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SYUDY ON APPLICATION OF NON-LINEAR ANALYSIS TO OUT-OF-PLANE STRESS OF FOUNDATION SLAB USING SOLID MODEL

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ABSTRACT

At some huge earthquake, the foundation slab may be generated large local stress by large deformation in the out-of-plane direction with uplifts. But, for the out-of-plane shear force, there are few evaluation methods applied in practice that adopt non-linear analysis considering the areal development of plasticization area.

Therefore, we carried out the out-of-plane stress analysis with non-linear model using shell elements and solid elements, and examined in detail about the spread of the out-of-plane stress in the foundation slab and its effect.

1. INTRODUCTION

In a seismic evaluation of the foundation slab for a M9 class earthquake, there is a possibility that a large stress will be generated locally due to the large deformation in the out-of-plane direction as the foundation slab uplifts. Therefore, it is important to accurately grasp the non-linear behaviour in order to make a highly accurate evaluation.

Regarding the evaluation of stress generated in reinforced concrete members, abundant evaluation results of method considering non-linear characteristics both for the tensile force in the reinforcing bar and compressive force in the concrete are found the tensile force in the reinforcing bar and the compressive force in the concrete have abundant evaluation results of the method considering non-linear characteristics.

On the other hand, for the out-of-plane shear force, there are few evaluation methods applied in practice that adopt non-linear analysis considering the areal development of plasticization area.

Therefore, we evaluate the stress of the foundation slab in the out-of-plane direction in detail by non-linear analysis using the solid elements. In addition, the out-of-plane shear resistance effect of the reinforcing bar is examined from the stress distribution for the out-of-plane shear force.

2. EXAMINATION POLICY

Figure 1 shows the study flow. First, the out-of-plane stress is evaluated for the entire foundation slab by non-linear analysis using the model of shell elements for the purpose of confirming the stress of the foundation slab when a huge seismic force acts, and identifying the location where local stress concentration in the out-of-plane direction occurs.

Next, the out-of-plane stress is evaluated by non-linear analysis using the model of solid elements for the area where local stress concentration occurs for the purpose of confirming the stress in detail.

Furthermore, regarding the out-of-plane shear force, the out-of-plane shear resistance effect of the reinforcing bar is examined from the stress distribution as the results of the analysis using the model of solid elements.

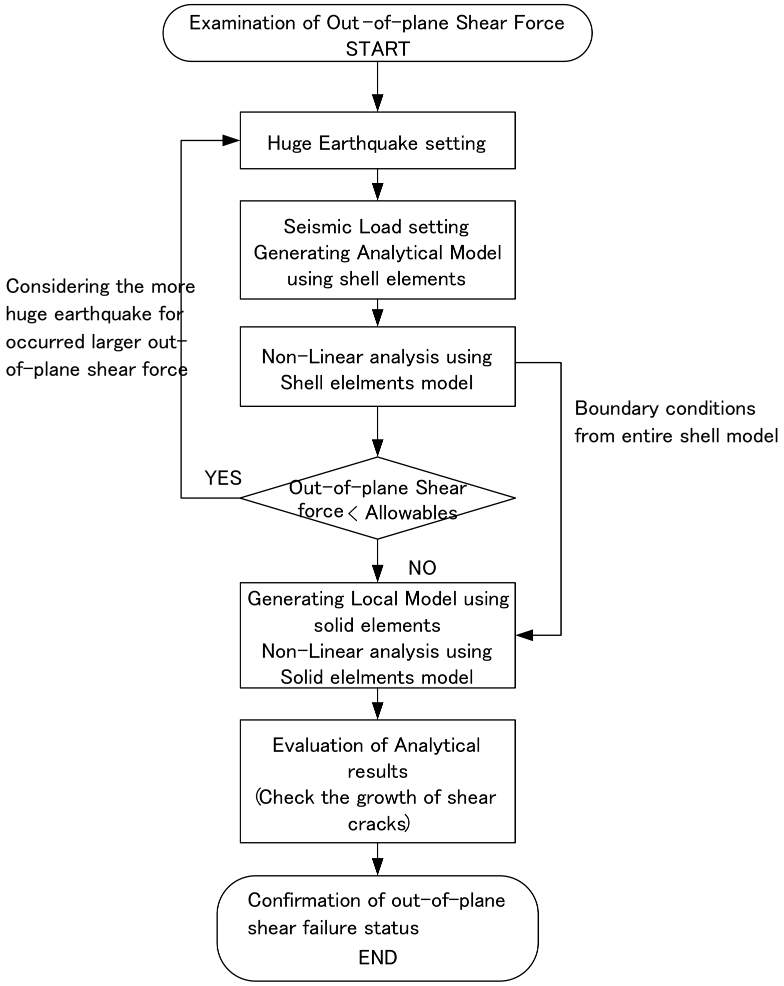


Figure 1. The study flow

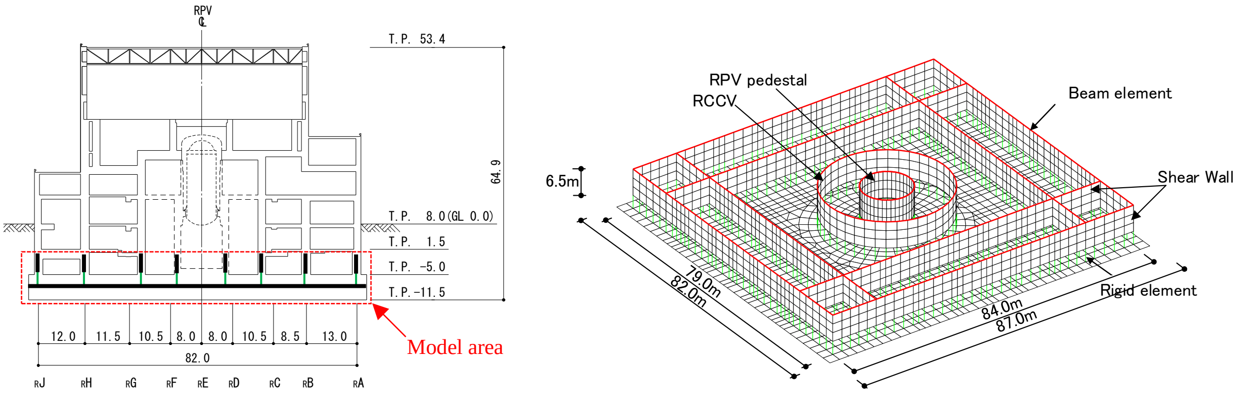
3. EXAMINATION BY SHELL MODEL

We evaluate the out-of-plane shear stress using the model of shell elements for the purpose of confirming the stress of an entire foundation slab.

3.1 Analysis conditions

The analysis model is the foundation slab supporting RCCV (Reinforced Concrete Containment Vessel), and the planar shape is 82m x 87m, and the thickness is 6.5m. The members supported by the foundation slab are modelled to take into account the load transfer from the superstructure.

Figure 2 shows the analysis model. About the FEM element used as the analysis model, the foundation slab are modelled as laminated shell elements, and the members supported by the foundation slab are modelled as shell elements with the beam element's at the top of them The laminated shell element is an element made of an anisotropic material that models the reinforcing bar layer.

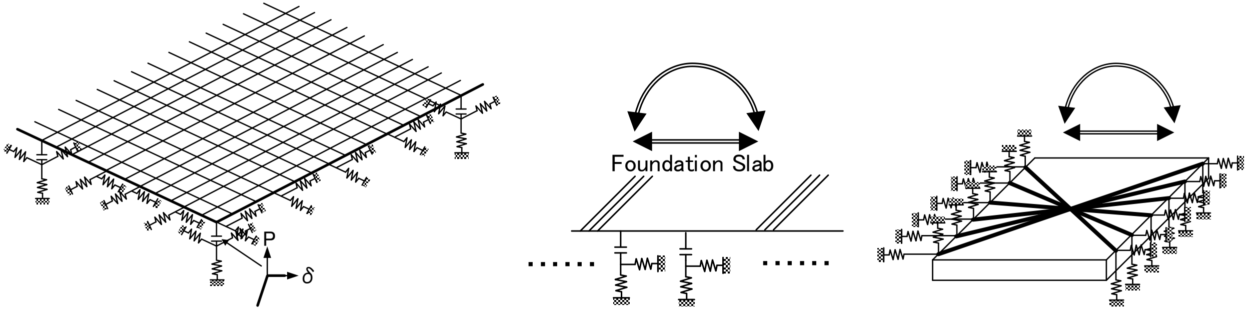


(a) Elevation

(b) Analysis model

Figure 2. Analysis model using shell elements

Figure 3 (a) shows the soil spring models and (b) shows the outline of the soil spring. Soil springs are located on the bottom and sides of the foundation slab discretely. Horizontal springs are set based on bottom and side horizontal springs, and vertical springs are set based on bottom and side rotation springs. The horizontal and vertical ground springs on the bottom of the foundation slab use GAP elements that transmit the load only during compression to be able to simulate the foundation uplifts when tensile force is generated.



(a) Soil spring model

(b) Bottom and side ground springs

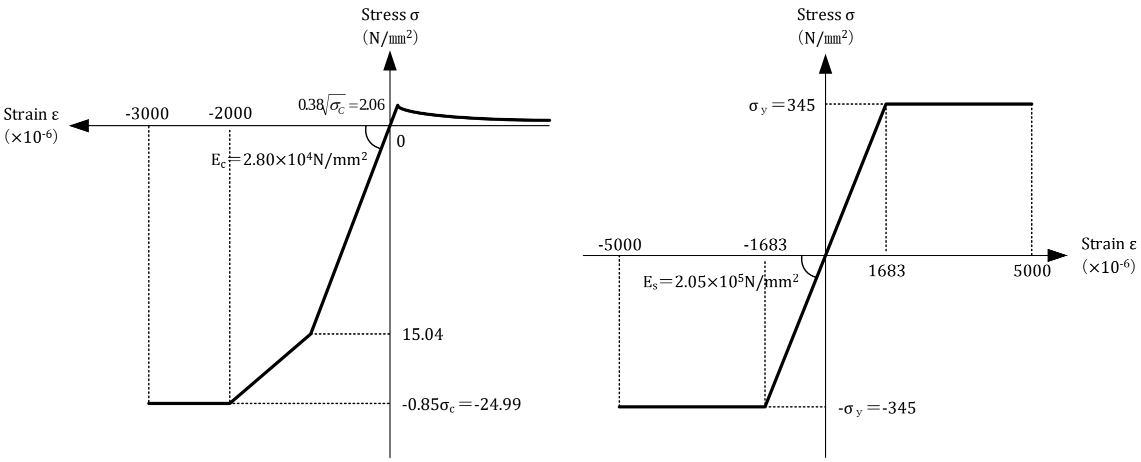
Figure 3. Soil springs of the analysis model

Table 1 shows the physical characteristics of the materials. For the Young's modulus of concrete, to account for actual stiffness of nuclear plants, the compressive strength of concrete by the compression experiment is adopted.

Table 1: The physical characteristics of the materials

member	Concrete			Reinforcing bar	
	Compressive strength Fc [N/mm^2]	Young's modulus E [N/mm^2]	Poisson's ratio ν	Yield stress σ_y [N/mm^2]	Young's modulus E [N/mm^2]
Foundation slab	29.4	2.90×10^4	0.2	345	2.05×10^5
Shear wall RPV pedestal RCCV	32.4	2.80×10^4	0.2	390	2.05×10^5

Figure 4 shows the material constitutive rule. The compression side of the concrete is set based on the CEB-FIP model code, and the tension side is set as the tensile softening curve after cracking occurs based on the formula by Izumo et al. (1987). Reinforcing bars have bilinear characteristics.



(a) Concrete

(b) Reinforcing bar

Figure 4. The material stress-strain relationship

Seismic loads and other loads (e.g. dead loads, pressure loads), are applied appropriately to the analytical model. The three directional seismic load (the two horizontal directions and the vertical direction.) is applied. The force of the seismic force is equivalent to 2G horizontally and 1G vertically assuming a huge earthquake, and the combination coefficient method is used for the load combination.

3.2 Evaluation conditions

From the generated stress, we evaluate the out-of-plane shear forces. In Japanese standards, Equation (1) is commonly used as the allowable value for out-of-plane shear force, but the allowable value is different by the idea of the premium coefficient(α) that the shear span ratio depending on the presence or absence of shear reinforcement, as shown in Table 2.

$$Q_A = b \cdot j \cdot \{\alpha \cdot f_s + 0.5 \cdot f_t \cdot (p_w - 0.002)\} \tag{1}$$

Q_A ：Allowable value of out-of-plane shear force [N]
b ：Cross section width [mm]
j ：Distance between stress centers in cross section, 7/8 times the effective depth of the section [mm]
α ：Coefficient to account for shear-moment ratio effect

$$\alpha = \frac{4}{M/(Q \cdot d)+1}$$

M：Bending moment [N・mm]
Q：Shear force [N]
d ：Effective depth [mm]

f_s : The short-term allowable shear stress of concrete [N/mm^2]
f_t : The short-term tensile stress of shear reinforcement [N/mm^2]
p_w : Shear reinforcement ratio according to the following equation （0.002 or more）

$$p_w = \frac{a_w}{b \cdot x}$$

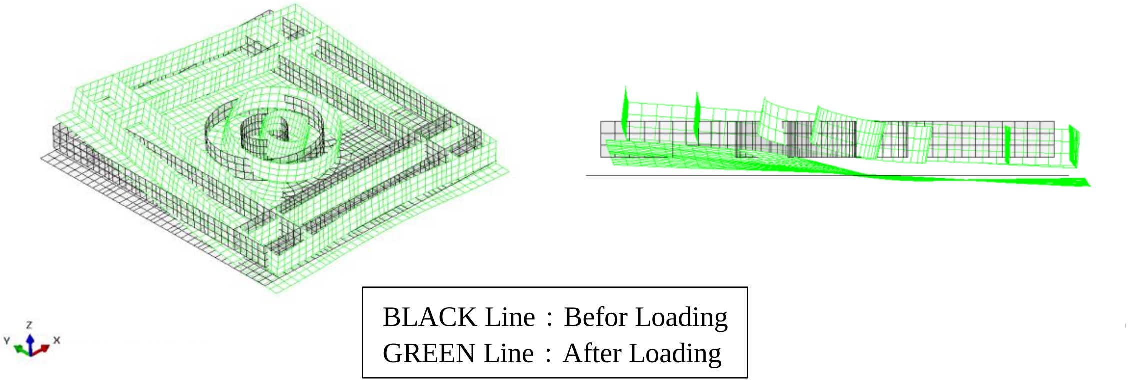
a_w : Cross-sectional area of shear reinforcement [mm^2]
x : Shear reinforcement spacing [mm]

Table 2: Treatment of the coefficient α

(a) Codes for Nuclear Power Generation Facilities – Rules on Concrete Containment Vessels for Nuclear Power Plants -	(b) AIJ Standard for Structural Calculation of Reinforced Concrete Structures for Nuclear Power Facilities
When $p_w = 0$, or $p_w \neq 0$ and the tensile force is 2N/mm^2 or more, α is not considered.	Always consider α regardless of p_w

3.3 Evaluation results

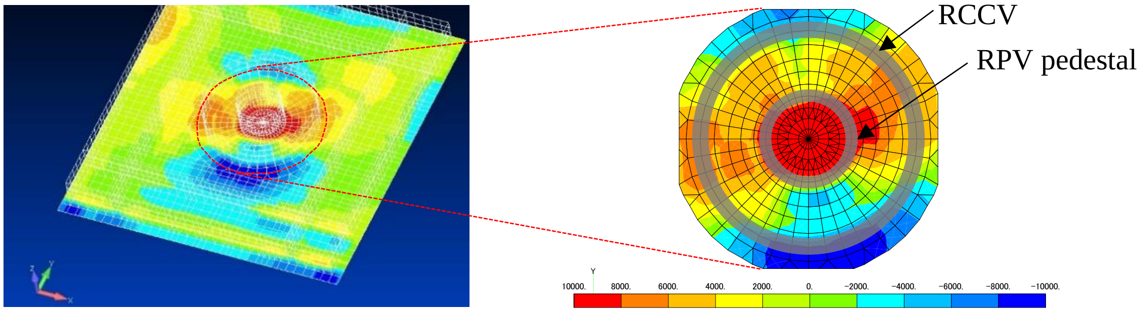
Figure 5 shows a deformation diagram of the foundation slab by stress analysis. It can be confirmed that the uplifts from the ground occurs near the center of the foundation slab due to the action as large seismic load in the horizontal and vertical directions



(a) Overall view (b) Sectional view

Figure 5. Deformation of the foundation slab (Deformation magnification: 100 times)

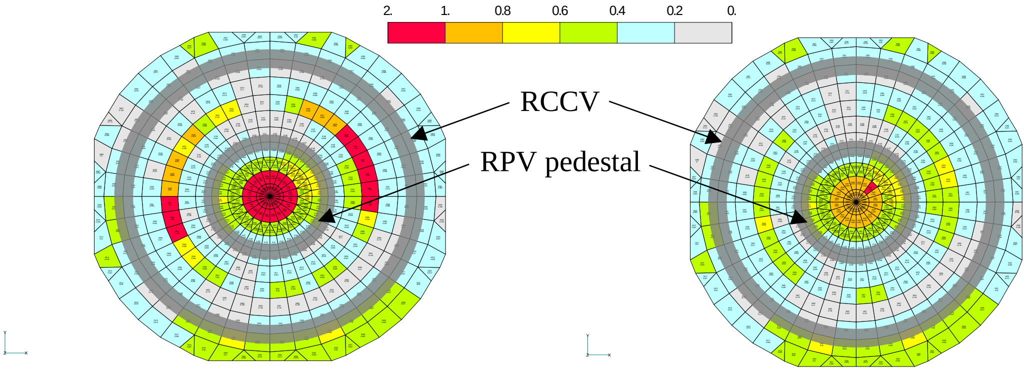
Figure 6 shows the stress condition of out-of-plane shear force inside the RCCV. It can be confirmed that the stress is concentrated at the center of the slab and the connection part with the RCCV and RPV pedestal. It is considered that the cause is a large stress generated in the RCCV and RPV pedestals due to the seismic load, and a large deformation occurred at the center of the slab. Since we focus on out-of-plane shear in this study, we skip the consideration of other stresses.



(a) Overall view (b) Detail view

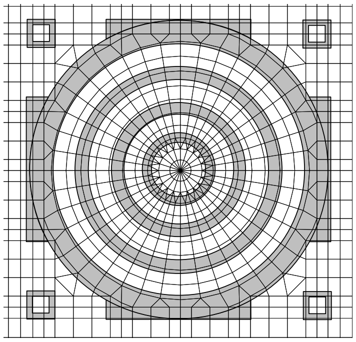
Figure 6. Stress condition of out-of-plane shear force

Figure 7 shows the out-of-plane shear stress ratio (generated value / allowable value) inside the RCCV, and Figure 8 shows the arrangement of shear reinforcements. In the Equation (1), when using a premium coefficient based on the shear span ratio accounting for the arrangement of shear reinforcements as shown in Table 2 (a), the allowable value is not satisfied in the area where the shear reinforcing bar is not arranged. On the other hand, in the case of the shear span ratio without accounting for the arrangement of the shear reinforcements as shown in Table 2 (b), the allowable value was satisfied in all area except only one mesh. From this result, it is necessary to confirm the effect of the shear reinforcing bar in the out-of-plane shear stress.



(a) Left: Case accounting for the arrangement of shear reinforcement
(b) Right: Case without accounting for the arrangement of shear reinforcement

Figure 7. Contour diagram of out-of-plane shear stress ratio

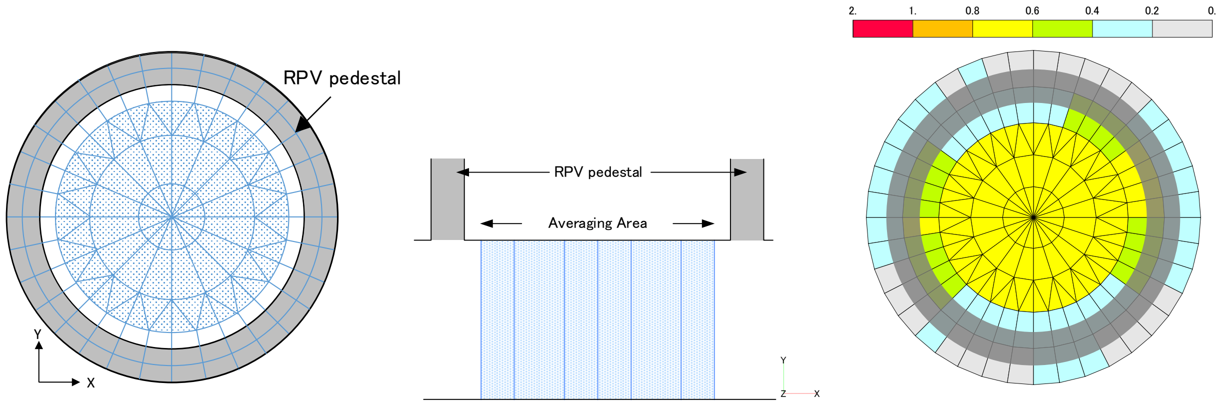


Shaded portion : shear reinforced area

Figure 8. Arrangement of shear reinforcement

In addition, for elements where stress concentration is observed, we will also consider a method of averaging stress in consideration of redistribution of stress to adjacent members. The averaging area is set as the member depth based on the experimental results of column and beam members regarding to load transmission in the thickness direction.

For the inside of the RPV pedestal where a large out-of-plane shear force is generated, Figure 9 shows the results when the generated stress can be averaged in the adjacent elements within the area of the slab thickness (6.5 m). It was confirmed that the out-of-plane shear stress degree satisfied the allowable value when the generated stress could be averaged by the slab thickness. From this result, it is necessary to confirm the validity of the range that the out-of-plane shear stress can be averaged.



(a) Averaging area (b) Average direction (c) Contour diagram

Figure 9. Results considering averaging of out-of-plane shear stress

4. EXAMINATION BY SOLID MODEL

Based on the examination results using the shell model, the effect of shear reinforcement in out-of-plane shear stress evaluation and the validity of the range in which the generated stress can be averaged are confirmed by analysis using the model of solid elements that can be evaluated in detail in the through thickness direction.

4.1 Analysis conditions

The area of analysis model is the center of the slab (radius 20.5 m) where a large out-of-plane shear stress was generated in the analysis by the shell model.

Figure 10 shows the analysis model. The analysis model are composed of solid elements for concrete such as foundation slabs, embedded truss elements for reinforcing bars, and shell elements for steel plates. The aspect ratio of solid elements are basically less than 2.0.

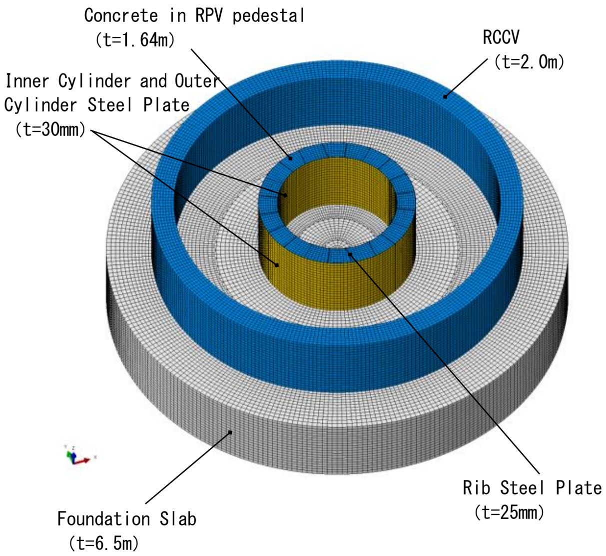


Figure 10. Analysis model using solid elements

As for the boundary conditions, the bottom surface of the foundation slab is set in the same way as the shell model. Except for the bottom surface, the displacement of each nodal points obtained from the shell model is applied.

The material constitutive rule is set in the same way as the shell model, and the load applied to the analysis model is set to be the same as the shell model.

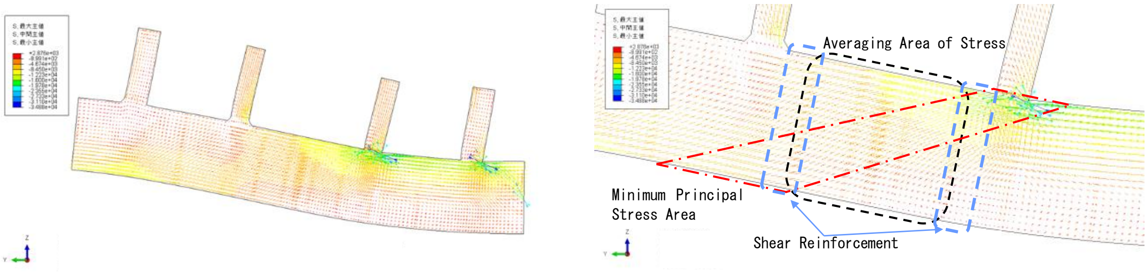
4.2 Evaluation results

Figure 11 shows a vector diagram of the principal stress. At the ultimate state of foundation shear failure, it is considered that the shear strength is related to the compression strut angle where the out-of-plane shear cracks remarkably appear. By using the solid model, it was possible to confirm the stress transmission in the slab depth direction, and there is no tendency for stress to concentrate in the central part of the slab as seen at the shell model. It is considered that the presence of the main bar and the shear reinforcing bar suppresses the generation of local compressive stress due to the seismic load transmitted from with the angle of the upper structure supported by the slab.

In addition, the vector of the principal stress indicating the compression strut progresses from 30 ° to 40 °, and it is considered that the stress is carried in a wider range than the stress averaging range of 45 ° assumed in Figure 9. When out-of-plane shear failure occurs, the out-of-plane shear force is thought to be transmitted from the top to the bottom of the foundation slab via the top bar, shear reinforcement, and bottom bar at the angle of the compression strut.

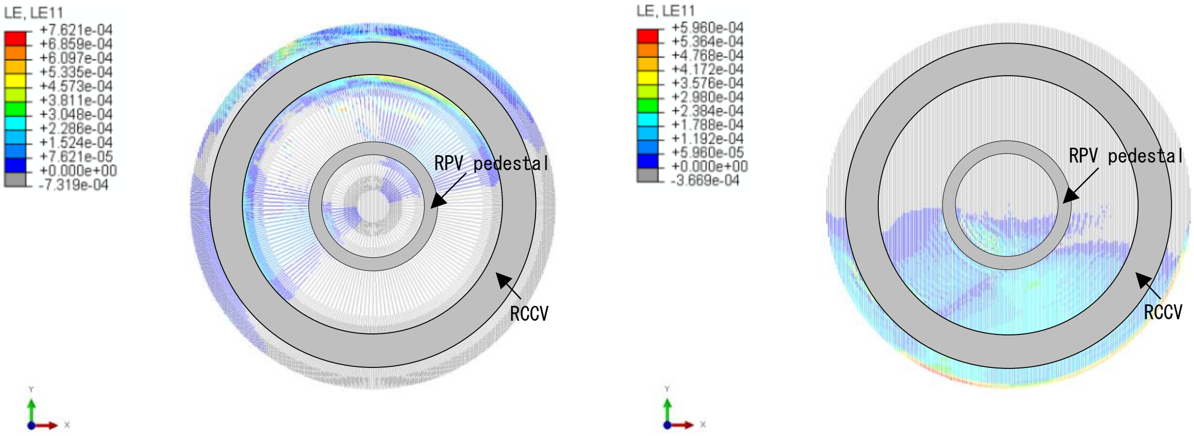
Figure 12 shows the deformation contour diagram of the reinforcing bar located in the compression strut. The deformation of the reinforcing bar is about several hundred micro, it can be confirmed that it is not in a deformed state that causes shear failure.

Based on the above, local stress is dispersed in the upper and lower parts of the slab and stress concentration is suppressed due to the effect of the shear reinforcement, it is considered that the stress is levelled spreading the out-of-plane shear force in the thickness direction. Furthermore, even when a local concentrate load is applied, the stress may be averaged within the area of the slab thickness (area of 45 °).

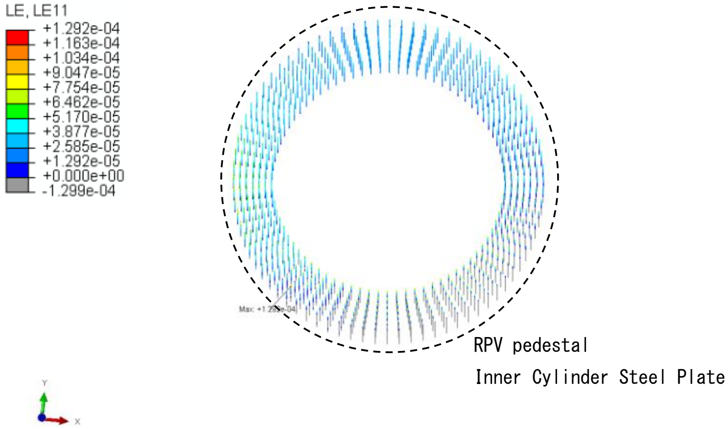


(a) Overall view (b) Detail view

Figure 11. Principal stress vector diagram (Deformation magnification: 100 times)



(a) Top main bar (radial direction) (b) Bottom main bar (Y direction)



(c) Shear reinforcement (inside RPV pedestal)

Figure 12. Deformation contour diagram of reinforcing bars

CONCLUSION

The stress of the out-of-plane direction is examined in detail by non-linear analysis using the model of shell elements and solid elements for foundation slabs under large seismic forces.

1) From analysis using the shell elements model, it was confirmed that the out-of-plane shear force tends to concentrate on the center of the foundation slab and a part of the connection with the RCCV and RPV pedestals due to the large deformation in the out-of-plane direction as the foundation slab uplifts, and the seismic force acting from the upper structure.

2) From analysis using the solid elements model, it was confirmed that the compression strut in the cross-sectional direction occurred at 30 ° to 40 °. Therefore, it is considered that the shear reinforcement has the effect of suppressing the development of local out-of-plane shear force, and that the generated stress can be averaged within the area of slab thickness (area of 45 °).

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