is maximum value of J-integral during the loading cycle. $J_{\max-1}$ is the maximum value of J-integral before the loading cycle.

Regarding the J-integral value for an elbow, since the existing solutions are intended to be used for leak before break analysis, their applicable ranges are limited to a crack with short length that may cause a small leak [18-20]. Thus, the J-integral solution for a straight pipe was applied instead, and the distributed hoop strain at the crack tips was used for the calculation of J-integral value for each cycle. The hoop strain was obtained from a dynamic elastic-plastic time history analysis for the piping system. As a reference, the hoop strain at the flank center (i.e., the largest hoop strain in the elbow) is presented in Fig. 9. The hoop strain was specified to decrease along with the longitudinal direction from the center to edges considering the obtained strain distribution at the elbow.

In the crack growth analysis, the crack transition among the three kinds of shape illustrated in Fig. 10 was considered by referring to the leak before break analysis [21]. The applied J-integral solution depended on the crack shape. Before the occurrence of leak, the crack has semi-elliptical shape at the inner surface shown as the 1st shape in the figure. For the crack shape, the J-integral solution for longitudinal surface crack at the straight pipe [22] was applied. When the crack depth reached wall thickness of 14mm, leak was determined to occur, and the crack transformed to non-idealized through-wall crack shown as the 2nd shape in the figure. The non-idealized crack has smaller length at outer surface than inner surface. Just after the leak occurrence, the crack length at the inner surface took the same value as that of semi-elliptical surface crack just before the leak occurrence. On the other hand, the crack length at the outer surface took smaller value either quarter of crack length at the inner surface or two times of wall thickness. J integral values at the crack tips of the inner and outer surfaces were calculated by calibrating the J integral value for idealized through-wall crack with rectangular shape by referring to the crack growth analysis approach [21]. The J-integral value at inner surface was calibrated to smaller value than that for idealized through-wall crack whereas that at outer surface was calibrated to larger one. The J-integral value of the idealized through-wall crack was calculated by using the solution for straight pipe with a longitudinal through-wall crack [22]. Because of the calibration, the difference of crack length between inner and outer surfaces became small. When the crack length at the outer surface became the same as that at the inner surface, the through-wall crack was treated to be the idealized shape shown as the 3rd shape in the figure. For the idealized through-wall crack, the J-integral solution for the straight pipe was applied as explained above.

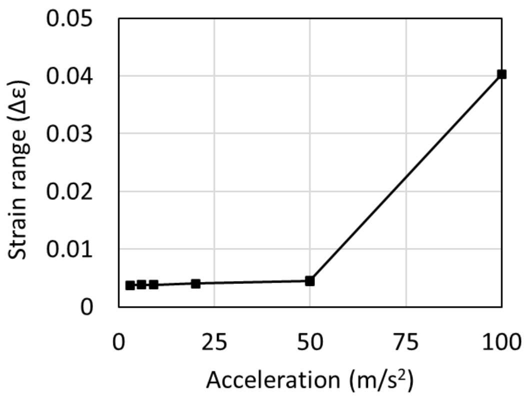


Fig. 9 Strain range at the elbow from the response analysis

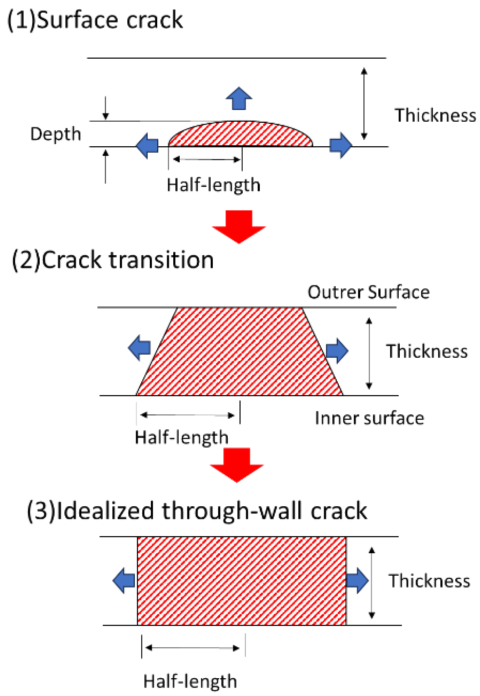


Fig. 10 Crack transition considered in the crack growth analysis

After the crack length after the earthquake is evaluated, the crack opening displacement δ and COA were calculated by Eqs. (11) and (12) [23]. These equations are for the flat plate with a crack at the center, in which strain distribution is like an elbow.

$$\delta = \frac{4b\sigma_\mathrm{m}}{E} \times \frac{E\varepsilon_\mathrm{ref}}{\sigma_\mathrm{ref}} \times H_2 \tag{11}$$

$$\mathrm{COA} = \frac{\pi b \delta}{2} \tag{12}$$

Here, b is half-length of through-wall crack at inner surface in mm, E is Young's modulus of 195000 MPa. σ_ref and ε_ref are reference stress and strain. σ_m is the membrane stress in MPa, and the hoop membrane stress caused by internal pressure was considered. H_2 is the coefficient to calibrate crack opening displacement value for the non-idealized crack [21] shown as the 2nd shape in Fig. 10. For idealized through-wall crack, the value of H_2 was set as one.

The leak rate G in m^3/h was calculated by Bernoulli's principal considering pressure loss due to rough wall friction and entrance of narrow flow pass described in the research on leak before break [24] using Eq.(13).

$$G = \mathrm{COA} \times \sqrt{\frac{2(P_{\mathrm{in}} - P_{\mathrm{out}})}{\rho\left(1 + \frac{1}{C_D^2} + \lambda \frac{t}{D_H}\right)}} \tag{13}$$

Here, P_{in} and P_{out} are the internal pressure and back pressure, respectively. C_D=0.95 is the discharge coefficient to calculate the pressure loss at entrance of flow path formed by the crack. D_H is hydraulic diameter based on the geometry of flow path. λ is a friction coefficient for the flow path with rough wall. The value varies by the hydraulic diameter, and approximate value was 0.1 here.

The factor of failure consequence C_L can be calculated by using leak rate G by Eq. (14) in accordance with the definition [8].

$$C_L = \frac{Max(q_{ex} - (q_0 - G), 0)}{q_{ex}} \tag{14}$$

Here, q_0 is the flow rate in case of no failure, q_{ex} is the flow rate expected to the piping system for the purpose of core cooling. In the evaluation, q_0 was assumed to equal to q_{ex}, and these values were set as 150 m^3/h. Thus, the factor was simply calculated by dividing leak rate by 150 m^3/h.

Regarding the break, occurrence probability is evaluated based on the crack size after propagation of earthquake. The criterion of break for a longitudinal crack expressed by Eq. (15) [13] was used.

$$\sigma_\theta = \frac{\sigma_f}{M} \qquad M = \sqrt{1 + \left(\frac{1.61}{Rt}\right) b^2} \tag{15}$$

σ_θ is the hoop stress to break, R is mean radius of a pipe, t is thickness of pipe. σ_f is flow stress calculated as the average of yield stress and ultimate strength. Yield stress and ultimate strength were taken as the random variables following to lognormal distribution. Their median values are 232 MPa and 586 MPa, respectively. Both standard deviations were set as 0.07. b is the half-length of through-wall crack at inner surface.

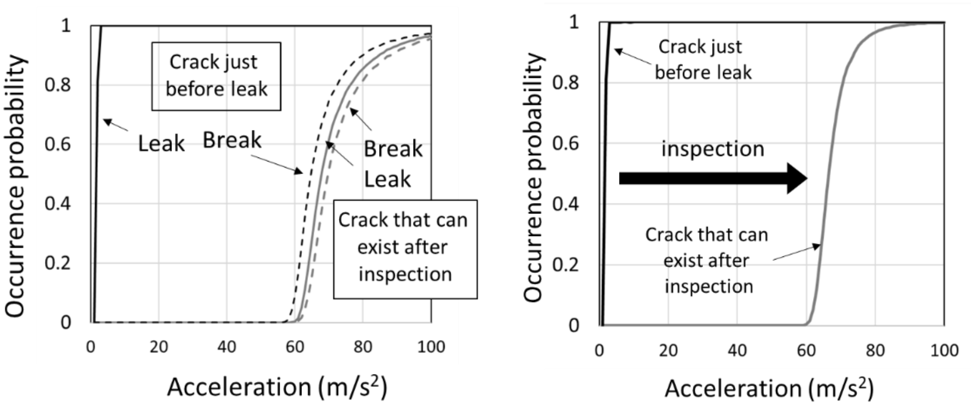
5.4 Analysis results

Figure 11 (a) shows the results of the occurrence probabilities for leak and break against magnitude of acceleration. Regarding the results for the crack just before leak (i.e., before inspection), occurrence probability of leak increases to one at low magnitude of acceleration. Uncertainty in crack growth rate did not affect the occurrence probability of leak because the crack soon propagated wall thickness to cause the leak. Regarding break, a very long length of crack was required to cause. As a result, its occurrence probability increases around 60 m/s^2, much higher than the case of leak. On the other hand, in the case of crack that can exist after inspection, the occurrence probabilities of leak and break increases to one at the almost same magnitude of acceleration. The reason can be explained as follows. In the analysis, only 300 loading cycles were considered. Thus, a large amount of crack growth is required per loading cycle for the crack with 3 mm depth leading to the leak occurrence. In addition, since crack growth rate depends on the crack size, crack size becomes large exponentially against loading cycle. Therefore, the crack propagates rapidly after the leak occurrence to become long length to cause break. As a result, there is the small difference in the acceleration between the occurrences of leak and break.

Figure 11(b) shows the occurrence probabilities of failure of piping system. Here, occurrence of failure means occurrence of leak or break. The acceleration level of failure occurrence is 1m/s^2 for crack just before leak whereas 60 m/s^2 for crack that can exist after inspection. Namely, owing to the inspection, the acceleration to failure expected to be improved around 60 m/s^2 at maximum.

Figure 12 shows the results of the factor of failure consequence of leak. Due to the small strain range shown in Fig. 9, the crack just before leak did not propagate much in length direction when the acceleration was lower than 50m/s^2. Thus, the factor of failure consequence took the tiny value. On the other hand, when acceleration was greater than 50m/s^2, the factor of failure consequence took large value due to crack propagation by large strain range. The factor for the crack that can exist after inspection shows the same tendency. In addition, because of the assumption regarding the strain distribution that the strain amplitude decreased as the crack tip was apart from the center of the elbow, the values of crack length were saturated regarding the two cracks.

Figure 13 shows that the performance loss function evaluated for the two cracks. Regarding the crack just before leak, the value of performance loss function took tiny value because of the small failure consequence when the acceleration was lower than 50m/s^2. Comparing the two performance loss functions, the acceleration for the risk increase is expected to be improved by around 10m/s^2 at maximum by the inspection. Compared with the occurrence probability of failure (i.e., the conventional fragility), the effect of inspection was evaluated small. This difference in the effect of inspection was caused by the consideration of failure consequence. Especially, for beyond design basis events, failure with small consequence on the performance is not important based on the risk concept. Inspection based on the conventional fragility may result in the inspection to prevent such failure, which does not reduce the risk. The developed performance loss function can provide the risk for importance of inspection from the viewpoint of the safety performance of a passive component including piping system.



(a)Failure modes **(b)Failure of piping system**

Fig. 11 Result of occurrence probability

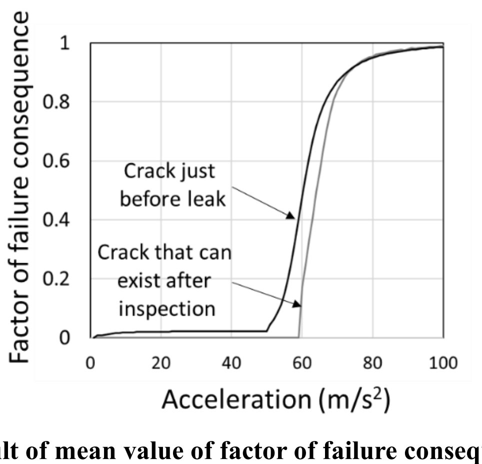


Fig.12 Result of mean value of factor of failure consequence

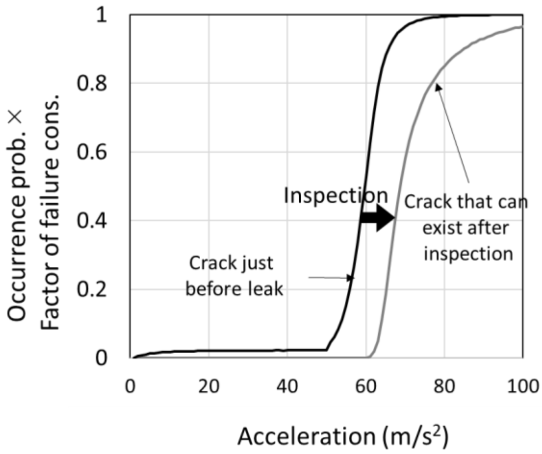


Fig. 13 Result of performance loss function

6. Conclusion

The inspection focusing on risk high significant parts of piping system is considered one of the effective approaches to reduce the risk in nuclear power plants. Generally, the risk is defined for the safety performance of the nuclear power plants, namely protection from harmful radiation. On the other hand, in the structural integrity field, investigation is carried out for another risk definition that focuses on the safety performance of a passive component. In the research, for the analysis of the risk of safety performance of piping system used for the effective inspections, the performance loss function concept to represent the risk was applied to a piping system subjected to earthquakes. In addition, the quantitative evaluation methodology was developed. As a result, the following conclusions were obtained.

The performance loss function considers the failure modes of leak and break caused by fatigue crack propagation. Regarding leak, probability distribution of factor of failure consequence is estimated based on the leak before break analysis approach considering relevant uncertainties. The performance loss function is obtained as the integral of probability distribution with regard to the factor. Regarding break, the factor of consequence can be assumed unity because it is a catastrophic failure mode to avoid in any situation. Thus, the performance loss function is equal to the occurrence probability of break. From the quantitative analysis result, by using the developed performance loss function, the importance of inspection can be evaluated in terms of risk of the cooling performance of piping system. The analysis result is expected to be used for more effective inspection considering a beyond design basis event.

References

[1] EPRI: "Revised Risk-Informed Inservice Inspection Evaluation Procedure," TR-112657 Rev.B-A (2000).
[2] ASME: "Alternative Piping Classification and Examination Requirements", ASME Code Case N-716 (2013).
[3] Westinghouse Electric Company LLC: "Westinghouse Owners Group Application of Risk-Informed Methods to Piping Inservice Inspection Topical Report," WCAP-14572, Revision 1-NP-A (1999).
[4] N. Kasahara, T. Sato, A. Blahoianu, "Contribution to Safety Enhancement for BDBE in Structure and Material Fields", Proc. of ASME 2018 PVP Conference, PVP2018-84353, Prague, Czech Republic, July 15-20 (2018).
[5] N. Kasahara, T. Wakai, I. Nakamura, T. Sato, M. Ichimiya, "Application of Fracture Control to Mitigate Failure Consequence under BDBE", Proc. of ASME 2020 PVP Conference, PVP2020-21072, Virtual, Online, August 3 (2020).
[6] N. Kasahara, H. Machida, K. Okamoto, T. Sato: "Structural Analysis Approach for Risk Assessment under BDBE," Proc. of ASME2016 PVP Conference, PVP2016-63416, Vancouver, Canada, July, 17-21 (2016).
[7] AESJ: "A standard for procedure of seismic probabilistic risk assessment for nuclear power plants: 2015", AESJ-SC-P006: 2015 (2015). (in Japanese)
[8] A. Mano, T. Sato, M. Ichimiya, N. Kasahara: "Proposal of performance-based fragility concept incorporating failure consequence and application to seismic fragility of piping systems", Mechanical Engineering Journal, Vol. 11, Issue 2, 23-00515, (2024).
[9] I. Nakamura, A. Otani, M. Shiratori: "Study on Estimation Method of Seismic Safety Margin of Aged Piping System and Equipment", Report of National Research Institute for Earth Science and Disaster Prevention,

(2001). (in Japanese)
[10] G. Wilkowski, R. Schmidt, P. Scott: "International piping integrity research group (IPIRG) program", NUREG/CR-6233, Vol.4, 1997.
[11] K. Yoshino, T. Sakakida, H. Yokota, Y. Asada: "Study on seismic design of nuclear power plant piping in Japan Part 3: Component tests results", PVP-Vol.407, Pressure Vessel and Piping Codes and Standards-2000, pp. 131-137, (2000).
[12] T. Zhang, F.W. Brust, D.J. Shim, G. Wilkowski, J. Nie, C. Hofmayer: "Analysis of JNES Seismic Tests on Degraded Piping", NUREG/CR-7015, 2010.
[13] The Japan Society of Mechanical Engineers: "Codes for nuclear power generation facilities: rules on protection design against postulated pipe rupture for nuclear power plant", JSME S ND1-2002 (2002). (in Japanese)
[14] H. Yoshikawa, T. Otaki, Y. Maeda, T. Nakamura: "Fragility curves and earthquake loss functions in earthquake risk analysis", Concrete Engineering, Vol.45, No.10, pp.26-34 (2007). (in Japanese)
[15] JANTI: "Guidelines for structural integrity assessment for component after earthquakes", JANTI-SANE-G2 (2012). (in Japanese)
[16] JNES: "Report on technique regarding inspection for nuclear facilities", (2005). (in Japanese)
[17] Y. Yamaguchi, J. Katsuyama, K. Masaki, Y. Li: "Guideline on Seismic Fragility Evaluation for Aged Piping", JAEA-Research 2020-017 (2021). (in Japanese)
[18] S. Marie, S. Chapulot, Y. Kayser, M. Lacire, B. Drubay, B. Barthelet, P. Delliou, V. Rougier, C. Naudin, P. Gilles, M. Triay: "French RSE-M and RCC-MR code appendices for flaw analysis: Presentation of the fracture parameters calculation—Part IV: Cracked elbows," International Journal of Pressure Vessels and Piping, Vol. 84, pp.659–686, (2007).
[19] K.M. Prabhakaran and V.V. Raj, "Closed form expression for plastic J-integral for an elbow with a through-wall crown under opening bending moment", International Journal of Pressure Vessels and Piping 80 (2003) 31–39.
[20] U.S.NRC, "The Battelle Integrity of Nuclear Piping (BINP) Program Final Report: Summary and Implications of Results, Appendix F The development of a J-estimation scheme for circumferential and axial through-wall cracked elbows", NUREG/CR-6837, (2005)
[18] xLPR Model Subgroup, "XLPR MODELS SUBGROUP REPORT -Crack Transition-," xLPR-MSGR-CTM, 2016.
[19] S. Marie, S. Chapulot, Y. Kayser, M. Lacire, B. Drubay, B. Barthelet, P. Delliou, V. Rougier, C. Naudin, P. Gilles, M. Triay: "French RSE-M and RCC-MR code appendices for flaw analysis: Presentation of the fracture parameters calculation—Part III: Cracked pipes," International Journal of Pressure Vessels and Piping, Vol. 84, pp.614–658, (2007).
[20] Afren: "Design and construction rules for mechanical components of nuclear installations, RCC-MRx 2012 edition," (2012).
[21] EPRI, "Calculation of Leak Rates Through Cracks in Pipes and Tubes," EPRI NP-3395, (1983).