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IDENTIFICATION OF THE REACTOR BUILDING DAMAGE MODE FOR SEISMIC FRAGILITY ASSESSMENT USING A THREE-DIMENSIONAL FINITE ELEMENT MODEL

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ABSTRACT

In Japan, the new regulatory requirements have strengthened the safety evaluation of external events, such as earthquakes, and the safety improvement assessment stipulated by the Japan Nuclear Regulation Authority requires the implementation of a probabilistic risk assessment (PRA). To implement a seismic PRA, the realistic evaluation of the seismic response and fragility assessment of a reactor building and equipment is essential. To meet these requirements, we carried out study on the improvement of the seismic response analysis method using a three-dimensional (3D) finite element model of reactor buildings. As a part of the estimation of the damage state of a reactor building subjected to large seismic motions, static pushover analyses using multiple analysis codes were performed. The progression of the local damage mode and the ultimate strength were identified by considering the 3D behavior of the reactor building.

INTRODUCTION

After the 2011 Tohoku Earthquake and the TEPCO Fukushima Daiichi accident, the new regulatory requirements for the evaluation of external events such as earthquakes have been strengthened, and the Japan Nuclear Regulation Authority required a probabilistic risk assessment (PRA) including seismic fragility assessment. A Standard for Procedure of Seismic Probabilistic Risk Assessment for Nuclear Power Plants is published by the Atomic Energy Society of Japan [AESJ (2015)]. To implement a seismic fragility assessment, analyses of a reactor building and equipment subjected to extremely large seismic loads are required. In this study, a three-dimensional finite element (3D FE) model of important reactor building and equipment was developed [Nishida et al. (2021), Choi et al. (2022)]. However, it is difficult to confirm the validity of the damage state of the entire reactor building by experiments. Therefore, as a part of study on the estimation of the damage state of a reactor building subjected to extremely large seismic loads, static pushover analyses with multiple analysis codes were performed using the 3D FE model of a reactor building. The progression of the local damage mode and the ultimate strength were evaluated considering the 3D behavior of the reactor building.

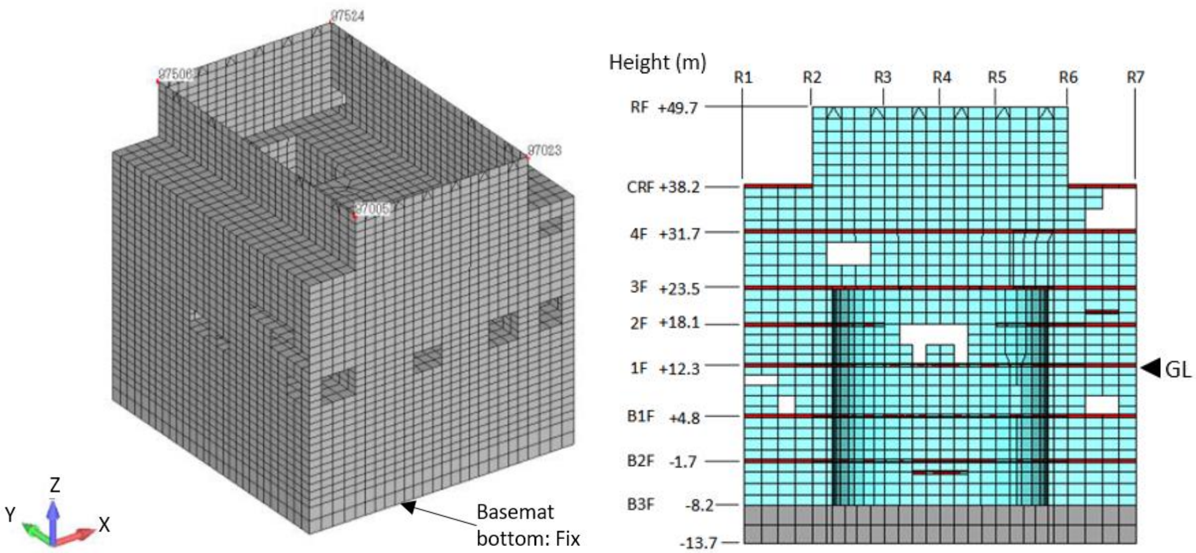
We aimed to improve the fragility assessment method of nuclear facilities and equipment for a realistic seismic PRA. Conventionally, the sway-rocking lumped mass model (SR model) was used. However, it employed rigid-floor assumption and overlooked multiple-direction input and the coupling of 3D responses. To improve the fragility assessment method considering the 3D behavior of a reactor building subject to the ground motion larger than the design seismic motion, the 3D behavior of the reactor building must be taken into consideration. In particular, it is necessary to evaluate the fragility of the important parts that are related to the safety assurance function.

In this paper, to develop a fragility assessment method for reactor buildings that are subject to seismic motion, static pushover analyses using a 3D FE model of a reactor building were conducted using two different analysis codes. Based on the results, we examined the applicability of building damage mode identification in fragility assessment.

ANALYSIS CONDITIONS

Analysis Model

We selected the reactor building of Unit 7 of the Kashiwazaki Kariwa Nuclear Power Station of TEPCO analyzed in the project "KARISMA benchmark exercise" by the IAEA as a model plant for analysis. Publicly accessible data provided in the KARISMA benchmark report were used as the analysis specifications [IAEA (2013)]. The 3D FE model of the reactor building with the surrounding ground was constructed based on the "standard guideline for the seismic response analysis method using 3D finite element model of reactor buildings" developed by the Japan Atomic Energy Agency [Choi et. al. (2022)]. Figure 1 presents the 3D FE model of the reactor building. This model consisted of solid elements for the base mat, shell elements for the walls and floors, and beam elements for the beams and columns.



(a) Reactor building and boundary conditions (b) Section of the reactor building

Figure 1. 3D FE model

Material Properties

Table 1 shows the material properties of the reactor building.

Table 1: Material properties for the reactor building

	Young's modulus (N/mm^2)	Poisson's ratio	Weight density (t/m^3)	Damping ratio
Concrete	31 300	0.2	2.45	0.05
Steel	205 000	0.3	7.80	0.02

To set the nonlinear properties of the RC for the shell elements of the earthquake-resistant wall and auxiliary wall in the 3D FE model, we used two types of analysis codes, FINAS/STAR [ITOCHU (2017)] and FINAL. Table 2, Figures 2 and 3 show the concrete models, constitutive law of concrete and the setting of the reinforcing rebar layer for FINAS/STAR and FINAL, respectively.

Table 2: Concrete model in the two codes

	FINAS/STAR	FINAL
Tension side	Maekawa model [1]	Model of Izumo et al.
Compression side	Maekawa model [1]	Modified Ahmad model [2]
Shear transfer characteristics after cracking	Maekawa model [1]	Al-Mahaidi model
Crack model	Multidirectional fixed and distributed crack model	Multidirectional fixed and distributed crack model
Crack shaft	4 directions	3 shaft (6 directions)

References: [1] Maekawa et al. (1999), [2] Naganuma et al. (1995)

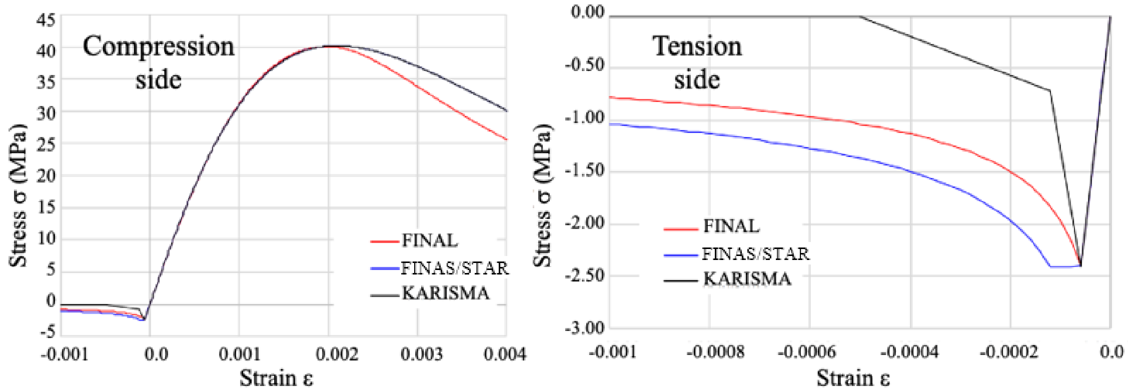


Figure 2. Constitutive law of concrete

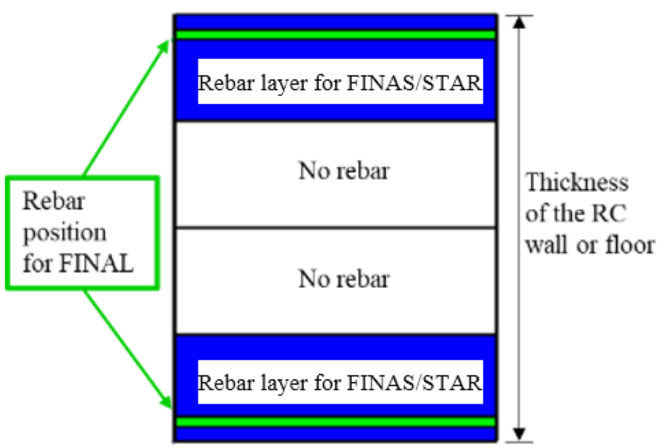


Figure 3. Setting of the reinforcing steel rebar layer

Boundary Conditions

The nodes on the bottom of the base mat were fixed.

Loading Method Based on Linear Dynamic Response Analysis

To determine the load level of the static pushover analysis, a seismic response analysis of linear materials using a design basis ground motion was conducted. Here the design basis ground motion had a maximum horizontal acceleration of 600 cm/s^2. The response acceleration obtained from the analysis result was converted into a nodal force and applied as a nodal load during pushover analysis. The loading direction was only the NS direction (+x direction). As shown in Figure 4, the average response accelerations at the nodes of the outer wall corners were calculated. They were almost the same for both analysis codes. Then, nodal forces were calculated by multiplying the seismic intensity at each height by the weight.

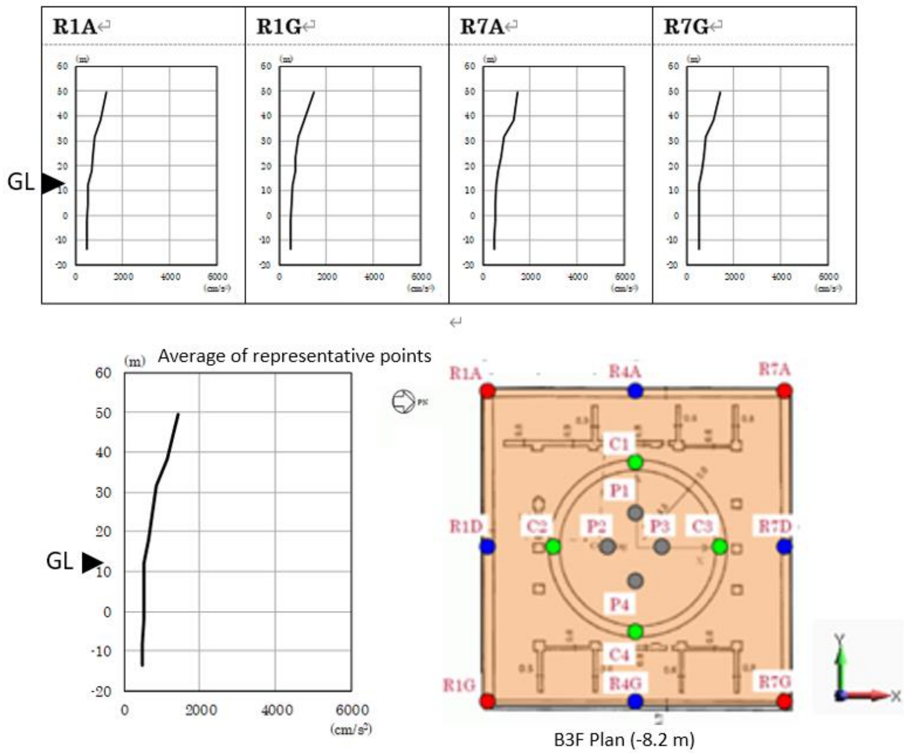


Figure 4. Maximum response acceleration in the x direction at the outer wall corner

Conditions of Numerical Analysis

- Analysis method: Static pushover analysis
- Nonlinear analysis method: Tangent stiffness method
- Convergence calculation: None (Residual force was carried over to the next step)
- Step number: 5,000 steps (calculated up to 10 times the load factor)

ANALYTICAL RESULTS

Load–displacement Relationship

Figure 5 shows the displacement output position. Here, the displacement on the horizontal axis is the average displacements at the four outer wall corners of the crane floor illustrated as red dots shown in Figure 5. Figure 6 shows the load–displacement relationship of pushover analysis by FINAS/STAR and FINAL. According to the load–displacement relationship, the difference between the two analysis codes can be seen from the load scale exceeding 1 due to nonlinearity, and the result of FINAL is slightly larger than the result of FINAS/STAR up to load scale 4. However, the effect of different analysis codes on the results is small. Moreover, nonlinearization starts when the acceleration level is about load scale 4, corresponding to 2400 Gal. When the load scale exceeds 4, the displacement becomes greatly larger because of the difference in the nonlinear material constitutive law and the setting of the reinforcing steel rebar layer of the two codes, resulting in a difference of approximately 10 % in the ultimate strength (ultimate load) due to the difference in the RC constitutive law of the two analysis codes, as shown in Table 2, Figures 2 and 3.

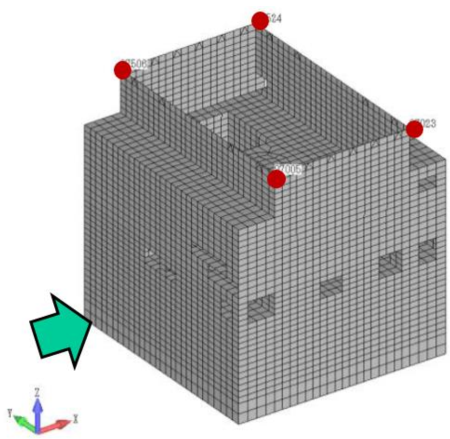


Figure 5. Displacement output position

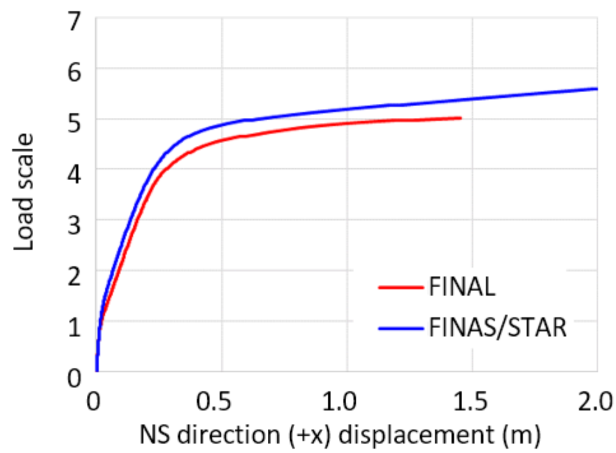
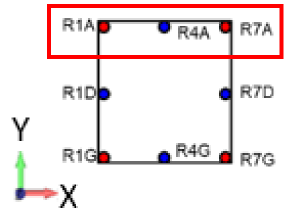


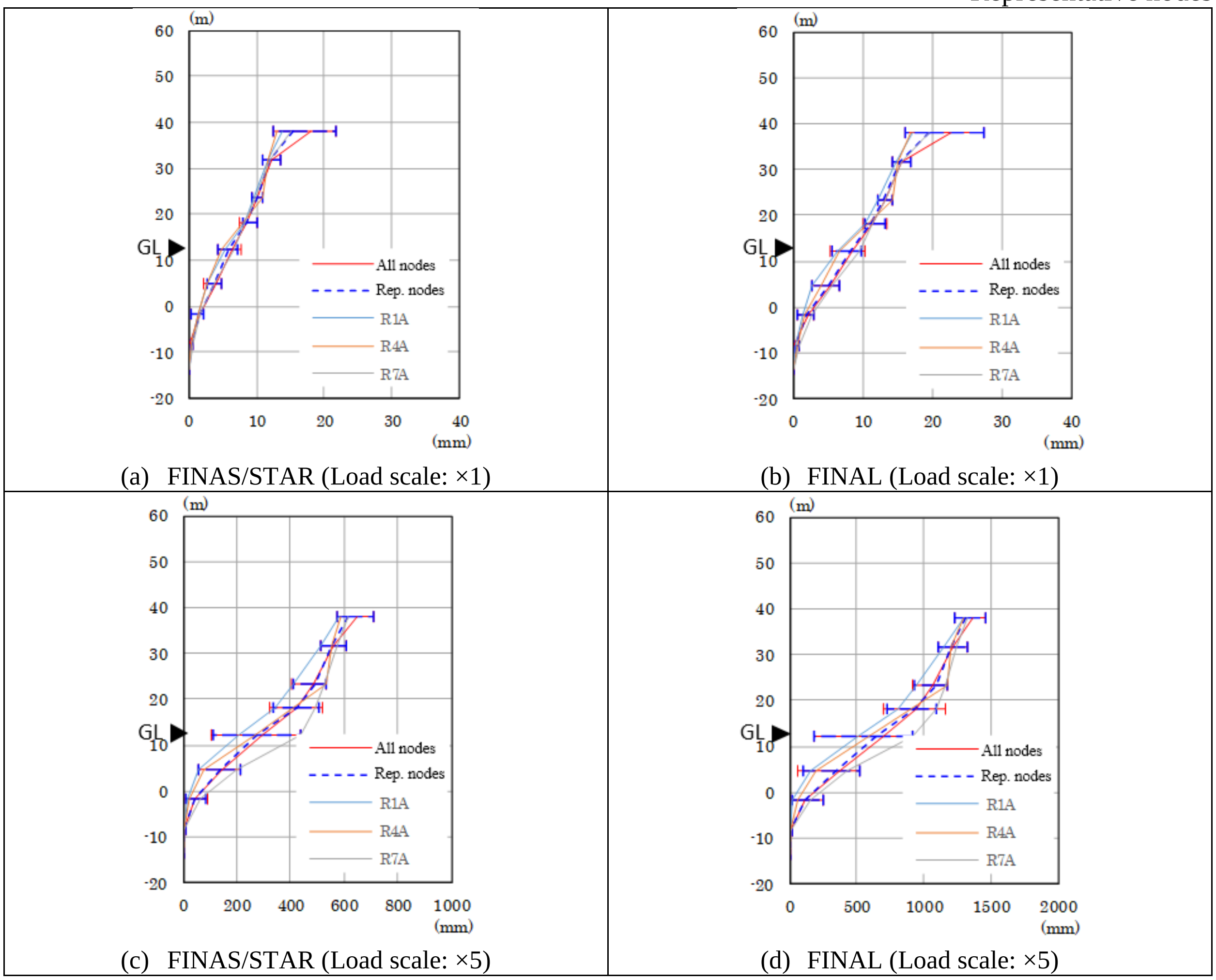
Figure 6. Load–displacement relationship

Maximum Response Displacements

Figure 7 shows the distributions of the maximum response displacement along the building height with load scales 1 and 5 by FINAS/STAR and FINAL. Since the displacements were similar for other line walls, those for the RA line wall are shown. In addition, to estimate the damage mode of the building, we focused on the deformation angle (top floor displacement/building height) of the entire building. In the displacement of load scale 1, the deformation angle of the entire building was about 1/2500, which is a level where the walls are slightly cracked. A slight difference existed between the two analysis codes, and the deformation angle obtained by FINAS/STAR was about 20% smaller than that obtained by FINAL. Moreover, when the load scale was 5, the deformation angle of the entire building was about 1/100, which is the building collapse level, and the displacement of FINAL was about 2 times larger than that of FINAS/STAR, caused by the difference in the strongly nonlinear region of the RC constitutive law used for the two analysis codes. Furthermore, response displacements varied greatly, depending on the location (R1A, R4A, and R7A) [e.g., 1F (+12 m)]. Although there was a large difference in the analysis results by the two analysis codes, the overall trends were similar, it was expected that the damage on the 1st floor will be large. In addition, these areas may experience local deformation, it is necessary to use a 3D FE model when examining the effect of local deformation on critical safety facilities.



Representative nodes



(a) FINAS/STAR (Load scale: ×1)

(b) FINAL (Load scale: ×1)

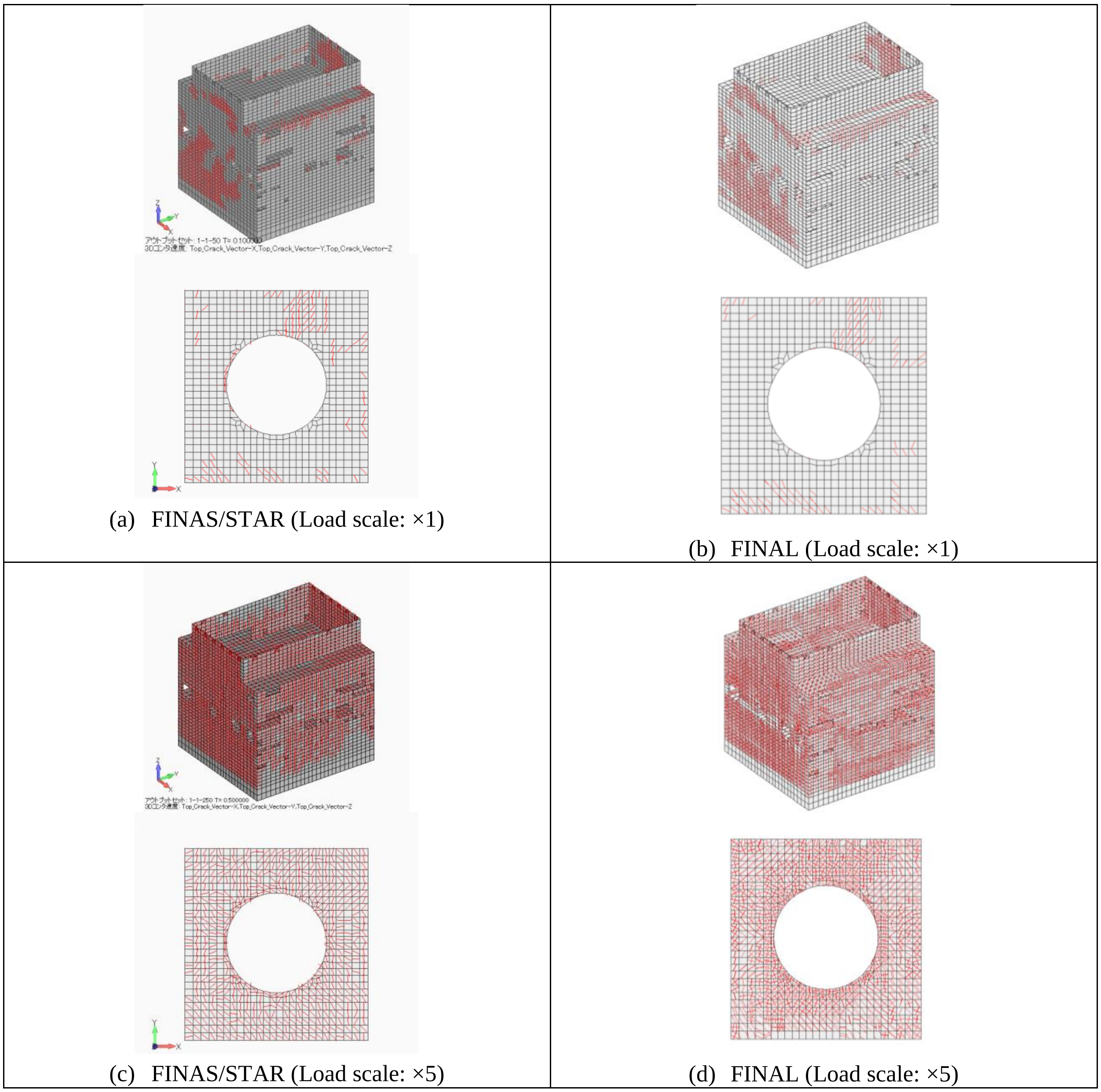
(c) FINAS/STAR (Load scale: ×5)

(d) FINAL (Load scale: ×5)

Figure 7. Distribution of maximum response displacements (X direction, RA line wall)

Crack Distribution

Figure 8 shows the crack distribution at load scales 1 and 5. At load scale 1, cracks occur at almost the same positions in FINAS/STAR and FINAL. At load scale 5, the deformation angle of the entire building was about 1/100, indicating that almost all walls are cracked. Focusing on the locations of crack occurrence, we found that the details of each crack region are slightly different. For example, using load scale 5 in FINAS/STAR, we obtained that the Y (−) surface (east side) is completely cracked, while in FINAL, the wall on the first floor remains healthy. This is because of the difference in the strongly nonlinear region of the RC constitutive law used by the two analysis codes. Therefore, variations due to the differences in the RC constitutive law must be examined.



(a) FINAS/STAR (Load scale: ×1)

(b) FINAL (Load scale: ×1)

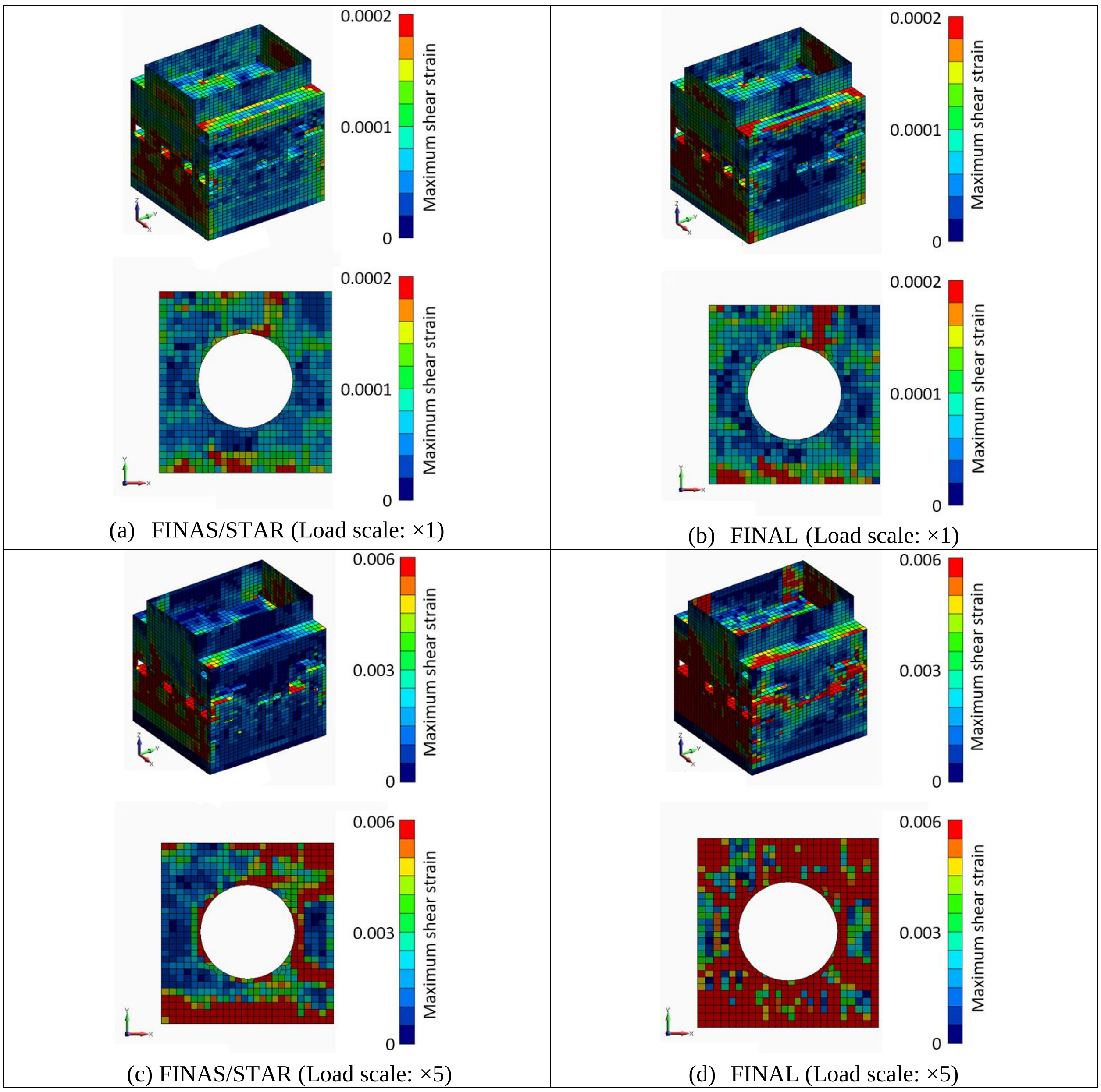
(c) FINAS/STAR (Load scale: ×5)

(d) FINAL (Load scale: ×5)

Figure 8. Crack distribution (Above: bird's eye view, down: 1F plan view)

Maximum Shear Strain Distribution

Figure 9 shows the maximum shear strain distribution at load scales 1 and 5. It was confirmed that the maximum shear strain was about 200 μ at load scale 1. Overall, the FINAL result was larger than the FINAS/STAR result. In addition, at load scale 5, the deformation angle of the entire building was about 1/100, verifying that the results of FINAL exceeded the shear strain of 0.005 (5000 μ) in a wider region than the FINAS/STAR result. This is due to the difference in the strongly nonlinear region of the RC constitutive law used for the two analysis codes. Therefore, it will be necessary to examine the variation due to the difference in the RC constitutive law. In addition, large strain was confirmed on the floor near the outer wall and the wall around the opening. The maximum strain distribution, which cannot be evaluated by the conventional SR model, can be evaluated using the 3D FE model, leading to a more realistic fragility assessment.



(a) FINAS/STAR (Load scale: ×1)

(b) FINAL (Load scale: ×1)

(c) FINAS/STAR (Load scale: ×5)

(d) FINAL (Load scale: ×5)

Figure 9. Maximum shear strain distribution (Above: bird's eye view, down: 1F plan view)

CONCLUSIONS

In this study, in order to contribute to the fragility assessment, as a part of the estimation of the damage state of a reactor building subjected to extremely large seismic loads, static pushover analyses using two analysis codes were performed using the 3D FE model of the reactor building. The progression of the local damage mode and the ultimate strength were assessed by considering the 3D behavior of the reactor building. We obtained the following results:

- According to the maximum displacement distribution, in load scale 1, the deformation angle of the entire building was about 1/2500, and the results from the two analysis codes corresponded well. However, when the load scale exceeded 5, the deformation angle of the entire building was about 1/100, which is the building collapse level, and the displacement of FINAL was about 2 times larger than that of FINAS/STAR. It may be caused by the difference in the strongly nonlinear region of the RC constitutive law used for the two analysis codes. Although there was a large difference in the analysis results by the two analysis codes, the overall trends were similar, it was expected that the damage on the 1st floor will be large. Moreover, the damaged parts of the building were estimated from the crack distribution and the maximum shear strain distribution.
- To improve the accuracy of the strongly nonlinear region, problems occur, such as the difference in the RC constitutive law and the improvement in the nonlinear analysis accuracy in the static pushover analysis. However, we confirmed that the deformation angle of the entire building can be analyzed up to about 1/100 and that it was possible to make progress toward a more realistic fragility assessment, which would otherwise require large-input response analysis.
- The large shear strain was confirmed on the floor near the outer wall and the wall around the opening. These results confirmed that it is possible to evaluate the local response (crack distribution, maximum strain distribution, etc.) of the important equipment location in detail using the 3D FE model, which cannot be evaluated by the SR model. Specifically, by extracting local parts that are important for safety and performing a fragility assessment using the results of the 3D FE analysis of the important parts, a more realistic evaluation can be obtained.

In the future, to contribute to the improvement of the seismic response analysis method using the 3D FE model for a reactor building, we will verify the validity of the seismic response analysis method by utilizing the data of previous experiments.

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