Fragility Evaluation of Electrical Raceway Considering Realistic Capacity of Cables against Earthquake and Its Effect on Seismic PRA

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ABSTRACT

In the current seismic Probabilistic Risk Assessment and stress tests conducted in Japan, the following conservative assumptions are made regarding the damage to electrical systems:
- The fragility of the least seismically robust electrical raceway is used as the representative.
- Failure of the electrical raceway is assumed to directly lead to core damage.
- Structural damage of cable tray is assumed to result in a total failure of the electrical raceway, ignoring the integrity of the cable.

Due to these assumptions, electrical raceways can become the dominant contributor in core damage when the seismic margin of the cable tray is not sufficiently large. In this study, we examined the calculation of cable fragility and electrical raceway fragility by referencing realistic assessments of cable strength after cable tray damage caused by earthquakes. Here, since cable damage occurs after cable tray damage, the fragility of the electrical raceway was evaluated as a conditional probability given the damage to the cable tray.

Furthermore, we assessed the effect on seismic Probabilistic Risk Assessment and stress tests when considering the realistic fragility of electrical raceways derived in this study, as opposed to the conventional conservative assumptions.
The results of this study enable improvements in the conservative assumptions regarding electrical raceways in seismic Probabilistic Risk Assessment , allowing for more realistic evaluations. Additionally, by further enriching information on cable strength, it is possible to advance studies on screening out electrical raceways from seismic Probabilistic Risk Assessment .

Keywords: Seismic PRA, Fragility, Electrical system, Cables, Realistic capacity

I. Introduction

Since the establishment of the first seismic Probabilistic Risk Assessment (PRA) standard by the Atomic Energy Society of Japan in 2007, risk information based on seismic PRA has played a crucial role in the licensing processes of regulatory authorities and in the voluntary safety enhancement activities of power companies. Additionally, as part of the activities called "Safety Assessment Report" in Japan, stress tests based on fragility as an indicator are also conducted. However, several significant assumptions exist in the current seismic PRA and stress tests regarding electrical raceways, which influence the risk assessment.

First, as the primary assumption, it is considered that damage to electrical raceways leads directly to core damage. This assumption is adopted conservatively due to the difficulty in clarifying the impacts of damage to specific circuits, given that electrical circuits are related to many system functions within the plant.

The second assumption is that the electrical raceway with the lowest seismic margin is treated as representative, and the fragility of this representative electrical raceway is applied to all electrical raceways. This assumption arises from the difficulty of assigning fragility to each individual circuit, considering the numerous circuits subject to evaluation and the need to take into account their installation locations and the impacts during damage.

The third assumption posits that if cable trays or their supporting structures are damaged, the electrical raceways will lose functionality even if the cables remain functionally sound. This assumption is conservatively set due to the lack of information regarding the ability of cables to maintain electrical functionality following damage to cable trays caused by earthquakes.

These assumptions imply that if the seismic margin of cable trays is low, they could become a dominant factor contributing to core damage. Furthermore, even if a fragility assessment based on conservative assumptions yields results indicating significant contributions from electrical raceways, it cannot be easily claimed that such results are appropriate as risk information. In light of this background, this study proposes a fragility assessment method for cables following damage to cable trays, based on the results of strength tests and seismic response analyses. Should this study demonstrate that the probability of cable damage due to earthquakes is sufficiently low, it may be possible to screen out electrical raceways in seismic PRA and stress tests. For this research, three representative plants have been selected from Japanese Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR), referred to as Plant A (BWR), Plant B (BWR), and Plant C (PWR) in the following sections.

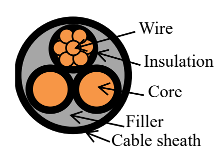
II. Selection of Evaluation Targets and Representative Cables

The cables used in nuclear power plants include metal cables and optical fiber cables. Since optical fiber cables can be considered structurally more robust than metal cables, they are excluded from direct consideration, as the evaluation can be encompassed by focusing on metal cables. Regarding the electrical conduits, the internal cables are the same as those in the cable trays, and the potential for damage is considered as follows. References [1][2] have conducted vibration tests to evaluate the strength of small-diameter piping with a diameter of 4 inches or less, and the results indicate that there is no damage even under seismic motions several times greater than the design earthquake motion. Based on this, it can be concluded that the electrical conduits are unlikely to sustain damage under realistically occurring seismic motions, and the possibility of breakage or falling that would affect the internal cables is also unlikely to occur. Therefore, the focus of this study will be on metal cables installed on cable trays. A comprehensive survey was conducted on metal cables used in safety systems and severe accident mitigation systems of PWRs and BWRs, covering cables related to high-pressure power, low-pressure power, control, and instrumentation. The specifications regarding the structure, dimensions, weight per unit length, and materials used for the cables were organized[3]. Based on the frequency and distribution of items related to cable strength, representative cables for analysis and testing were selected[3]. Examples of the representative cables selected, along with the specifications obtained from subsequent tests, are shown in Table 1.

Table 1: Specification of the representative cables (Plant A:BWR)[3]

Cable No.	Ac1	Ac2	Ac3	Ac4	Ac5	Ac6	Ac7	Ac8	Ac9	Remarks
Cable Outer Diameter [mm]	9	6.9	7.5	8	13	15.5	19	26	35	
Cross-sectional area (Total core wire) [mm^2]	1.25	2	3.5	5.5	38	60	100	200	400	
Number of cores	2	27	8	4	2	3	2	3	1	
Number of wires	7	7	7	7	7	19	19	37	61	
Modulus of Elasticity E [MPa]*1	10232	8960	8169	9557	10025	8019	5192	7565	5129	Test results
Poisson's ratio [-]	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	0.145	
Second moment of area [mm^4]	1.384E-02	4.453E-02	1.373E-01	3.301E-01	1.821E+01	1.516E+01	3.925E+01	7.548E+01	1.953E+02	
Approximate mass [kg/km]	100	75	95	110	445	680	1070	2080	4030	
Density ρ [t/mm^3]	8.000E-08	3.750E-08	2.714E-08	2.000E-08	1.171E-08	1.133E-08	1.070E-08	1.040E-08	1.008E-08	
0.2% offset yield strength [MPa]	168.7	180.3	178.3	181.1	227.2	225.5	212.7	242.9	195.9	Test results

(*1) The modulus of elasticity E at dogleg fracture shall be 10 times the stated value.



Cross section of the metal cable
(conceptual view)

III. Seismic Evaluation of Cables After Cable Tray Damage

This section presents the tests conducted to obtain the realistic strength of the cables and the evaluation of the cable response that is assumed to occur after damage to the cable trays due to an earthquake. These serve as input information for the fragility assessment of the cables.

III.A. Cable Strength Tests

Strength tests were conducted on the target cables to obtain realistic strength values and the material properties (longitudinal elastic modulus) used in subsequent analyses [3]. It is considered that if the stress experienced by the cable remains within the range corresponding to a strain of 0.2% offset yield strength, the cable will not fracture. Additionally, the effects of reduced cross-sectional area of the core conductor due to cable strain and the reduction in insulation thickness on insulation integrity are deemed to be within acceptable limits, allowing for the maintenance of integrity from both mechanical strength and electrical functionality perspectives. Therefore, in this study, the 0.2% offset yield strength obtained from the stress-strain curve of tensile tests was adopted as the strength of the metal cables. The specifications obtained from the tests are presented in Table 1.

III.B. Cable Tray Damage Modes

To evaluate the seismic resistance of cables, it is necessary to examine the loads applied to the cables following damage to the cable trays due to an earthquake. Consequently, various damage modes of the cable trays were considered to represent the cable conditions after damage. Multiple potential damage states of the cable trays were established, and for each damage state, the trends of loads acting on the cables when the cable trays are damaged were considered in selecting evaluation cases for the damage modes referenced in the fragility assessment [3]. For reference, a conceptual diagram of the structure of the cable tray is shown in Figure 1. Additionally, conceptual diagrams of each damage case are shown in Figure 2.

Case 1: Basic damage condition; a base case considering the state where the cable tray has fallen off.
Case 2: Set as a case due to the observed trend of increased moment and axial force compared to the base case, considering the excess length of the cable.
Case 3: Set as a case where the increased length of the fallen cable tray leads to increased loads compared to the base case.
Case 4: A case focusing on the state where the cable tray has fallen off on both sides and is resting on the cable.
Case 5: A case focusing on the state where the fallen cable tray bends in a V shape, applying concentrated loads to the center of the cable.

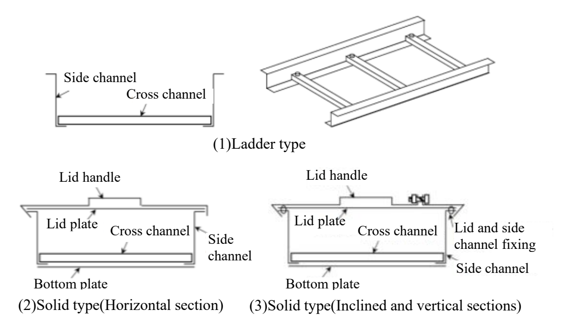


Figure 1: Example of cable tray types and covers[3]

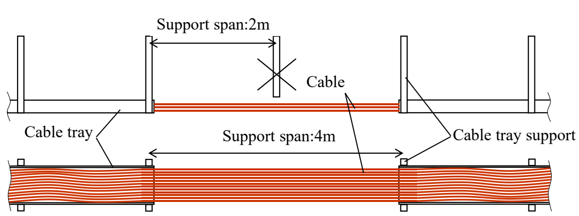


Figure 2(a): Cable tray damage mode: Case 1(base case) [3]

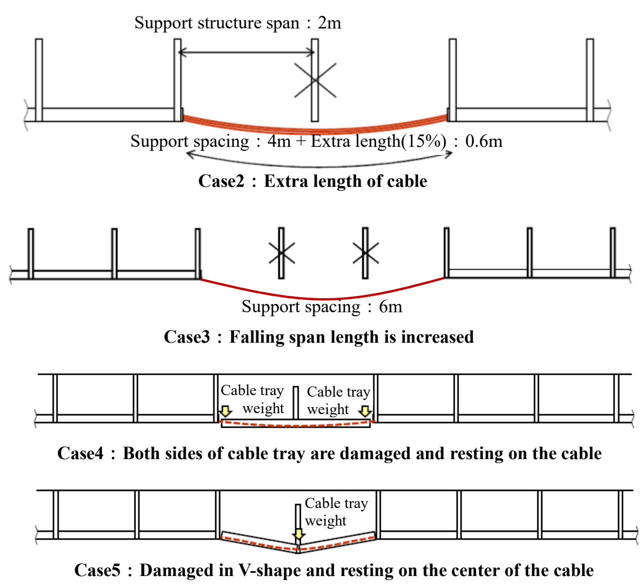


Figure 2(b): Cable tray damage mode : Case 2 through 5[3]

III.C. Response Analysis

Beam models capable of simulating the displacement state of cables during cable tray fall were created, and response analyses of the cables following cable tray damage were conducted [3]. The specifications of the cables used were those obtained from the aforementioned tests (see Table 1), and the seismic acceleration was based on the design floor response acceleration of the representative plant (horizontal: 2.05G, vertical: 0.88G). The results of the maximum values of the responses (von Mises stress) obtained from the analyses for each case shown in the previous section, along with comparisons to the capacity, are presented in Figure 3, and the margins (capacity/von Mises stress maximum value) are shown in Table 2.

III.D. Summary of Seismic Evaluation

It was demonstrated that even under the assumption that the design basis seismic motion acted while the cable tray was damaged and had fallen, cable damage would not occur (the stress generated in the analysis does not exceed the capacity values obtained from the tests). From the perspective of margin, it is generally observed to be approximately 3 to 8 times greater than the design basis seismic motion, with many cases exceeding 10 times, and even in the most severe cases, the margin exceeds 2 [3]. This indicates that even when considering the possibility of cable tray damage, the cables maintain their functionality as electrical raceways and possess sufficient margins against the design basis seismic motion. Furthermore, this analysis includes several conservative assumptions, such as:

- The maximum floor response due to the design basis seismic motion continues after the cable tray has fallen.
- The adoption of 0.2% offset yield strength as the capacity value for maintaining the electrical functionality of the cables.
- The response analysis was conducted using static analysis.

Considering the conservativeness introduced by these assumptions, it is believed that the margin of the cables against the design basis seismic motion is even larger. And realistically, even when assuming cable tray damage, the cables are expected to have several times the strength required to maintain their electrical functionality against the design basis seismic motion.

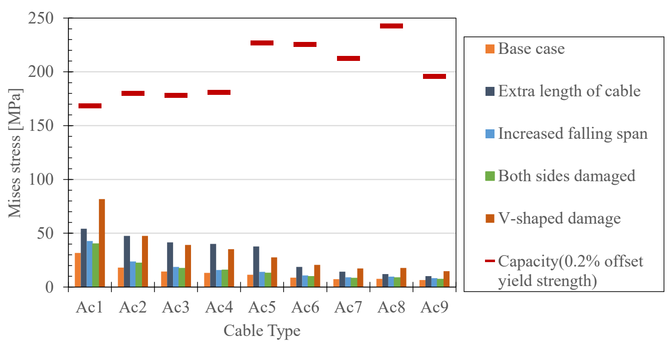


Figure 3: Results of analyses (Plant A): Comparison between stress and capacity [3]

Table 2: Seismic margin of cable (Plant A) [3]

Cable	Seismic margin				
	Base case	Extra length of cable	Increased falling span	Both sides damaged	V-shaped damage
Ac1	5.3	3.1	3.9	4.2	2.1
Ac2	10.0	3.8	7.6	8.1	3.8
Ac3	12.3	4.3	9.6	10.3	4.6
Ac4	13.7	4.5	11.5	11.6	5.1
Ac5	19.8	6.0	16.2	17.6	8.2
Ac6	26.0	12.1	20.9	23.2	10.9
Ac7	29.0	14.9	23.4	26.0	12.3
Ac8	31.7	20.1	25.2	28.5	13.7
Ac9	30.2	19.2	23.9	27.3	13.2

IV. Fragility Assessment of Cables

This section outlines the methodology for conducting a fragility assessment of electrical raceways using the results of the strength tests and cable response analyses that follow cable tray damage discussed in previous sections. Generally, fragility assessments consider both structural damage modes and functional damage modes. In the case of electrical raceways, the focus is on whether the electrical functionality is maintained. Therefore, this assessment will concentrate on functional damage modes, treating the "0.2% offset yield strength" of the cables as the capacity related to functional damage (maintenance of electrical functionality) and the stress experienced by the cables as an indicator.

Next, the uncertainties associated with the realistic capacity distribution and realistic response distribution, which are considered in the calculation of damage probabilities in the fragility assessment focusing on cables, were analyzed. The major uncertainty factors are outlined below.

Uncertainty Factors Related to Strength

· Uncertainty in Material Properties of the Cable Core Wire: Variability in the material properties governing the strength of the cable core wire introduces uncertainty in the cable's capacity. However, since quality control is rigorously implemented for nuclear-grade cables, this variability leads to minimal uncertainty regarding capacity.

· Uncertainty in Cable Manufacturing Precision: Variability in product precision during the cable manufacturing process contributes to uncertainty in the cable's capacity. Nonetheless, due to stringent quality control for nuclear-grade cables, this uncertainty is also minimal.

· Uncertainty in the Strength of Components Other than the Cable Core Wire: The strength of the cable is considered to be predominantly determined by the core; however, contributions to the capacity from components other than the core wire, such as the cable sheath and insulation, and different configurations across cables may introduce uncertainty in the cable's capacity. On the other hand, the contribution of components other than core wire to the cable's capacity is small because the behavior (such as elongation) of the core wire and non-core wire components differs when subjected to loads. Additionally, the influence of the configurations of non-core wire components on capacity is not significant. Therefore, it can be stated that the uncertainty in cable's capacity due to these factors is small.

· Uncertainty in Testing Methods: The selection of test samples, testing methods, and data organization are considered to be factors that contribute to the uncertainty in the realistic capacity obtained from the tests. Given the challenges associated with narrowing down test samples from a variety of cable types and the complexities involved in securing cables during strength tests, it can be stated that this uncertainty is significant.

· Uncertainty in the Limit Capacity: The limit capacity for maintaining cable functionality is set at "0.2% offset yield strength," which is somewhat conservative. However, there is a lack of information regarding the conditions under which cable's functionality may be lost, necessitating the consideration of uncertainty. On the other hand, it is evident that if plastic deformation occurs, leading to a change in the cross-sectional area of the cable, electrical functionality cannot be maintained, indicating that the uncertainty regarding this limit capacity setting is small.

· Uncertainty Regarding Actual Cable Installation Conditions: Variability in conditions such as the type, position, application, and routing of cable trays in actual plants contributes to uncertainty in capacity. The diversity in the types and quantities of cables mounted on cable trays results in significant uncertainty in capacity.

Uncertainty Factors Related to Response

· Uncertainty in Modeling for Analysis: The uncertainties associated with the modeling of cable response analyses are taken into account. The analysis model used in this study is a beam model, which is considered to have more uncertainty compared to a solid model that would replicate the structure in detail.

· Uncertainty in Analysis Methods: When conducting response analyses using the spectral modal method, it is necessary to consider uncertainties due to mode combination.

· Uncertainty in Nonlinear Response: If fragility evaluation methods that assume a linear relationship between input and response, such as the SOV(Separation of Variables) method (also known as the Zion method), are used, the effects of nonlinear responses of buildings and equipment during increased input seismic motions (deviations from linear assumptions) must be considered as uncertainties. (For details on the SOV method, refer to the EPRI Fragility Assessment Guides (e.g., References [4][5]) and the Japan Atomic Energy Society's Seismic PRA Standards.)

· Uncertainty Regarding Cable Tray Damage Modes: The differences in responses due to various damage mode cases of cable trays (e.g., both side damaged, V-shaped damaged, extra length of cable, etc.) should be considered as uncertainties.

· Uncertainty Regarding Cable Types: The differences in responses based on the types of cables mounted on the cable trays should also be considered as uncertainties. Given the diversity of cable types actually used, this uncertainty is significant.

Based on the results of the tests and the analyses, the median values for capacity and response can be obtained, and by quantifying the uncertainties outlined above, the capacity distribution and response distribution can be established to determine the fragility of the cables. When conducting fragility assessments using the SOV method, safety factors corresponding to the analyzed uncertainty factors will be introduced for evaluation. Here, the results of the fragility assessment for the cables of Plant A, one of the representative plants, are provided as an example using the SOV method.

The fragility is evaluated using the following equations:

$$A_m = F \times D_{PGA}, \quad \text{HCLPF} = A_m \times \exp\left(-1.65 \times (\beta_R + \beta_U)\right) \tag{1}$$

where:

A_m: Median fragility, F: Safety factor, D_{PGA}: Peak ground acceleration of the design earthquake
β_R: Total aleatory uncertainty, β_U: Total epistemic uncertainty

The safety factor F is expressed as:

$$F = F_C \times F_R \tag{2}$$

where:

F_C: Capacity factor, F_R: Response factor

The capacity and response factors, along with their uncertainties, are further subdivided for evaluation based on their respective conservatisms and uncertainty factors. In this assessment, the uncertainties related to the damage modes of cable trays and the types of cables were focused on, leading to the introduction of a factor F_{CSS} corresponding to these uncertainties in the response factor. Therefore, the response factor F_R is expressed as follows:

$$F_R = F_{ESS} \times F_D \times F_{EMC} \times F_{EM} \times F_{CSS} \times F_{SR} \tag{3}$$

where:

F_{ESS}: Spectral shape factor accounting for uncertainties in the evaluated floor response,
F_D: Damping factor accounting for uncertainties in response due to damping,
F_{EMC}: Mode combination factor related to uncertainties in combining vibration modes of response,
F_{EM}: Modeling factor related to modeling assumptions for analysis,
F_{CSS}: Factor to account for uncertainties in response due to cable tray damage modes and cable types,
F_{SR}: Building response Factor

This factor F_{CSS} is evaluated based on the variability observed when comprehensively reviewing the response analysis results presented in the previous section. The capacity, material properties, and their variability from the test results, along with the cable response analysis results (with an input seismic motion of 1.23G), were used as inputs for the fragility evaluation. The calculations were based on the largest response values obtained from the cable response analyses, resulting in A_m=10.15G、β_R=0.2, β_U=0.46 and HCLPF=3.24G. Additionally, for the evaluation focusing on the most severe case of V-shaped damage as one cable tray damage mode, the results were A_m=5.21G、β_R=0.23, β_U=0.54 and HCLPF=1.54G. It should be noted that these results are specific to Plant A and may differ in other plants.

In this evaluation, a representative fragility was derived by compiling the response analysis results of various cable tray damage modes and cable types, leading to a significant overall uncertainty. Therefore, if the scope of the evaluation can be narrowed, it is believed that the uncertainties could be reduced, allowing for further improvements in the fragility results. Furthermore, since the SOV method assumes a linear relationship between input and response and does not consider changes in response trend due to nonlinear behavior, this results in a conservative assessment of responses during increased input seismic motions, leading to an overestimation of damage probabilities. A more realistic evaluation could be achieved by constructing fragility curves based on damage probabilities calculated from response analyses conducted at varying levels of input seismic motion.

Additionally, it is important to note that this fragility assessment does not take into account the probabilities of occurrence for each cable tray damage mode. If the occurrence probabilities and weighting in the overall assessment could be established, a more realistic fragility could be obtained, which remains a challenge for future work. Therefore, the fragility assessment conducted using the methods described here yields somewhat conservative results, also taking into account the influences of conservatism in the response analyses discussed in the previous section. However, it is deemed feasible to incorporate this into the operational practices of actual plants as a conservative evaluation at this stage.

V. Fragility of Electrical Raceway

As mentioned in the Introduction, there was a lack of information regarding the integrity of the electrical functionality of cables following cable tray damage due to earthquakes. Consequently, the current evaluation assumes that if the cable trays or their supporting structures are damaged, the cables will invariably lose their functionality as electrical raceways, regardless of their condition. However, with the findings of this study enabling the assessment of cable fragility after cable tray damage, this assumption can be revisited. It can be stated that the cables themselves will not sustain damage unless the cable trays are damaged. In other words, the probability of cable damage can be viewed as a conditional probability based on the damage to the cable trays, and the fragility of the electrical raceway can be expressed as:

$$\begin{aligned}&\text{Probability of loss of funciton of electrical raceway}\\&\quad= (\text{Probability of cable tray damage}) \times (\text{Probability of cable damage}) \qquad (4)\end{aligned}$$

Therefore, by considering the probability of cable damage, the current assumption that cable tray damage equates to electrical raceway damage (loss of functionality) will invariably improve. An illustration of the fragility curve of the electrical raceway when considering the probabilities of damage to both the cable trays and cables is shown in Figure 4.

VI. Integration into Accident Sequence Evaluation

In the current practice of the seismic PRA, as shown in Figure 5, the functional damage of electrical raceway is assumed to directly lead to core damage. Thus, as mentioned earlier, the fragility evaluation assumes that cable tray damage equals the loss of electrical raceway functionality, which may make the structural damage of representative cable trays a dominant factor contributing to core damage. Such evaluation results raise concerns that other significant risk factors may be obscured (relatively underestimated), and it cannot be claimed that appropriate risk information regarding plant safety improvement is obtained. On the other hand, while it may be technically possible to relate the individual fragility of electrical raceways located in various systems and places within the plant to the accident sequence evaluation model (event tree and fault tree), it is practically very challenging for actual plants due to the costs and time required for the evaluation. Therefore, it is not feasible to revise the evaluation from the perspective of accident sequence modeling. However, with the results of this study allowing for the assessment of cable fragility after cable tray damage, it has become possible to realistically consider the probability of functional damage to electrical raceways in accident sequence evaluations. The probability of electrical raceway damage can be incorporated in the fault tree related to electrical raceway functional damage by introducing an AND gate for cable tray damage and cable damage, as shown in Figure 6. As a result, while conservative assumptions regarding the events resulted from the loss of electrical raceway functionality remain, a more realistic evaluation of the occurrence probability of electrical raceway damage can improve the frequency of core damage and provide a more accurate understanding of the overall risk profile of the plant. Furthermore, if it can be generally stated that the probability of electrical raceway damage due to earthquakes is sufficiently low within the defined range of probabilistic seismic hazard, it may also be possible to screen out electrical raceways from seismic PRA.

From the perspective of stress tests, electrical raceways are related to various headings in the event tree. If the fragility of the cable trays (HCLPF) is not large enough, the electrical raceways may become equipment that represents a cliff edge of the plant. Additionally, as electrical raceways are factors that govern numerous headings in the event tree, the information regarding the plant's risk profile that will be obtained as a result of the stress test may become unclear. Similarly to the seismic PRA case, by introducing the fragility of the cables after cable tray damage into the assessment of electrical raceway fragility, it will become possible to evaluate the strength of each heading and cliff edge of the plant more accurately. If it can be demonstrated that the fragility of the electrical raceway is sufficiently high (compared to the general cliff edge acceleration), it is possible to screen out electrical raceways from stress tests and contribute to rationalizing the evaluation.

VII. Conclusion

This study focused on the conservative assumption in seismic PRA that electrical raceways lose functionality due to cable tray damage, and aimed to provide a more realistic assessment by evaluating the fragility of cables by using the results of cable strength tests and response analyses. The evaluation method is based on the widely used SOV method (also known as the Zion method), and a new factor addressing uncertainties related to cable response was developed for the evaluation. Using this method, fragility evaluations of cables were conducted based on the data from cable strength tests and response analyses. The results of the evaluations indicated that by taking into consideration the influence of the remaining conservatism and the probability of cable tray damage, the fragility related to maintaining the functionality of the electrical raceways could be expected to allow for the screening out of the electrical raceways from the seismic PRA. The findings of this study indicate that it has become feasible to apply the evaluation of cable fragility and the corresponding fragility of electrical raceways to the seismic PRA of individual plants. In the future, plans are in place to conduct shaking tests simulating the state of cable tray falls to obtain a more realistic response of the cables. Further details on this will be reported in future papers.

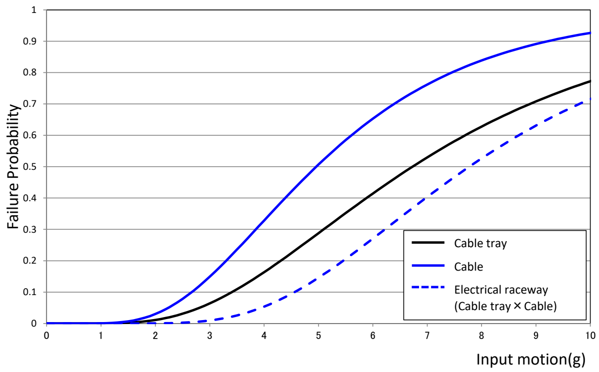


Figure 4: An image of the electrical raceway fragility curve

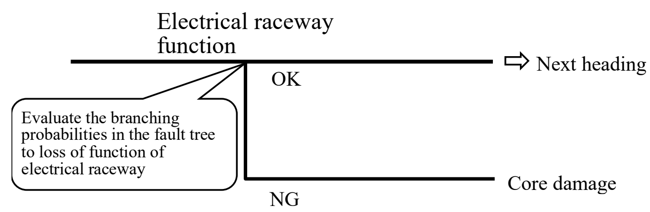


Figure 5: A highly simplified conceptual illustration of the event tree regarding the failure of electrical raceway

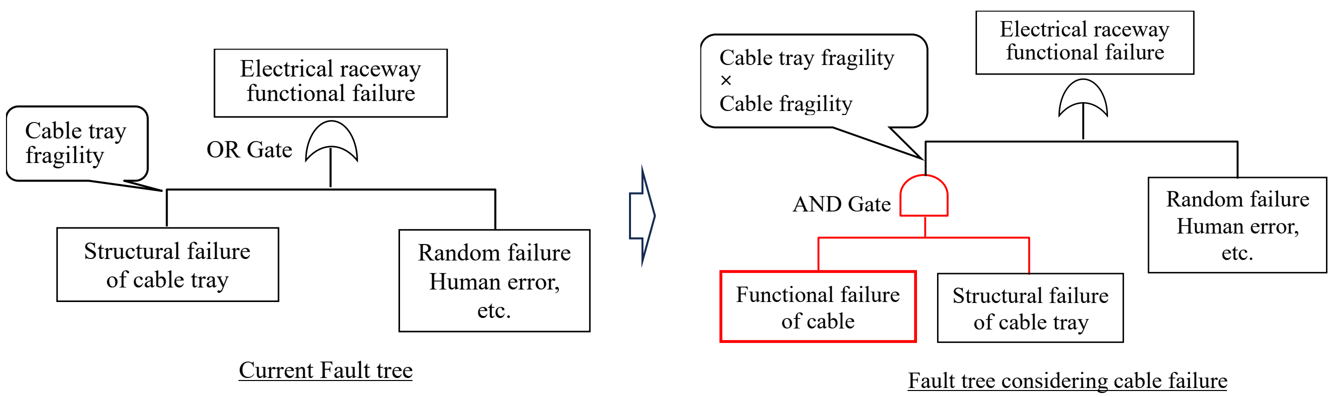


Figure 6: Fault tree related to electrical raceway functional failure

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