IASMiRT

SMiRT 26
50 Anniversary Berlin/Potsdam

Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VII

STUDY FOR SAFETY EVALUATION OF REACTOR BUILDING WITH VERTICAL FAULT DISPLACEMENT

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1. ABSTRACT

Background and Purpose

Since the enforcement of the new regulatory requirements in July 2013, it is required to evaluate the margin for beyond design events including the potential subsidiary fault directly under the building. In the discussion of beyond design for reactor building, safety of whole structure should be secured allowing the partial damage. For example, in terms of safety of the basemat for the potential fault displacement, it is issuing that safety of the structure is secured with whole basemat. In addition, the time transition of the damage probability is of interest considering that the damage probability varies with time in the basemat failure event for potential fault displacement. It is extremely useful for safety evaluation of structure to reveal the damage probability at any time.

Evaluation of load-displacement relationships of the basemat

In this study, we perform finite-element-model analysis for the PWR type reactor building with the vertical fault displacement, focusing on the safety of basemat.

We evaluate load-displacement relationships by several methods including the primitive method based on the accumulation of shear capacity through critical sections, the method based on the energy balance and so on.

Evaluation of damage probability of basemat

We discuss the time transition of the damage probability of basemat by using the load-displacement relationships. In the field of medical statistics, the survival analysis with counting process is used in practice. The survival event has similarities with the basemat failure event for fault displacement because they also deal with the monotonous increase failure event. Thus, we apply the survival analysis to evaluation of the damage probability of the basemat for the potential fault displacement.

Conclusions

We suggest the evaluation method for the safety of the basemat for the potential fault displacement, as part of establishing the evaluation method for beyond design events. We apply the survival analysis to evaluation of the time-dependent damage probability of the basemat. Focusing on not the partial damage but the whole damage, it is possible to figure out the realistic capacity of basemat. In addition, this evaluation method would be applicable to other beyond design events.

2. INTRODUCTION

Since Fukushima Daiichi nuclear disaster in March 2011, a variety of margin evaluations is required for beyond design events including the potential subsidiary fault directly under the building.

In general, a elasto-plastic finite-element-model analysis method considering upper structure-basemat-soil interaction is used for a margin evaluation of basemat, which enables us to obtain load-displacement relationships of whole building structure and failure modes of the building in detail. Fault displacement is simulated by the relative gap in the vertical direction at the bottom of the soil FE model. However, load bearing curves calculated by this method are affected by the plasticization of surrounding soil and upper building so that the capacities of basemat cannot be evaluated directly (Evaluation Method 1). In addition, a method that the shear forces of elements on a separately assumed failure line are summed to give the capacities of basemat can be considered, although in which case the failure line should be set very carefully with engineering judgement (Evaluation Method 2).

Although the damage probability evaluation is required in the discussion on safety of a structure for beyond design event, the evaluation method has not established yet. The subject of interest for the basemat damage due to fault displacement would be the time-dependent damage probability of the basemat. To identify damage probability for any level of fault displacement would be very effective index for safety evaluation of a structure.

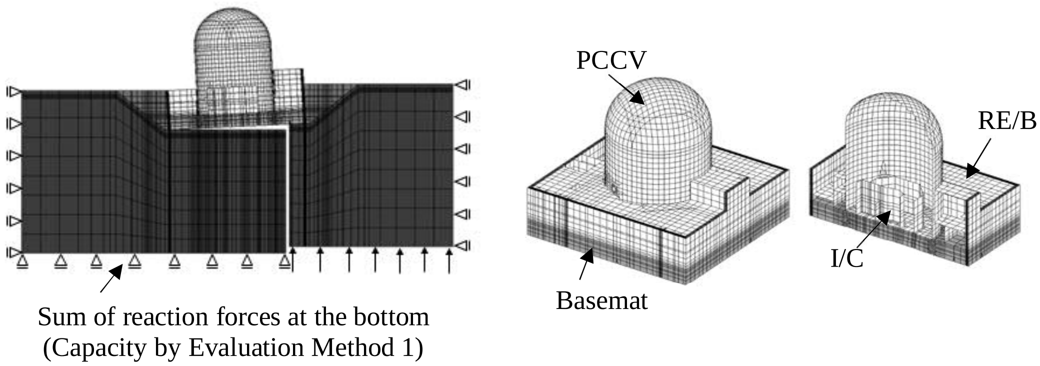
In this study, we propose evaluation method of capacity of basemat concerning increment of energy of basemat. Then, its validity is discussed by applying the evaluation method to elasto-plastic finite-element-model analysis results with vertical fault displacement.

In addition, time transition of damage probability of a reactor building basemat which is subjected to vertical fault displacement is discussed using evaluation results mentioned above. In the field of medical statistics, survival analysis with counting process is used in practice. The survival event has similarities with the event in this study, i.e. dealing with the event showing monotonous increase. By applying this survival analysis method, the evaluation of time-dependent damage probability of a reactor building subjected to fault displacement is performed.

3. SUBJECT OF STUDY

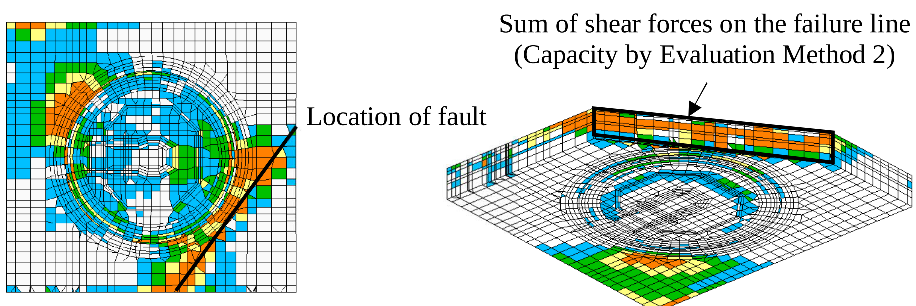
Summary of analysis model of the subject to be studied in this study is shown in Figure 1. The analysis m0odel focuses on the basemat, extracting the area of 80 m in NS direction by 75 m in EW direction, of PWR type reactor building. The upper buildings (PCCV, RE/B and I/C), the basemat and the surrounding soil (backfilling soil and supporting ground) are modelled in solid elements or shell elements, and contact elements are inserted between the structure and the surrounding soil. In addition, material non-linearities are considered of concrete, reinforcement bar and the backfilling soil.

Imposed displacement is input at the bottom part of supporting soil to assume that southern part of fault will be upheaved at the tilt angle of 90 degrees. Versatile elasto-plastic finite-element-model analysis program DIANA is used as an analysis application program. Failure condition of a basemat for a fault displacement of 30 cm is shown in Figure 2. The capacity of basemat showed maximum value after shear failure line are developed and formed along a fault line, and diagonal failure is occurred in basemat concrete at 45 degrees within slab thickness.



(a) Input method of fault displacement (b) Upper structure and basemat

Figure 1. Elasto-plastic finite element analysis model



(a) Top of basemat (b) Failure line section

Figure 2. Shear failure line of basemat

4. EVALUATION METHOD OF CAPACITY OF STRUCTURE BASEMAT

Summary of each evaluation methods of capacity to be compared is shown below.

- Evaluation Method 1: Reaction force acting on bottom of model
  The sum of the reaction forces acting on the fixed points of soil model is considered the capacity.
- Evaluation Method 2: Shear force acting on shear failure line
  The sum of the out-of-plane shear forces of elements on the assumed shear failure line is considered the capacity.
- Proposed Evaluation Method:
  Load at capacity evaluation point is set to be P, and imposed displacement (which is vertical fault displacement here) $\tilde{u}$. Then, under the quasi-static condition, increment of work $Pd\tilde{u}$ is equal to the increment of inner energy dE_{inner} and potential energy $dE_{potential}$.

$$Pd\tilde{u} = dE_{inner} + dE_{potential} \tag{1}$$

Therefore, load at evaluation point of capacity can be expressed as below.

$$P = \frac{dE_{inner}}{d\tilde{u}} + \frac{dE_{potential}}{d\tilde{u}} \quad (2)$$

Each increment of energy can be expressed as follows, respectively.

$$dE_{inner} = \int_V \left(\sigma_{ij} d\varepsilon_{ij}^p\right) dv \quad (3)$$

$$dE_{potential} = \int_V (\rho g du) dv \quad (4)$$

Where:

σ_{ij}: stress tensor,
ε_{ij}^p: plastic strain tensor,
v: element volume,
V: basemat volume,
ρ: density,
u: element displacement and
g: gravity acceleration.

Although the inner energy is a sum of elastic strain energy and plastic energy, only plastic strain energy is used considering two factors: it is suitable that the capacity evaluation is performed with plastic strain energy which is monotonous increase function as a function of time; impact of elastic strain energy is slight enough to be neglected after the damage is developed sufficiently.

5. EVALUATION RESULT OF STRUCTURE BASEMAT CAPACITY

The relationship between inner energy and load-displacement obtained by the proposed evaluation method is shown in Figure3. This figure indicates that the inner energy E_{inner} shows almost linear increase as the fault displacement $\tilde{u}$ developed and that its differential value reaches a constant value, therefore, the constant value is assumed to be the ultimate load P of the basemat for this event.

Then, load-displacement relationship by each evaluation method is shown in Figure 4. From the figure, the ultimate load evaluated by the proposed method seems to be almost the same as the evaluation results by the sum of the out-of-plane shear force of basemat (Evaluation Method 2). In general, it is necessary to choose a method with engineering judgement after confirming the failure mode when the capacity of a structure is evaluated. However, the judgement becomes difficult as the system becomes complicated due to the interaction with attached object such as exterior walls and surrounding soil. It indicates that the evaluation by this proposed method of accurate damage load may be possible without making engineering judgement on the failure mode.

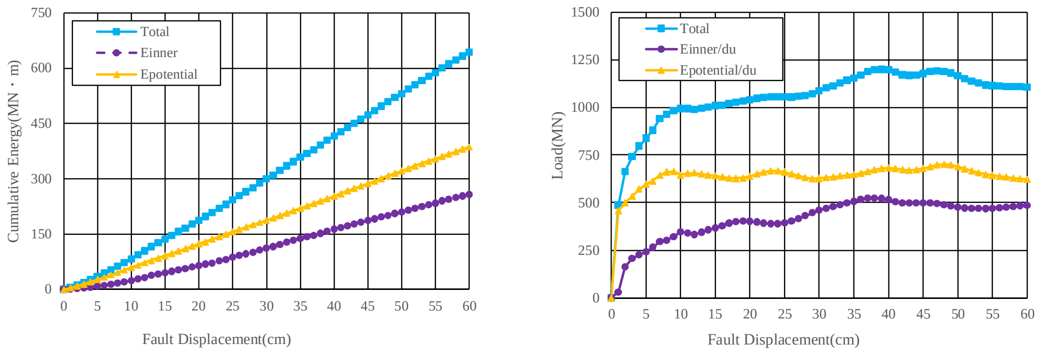


Figure 3. Inner Energy and Load-Displacement Relationship by Proposed Evaluation Method

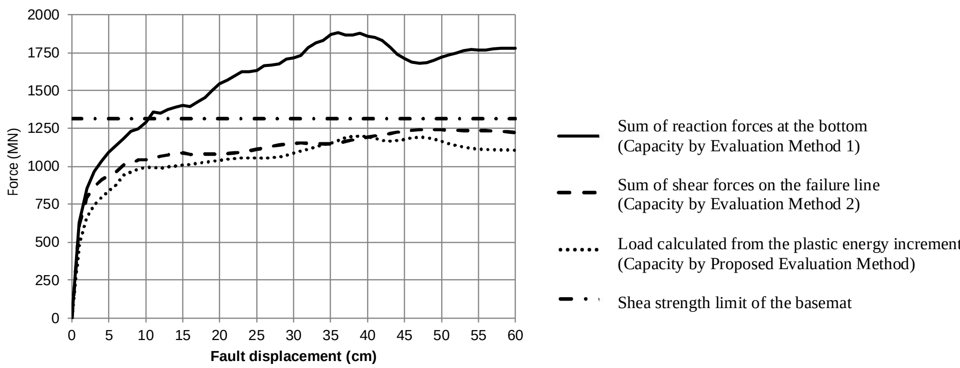


Figure 4. Comparison of Load-Displacement Relationship by Each Evaluation Method

6. FRAGILITY EVALUATION METHOD

(i) counting process

Stochastic process model can be divided in two large parts, namely distribution process and counting process. Distribution process is suitable for handling phenomena which vary the value along a time sequence and is employed for the evaluation of stock value fluctuations and so on in financial field. On the other hand, the damage is irreversible and shows monotonous increasing tendency. Counting process $N(t)$ is expressed as the sum of a predictable monotonous increasing trend $\Lambda(t)$ and a noise $M(t)$ which satisfies the orthogonality.

$$N(t) = \Lambda(t) \ + M(t) \tag{5}$$

$N(t)$ corresponds to the numbers of something such as damaged members and FEM elements.

(ii) Survival Analysis

Main application example of counting process includes survival analysis in medical statistics field. The purpose of survival analysis is to assume personal survival curve $S(t)$, i.e. probability of survival for each time sequence, and baseline hazard $\alpha(t)$, i.e. probability of death for each time sequence, from limited observation data.

The estimated survival curve and the estimated value of accumulated hazard can be assumed by non-parametric models such as Kaplan-Meier Estimator and Nelson-Aalen Estimator.

Nelson-Aalen Estimator

$$A(t) = \sum_{t_i \leq t} \frac{dN(t_i)}{Y(t_i)} \approx \int_0^t \alpha(s)\, ds \quad (6)$$

Kaplan-Meier Estimator

$$S(t) = \prod_{t_i \leq t} \left(1 - \frac{dN(t_i)}{Y(t_i)}\right) \approx \exp\left(-\int_0^t \alpha(s)\, ds\right) \quad (7)$$

Where:
$Y(t_i)$: Number of survivors (risk set) at time t_i,
$dN(t_i)$: Number of deaths at time t_i.

(iii) Fragility Evaluation Formula

By modeling in counting process, the capacity curve, the damage probability of observation unit (individual element), and the damage probability of whole system can be obtained.

Capacity curve $\Lambda(t)$ corresponds to the expectation of the number of dead individuals $E[N(t_k)]$, which can be obtained with standard deviation $\sigma(t)$.

$$\Lambda(t) = E[N(t_k)] = n\big(1 - S(t)\big) \quad (8)$$

$$\sigma(t) = \sqrt{\Lambda(t)} \quad (9)$$

In the formula above, n is the number of individuals, which corresponds to the number of sensors observing damages for a structure, and $\sigma(t)$ is the variation of capacity curve in the loading direction.

In addition, damage probability of observation unit (individual element) is given as a cofunction of a survival curve.

$$P_I(t) = 1 - S(t) \quad (10)$$

The damage probability of whole system is given using a survival curve as follows:

$$P(t) = exp\left\{-\int_t^{\infty} d\Lambda(s)\right\} = exp\big(-n \cdot S(t)\big) \quad (11)$$

The right side of Equation (11) can be also expressed as follows:

$$P(t) = \left\{exp\big(-S(t)\big)\right\}^n \quad (12)$$

7. FRAGILITY EVALUATION USING FEM ANALYSIS RESULTS

(i) Setting of Failure Mode of Basemat

A calculation of fragility curve is performed using proposed method for elasto-plastic FEM analysis results of basemat. The analysis model is shown in Figure 5. The basemat is composed of solid elements, and the failure of the basemat is considered when all solid elements in the region, shown in the red frame in Figure 5, along fault line are failuerd. It is considered that the damage develops in the direction at an angle of 45 degrees from the fault line. The criterion of failure is the shear strain corresponding to the secondary breakpoint specified in JEAG.

(ii) Evaluation of Capacity Curve

The comparison of the capacity curve (Equation (8)) calculated in the counting process and the capacity curve calculated by elasto-plastic FEM analysis is shown in Figure 6. The maximum value of counting process is scaled at the maximum load. The tendencies of both curves are in good agreement with each other, and it is indicated that the capacity curve can be obtained by the counting process modeled under the natural condition without arbitrariness.

(iii) Evaluation of Fragility

Damage probability of individual elements and whole system (n=10, 50, 100 and 200) is plotted in Figure 7. From the figure, the fragility evaluated with the whole system is more redundant than the one with individual elements, and the tendency becomes more remarkable as the number of sensors increases.

The damage probability of whole system is in extreme value distribution, and using Equation (11) and Equation (7) it seems to follow the Gumbel distribution expressed below:

$$P(t) = exp\ (-n\ exp\ (-\int_0^t \alpha(s)ds)\ ) \tag{13}$$

$\alpha(t)$ in the equation above is the baseline hazard whose accumulated value is identified from Equation (10) as shown in Figure 8. The hazard seems to show a mild non-linearity. Gumbel distribution (n=10, 50, 100 and 200) using $\alpha(t)$ by bi-linear approximation is shown in Figure 7 in solid line with the same color. The Gumbel distribution was in good agreement with the calculated damage probabilities. In addition, the Gumbel distribution using the baseline hazard α which is identified as a constant by the performance of a regression analysis is shown in the same figure in dashed lines. The impact of non-linearity of α decreases as n increases, which can be assumed from Equation (12), in other words, the distribution approaches asymptotically to the curve with a constant α.

With this evaluation method it tends to show redundancy as increases, which is explainable that the final reach time with larger n is shifted to the right side as shown in Figure 9 in which counting processes having the same trend but different n are compared.

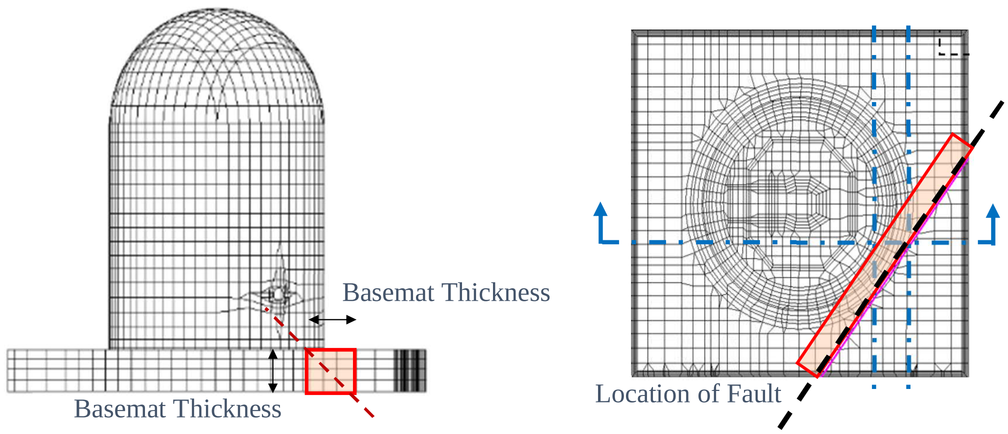


Figure 5. FE Model of Structure and Setting of Failure Mode

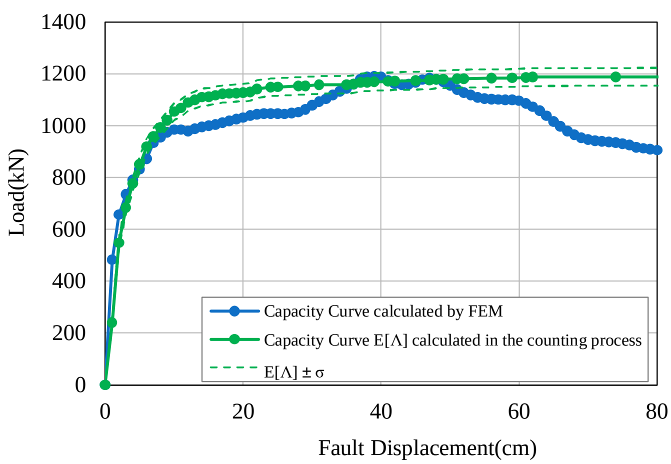


Figure 6. Capacity Curve

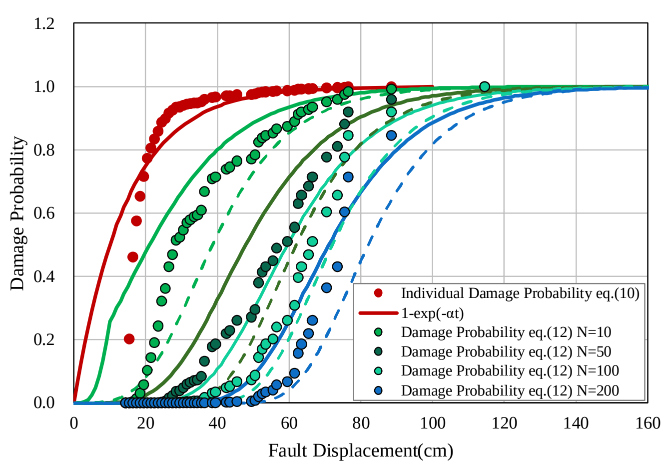


Figure 7. Fragility Curve

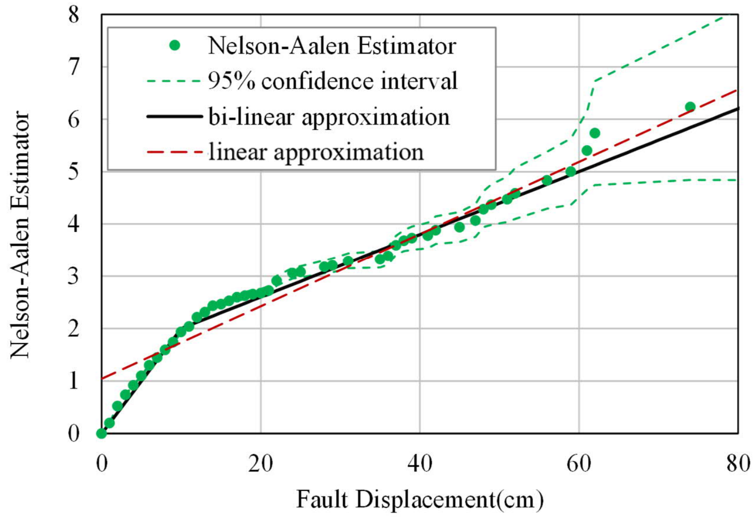


Figure 8. Nelson-Aalen Estimates

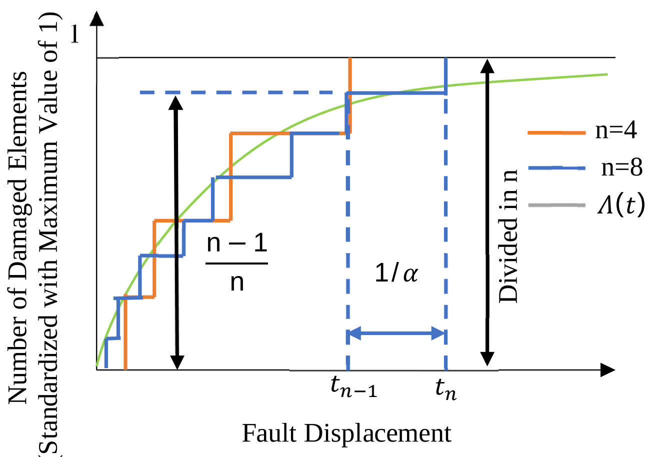


Figure 9. Relationship Between n and Redundancy of System

8. CONCLUSION

In this paper, an evaluation method of basemat capacity was proposed focusing on the increase of energy. The validity of the proposed method was confirmed by applying the method to the test calculation results using elasto-plastic FEM analysis.

The proposal of the evaluation method of fragility in counting process is shown along with its test calculation result. Using this proposed method, the redundancy of a system can be evaluated from general survival analysis results.

A simple model was employed in this paper however the method may be applied to counting processes (e.g., Cox model) which can express more complicated phenomena in the future.

9. REFERENCES

S. Yoshida (2020). *Research for Risk Analysis of Nuclear Power Plant for Faults Displacement*, Journal of Japan Association for Earthquake Engineering, Vol20-3, p. 84-95

On-site Fault Assessment Method Review Committee Japan Nuclear Safety Institute (2013). *Assessment Methods for Nuclear Power Plant against Fault Displacement*

Y. Nishiyama (2011). *Statistical analysis with martingale theory*, Kindaikagakusha

University of Oslo (2016). *Lectures in STK4080 autumn*

The Japan Electric Association (2015). *Japan Electric Association Code*