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FINITE ELEMENT ANALYSIS METHOLOGY REFLECTING NEUTRON IRRADIATION EFFECTS FOR STRUCTURAL ANALYSIS

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ABSTRACT

This paper is a preliminary study on the structural integrity evaluation method of nuclear structures that reflect neutron irradiation effect caused by long - term operation of nuclear power plants. Hardening, creep, and void swelling occur due to the effect of neutron irradiation accumulated during operation of the nuclear power plant. We have developed a subroutine to realize hardening, creep and void swelling according to the degree of neutron irradiation. In this study, we focus on the feasibility of subroutines and applicability of finite element analysis before applying these subroutines to reactor vessel and internal structure. The subroutine was used to confirm the effect of hardening, creep, and void swelling by neutron irradiation.

INTRODUCTION

After the Fukushima nuclear accident, structural integrity evaluation of nuclear power plants for BDBE (Beyond Design Basis Earthquake) has been reconsidered. The National Security Council in Japan has issued the regulatory guide for seismic design based on strain considering BDBE, and structural integrity regulation against earthquake has been strengthened. The regulatory requirements of the International Atomic Energy Agency (IAEA), the Western European Nuclear Regulators Association (WENRA), and the Finnish Regulations mandate that the BDBE be classified into Design Extension Conditions (DEC) separately. In Korea, there is an increasing interest in earthquake safety margin of nuclear power main components for BDBE.

Based on the existing elastic analysis, the stress-based structural integrity evaluation for earthquake is difficult to reflect cumulative damage and has excessive conservatism. Existing methods have the complexity of classifying primary and secondary stresses. Therefore, in order to overcome the limitations of existing methods, the final goal of this study is to develop strain-based structural integrity evaluation method. Accurate strain calculations are essential to develop a structural integrity assessment method based on strain rates. Accurate strain calculations are essential to develop a structural integrity assessment method based on strain rates. In order to calculate the exact strain, various strain caused by aging effect should be considered. RVI are irradiated directly to the neutrons emitted from the core. There are many cases of long-term aging such as Irradiation embrittlement, creep, void swelling, Irradiation-Assisted Stress Corrosion Cracking (IASCC) and Fatigue. These changes in material behavior and properties reduce the maximum absorption energy of the reactor vessel and internal structure It is necessary to closely evaluate the structural integrity for earthquake considering the material damage caused by the neutron irradiation because local damage and cracks can cause the seismic safety of the nuclear reactor structure to deteriorate greatly.

In order to reflect these effects, this study aims to carry out the elasto-plastic analysis on BDBE considering the change of material properties and material behavior due to aging of reactor vessel and internal structure subjected to neutron irradiation. This paper is a preliminary study to reach the final goal above. In this paper, we focused on constructing and verifying the finite element analysis method to reflect hardening, creep, and void swelling according to representative neutron irradiation.

EFFECT OF NEUTRON IRRADIATION

Neutron irradiation may cause irradiation embrittlement in which yield/tensile strength and elongation /fracture toughness are lowered, and material behavior changes such as neutron irradiation creep strain and void swelling strain occur and increase. Especially, the internal structure near reactor core is mainly made of austenitic stainless steel, which is caused by deterioration such as IASCC, irradiation embrittlement, irradiation creep and void swelling by core deterioration. Especially, the internal structure near reactor core is mainly made of austenitic stainless steel, which is caused by deterioration such as irradiation embrittlement, irradiation creep and void swelling. Therefore, in order to evaluate the structural integrity during the operation period, it is necessary to consider the change of material behavior due to neutron irradiation in the reactor internal structure.

Yield strength and tensile strength change by neutron irradiation

EPRI MRP-211 showed the change in yield strength / tensile strength according to neutron irradiation of 300 series austenitic stainless steels as follows.

$$\sigma_{YS}(\gamma_{cw}, d, T) = \sigma_{YS}(\gamma_{cw}, d)\phi_{YS}(T) \tag{1}$$

$$\sigma_{UTS}(\gamma_{cw}, d, T) = \sigma_{UTS}(\gamma_{cw}, d)\phi_{UTS}(T) \tag{2}$$

$$\sigma_{YS}(\gamma_{cw}, d) = \sigma_{YS}(\gamma_{cw}) + \{\sigma_{YSI} - \sigma_{YS}(\gamma_{cw})\}(1 - e^{-\frac{d}{d_0}}) \tag{3}$$

$$\sigma_{UTS}(\gamma_{cw}, d) = \sigma_{UTS}(\gamma_{cw}) + \{\sigma_{UTSI} - \sigma_{UTS}(\gamma_{cw})\}(1 - e^{-\frac{d}{d_0}}) \tag{4}$$

$$\phi_{YS}(T) = e^{-(0.0015 - 1.144\times10^{-6}\sigma_{YS}(\gamma_{cw},d)(T-330))} \tag{5}$$

$$\phi_{UTS}(T) = e^{-(0.0015 - 1.144\times10^{-6}\sigma_{UTS}(\gamma_{cw},d)(T-330))} \tag{6}$$

$$\sigma_{YS}(\gamma_{cw}) = \sigma_{YS0} + 2(\sigma_{YSI} - \sigma_{YS0})\gamma_{cw} - (\sigma_{YSI} - \sigma_{YS0})\gamma_{cw}^2 \tag{7}$$

$$\sigma_{UTS}(\gamma_{cw}) = \sigma_{UTS0} + 2(\sigma_{UTSI} - \sigma_{UTS0})\gamma_{cw} - (\sigma_{UTSI} - \sigma_{UTS0})\gamma_{cw}^2 \tag{8}$$

Where $\sigma_{YS}(\gamma_{cw}), \sigma_{UTS}(\gamma_{cw})$ are yield strength (MPa) and tensile strength (MPa) in consideration of the cold working ratio, γ_{cw} ($0 \le \gamma_{cw} \le 0.2$), respectively. $\sigma_{YS0}, \sigma_{UTS0}$ mean the initial yield strength and tensile strength without neutron irradiation and cold working, respectively. $\sigma_{YSI}, \sigma_{UTSI}$ mean saturation yield strength and tensile strength, which are no longer changed by neutron irradiation. d, d_0, T are the neutron irradiation dose (dpa), the neutron irradiation dose (3 dpa), and the temperature (° C).

Change of uniform elongation/tensile elongation due to neutron irradiation

$$\epsilon_{UE}(\gamma_{cw}, d, T) = \epsilon_{UE}(T)\eta_3(\gamma_{cw})\xi_3(d) \tag{9}$$

$$\epsilon_{TE}(\gamma_{cw}, d, T) = \epsilon_{UE}(\gamma_{cw}, d, T) + \{\epsilon_{TE}(T) - \epsilon_{UE}(T)\}\eta_4(\gamma_{cw})\xi_4(d) \tag{10}$$

$$\epsilon_{UE}(T) = C_{UE0} + C_{UE1}T + C_{UE2}T^2 + C_{UE3}T^3 \tag{11}$$

$$\epsilon_{TE}(T) = C_{TE0} + C_{TE1}T + C_{TE2}T^2 + C_{TE3}T^3 + C_{TE4}T^4 \tag{12}$$

$$\eta_3(\gamma_{cw}) = f_{30} + f_{31}(1 - e^{-\frac{\gamma_{cw}}{0.145169378}}) \tag{13}$$

$$\eta_4(\gamma_{cw}) = f_{40} + f_{41}\left(1 - e^{-\frac{\gamma_{cw}}{0.145169378}}\right) + f_{42}e^{-\frac{\gamma_{cw}}{0.151016372}} \tag{14}$$

$$\xi_3(d) = g_{30} + g_{31}\left(1 - e^{-\frac{d}{d_{31}}}\right) \tag{15}$$

$$\xi_4(d) = g_{40} + g_{41}\left(1 - e^{-\frac{d}{d_{41}}}\right) + g_{42}e^{-\frac{d}{d_{42}}} \tag{16}$$

Where $\epsilon_{UE}, \epsilon_{TE}$ mean the uniform elongation (%) and the tensile elongation (%), respectively. $C_{UEi}, C_{TEi}, f_{3i}, f_{4i}, g_{3i}, g_{4i}, d_{31}, d_{4i}$And so on are constants that are determined according to the material. In the case of 304 series austenitic stainless steels, the values given in Table 1 are the same.

Table 1: Parameters of equations (9) ~ (16).

Parameter	304 Stainless Steel	Parameter	304 Stainless Steel
$C_{UE0},$	55.8688	f_{40}	-0.98861001
C_{UE1}	-0.1893	f_{41}	1.143317172
C_{UE2}	0.00053656	f_{42}	1.399110009
C_{UE3}	-4.5779×10^{-7}	g_{30}	1.0
C_{TE0}	71.6321	g_{31}	-0.9875
C_{TE1}	-0.1956	g_{40}	8.9
C_{TE2}	0.00057562	g_{41}	-7.4
C_{TE3}	-7.1266×10^{-7}	g_{42}	-7.9
C_{TE4}	3.2172×10^{-10}	d_{41}	1.0
f_{30}	1.2105	d_{42}	2.5
f_{31}	-1.20013434		

Creep strain due to neutron irradiation

EPRI MRP-211 presented the creep strain according to neutron irradiation of 300 series austenitic stainless steels as follows.

$$\epsilon_{cr} = 0 \qquad (\sigma d < \frac{B_1}{B}) \tag{17}$$

$$\epsilon_{cr} = 100(B\sigma d - B_1\,) \qquad (\sigma d < \frac{B_1}{B})$$

Where ϵ_{cr}, σ are the effective creep strain (%), and Von Mises stress, respectively. B and B_1 are constants that are determined according to the material and are 3.06×10^{-6} and 2.21×10^{-3} for 304 series austenitic stainless steels.

Void swelling strain due to neutron irradiation

EPRI MRP-211 presented the void swelling strain according to the neutron irradiation of austenitic stainless steels of 300 series as follows.

$$\dot{\epsilon}_{sw} = \mathrm{N}\{\mathrm{Q} + 2\mathrm{d}(1 - \mathrm{e}^{\mathrm{Md}})\}\dot{\psi}^{-0.731} e^{22.106 - \frac{18558}{T+273.15}} \tag{18}$$

Where $\dot{\epsilon}_{sw}$ is the change in void swelling (% / dpa), and $\dot{\psi}$ is the neutron irradiation rate (10^{-7}dpa / sec). N, Q and M are coefficients or exponents determined by the material and are 1, 0, ∞ for 304 series austenitic stainless steels.

SUBROUTINE FOR FINITE ELEMENT ANALYSIS

Subroutines were developed to apply the hardening, creep, and void swelling effects of neutron irradiation to the finite element analysis program. For generality of the results of the subroutine, round robin was performed using two general purpose analysis programs, ANSYS and ABQUS. Round robin was carried out under neutron irradiation at a constant temperature of 330 ℃ with 173.57 GPa Young's Modulus, 0.3159 Poisson's ratio, 200 MPa (800MPa; Fully irradiation-saturated) yield strength, and 450 MPa (810MPa; Fully irradiated-saturated) tensile strength. The object for analysis was set as a round bar specimen as shown in Figure 1.

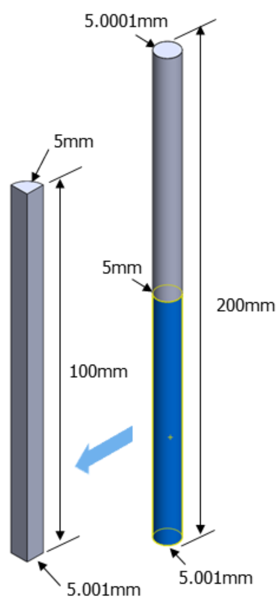

Figure 1. Round bar specimen for analysis

Boundary conditions were set in 3-axis symmetry condition at the center of round rod specimen and tensile force was applied to the end of specimen. In order to minimize the analysis error due to the element size and quality, 3-D solid hexa-elements were constructed so that the aspect ratio was between 1 and 1.1. The total number of nodes is 10,570 and the number of elements is 8,250.

The analysis cases for verifying the three effects of the neutron irradiation are shown in Table 2 below.

Table 2: Analysis case

Case	Subroutine	Analysis time	Load [MPa]	Neutron dose [dpa]
1	“Hardening"	1 sec	650	3
2			790	10
3	"Creep"	10000 hr	0 hr : 0 0.001 hr : 650 10000 hr : 650	3
4			0 hr: 0 0.001 hr: 790 10000 hr: 790	10
5	"Void Swelling"	10000 hr	-	0 hr : 0 10000 hr : 3
6			-	0 hr : 0 10000 hr : 10
7	Total	10000 hr	0 hr : 0 10000 hr : 650	0 hr : 0 10000 hr : 3
8			0 hr : 0 10000 hr : 790	0 hr : 0 10000 hr : 10

The analysis for confirming the hardening behavior by the neutron irradiation was divided into cases 1 and 2. In Case 1, the working pressure of the specimen is 650MPa and the total dose of the specimen is 3 dpa. In Case 2, the working pressure of the specimen is 790MPa, and the total dose of the specimen is 10 dpa. The effective stress (Von Mises) and the equivalent plastic strain distribution of the specimen (ABAQUS and ANSYS) for Case 1,2 are shown in Figure 2 and Figure 3.

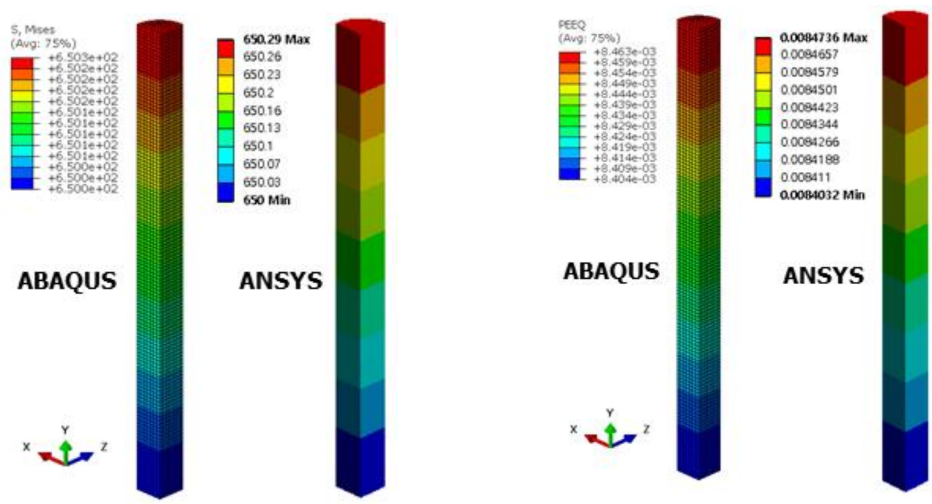

Figure 2. Effective stress (left) and the equivalent plastic strain distribution (right) of Case1

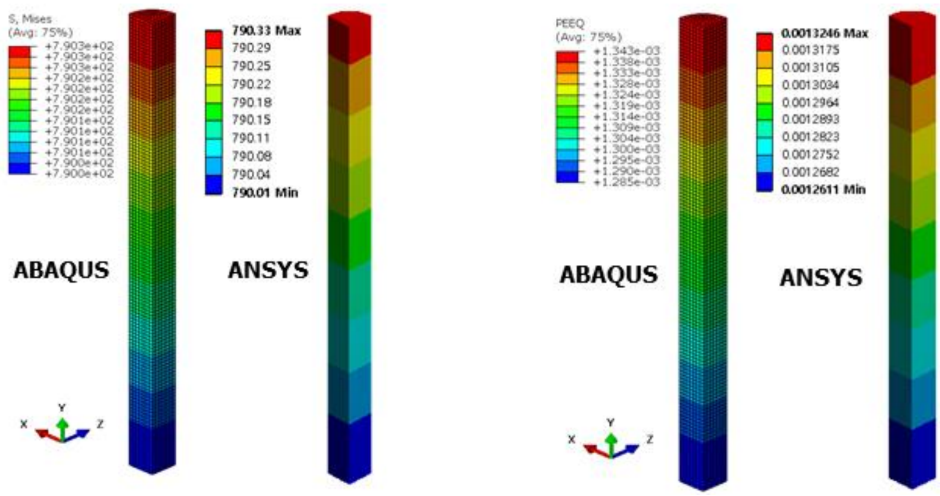

Figure 3. Effective stress (left) and the equivalent plastic strain distribution (right) of Case2

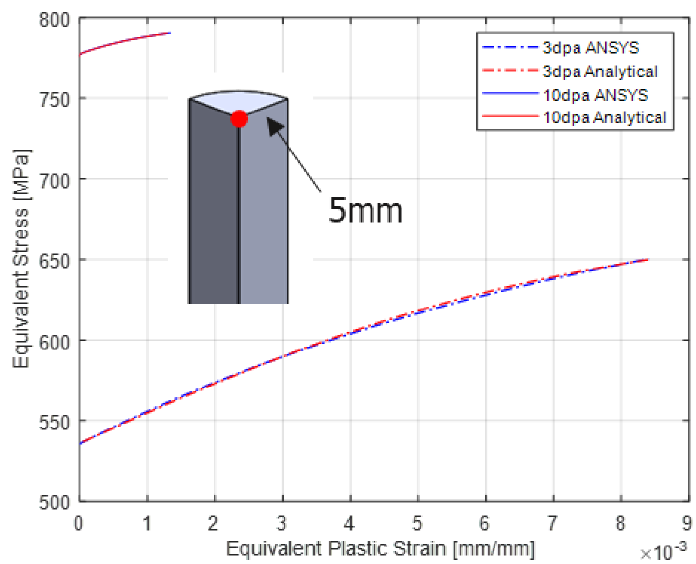

Figure 4. Stress-strain curve of Case1, 2 at center of specimen

Figure 4 shows the von Mises effective stress-equivalent plastic strain curve at the center of the specimen for numerical verification of the two analysis cases. Both analysis results and theoretical values show error rates of around 1%, and it can be confirmed that the strain-stress curve in the plastic section follows. Therefore, it was confirmed that the equation of plastic hardening material behavior by neutron irradiation was applied accurately through the developed subroutine.

The analysis for the creep strain by the neutron irradiation was divided into cases 3 and 4. In Case 3, the working pressure of the specimen is 650 MPa and the total dose of the specimen is 3 dpa. In Case 4, the working pressure of the specimen is 790 MPa, and the total dose of the specimen is 10 dpa. The equivalent creep strain distribution of the specimen (ABAQUS and ANSYS) for Case 3,4 are shown in Figure 5. As shown in Figure. 6, the strain rate at the center of the specimen was expressed with time to numerically verify the creep subroutine.

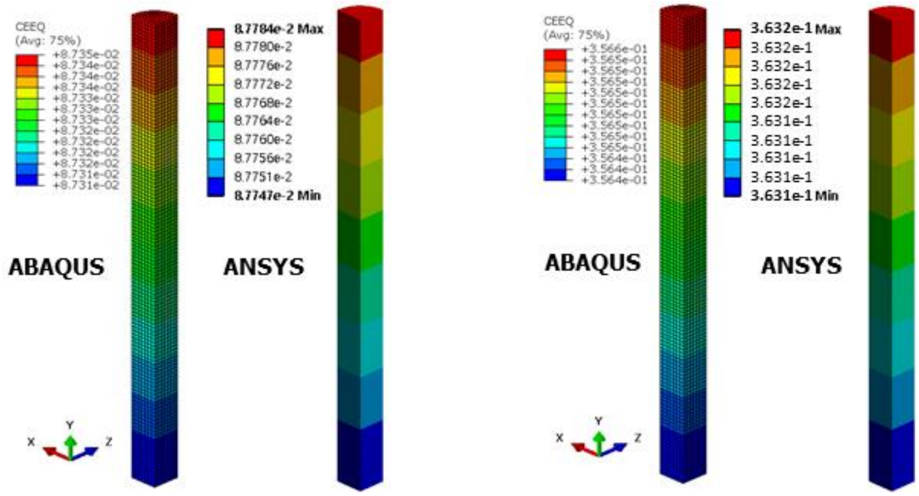

Figure 5. Equivalent creep strain distribution of Case 3 (left), Case 4 (right)

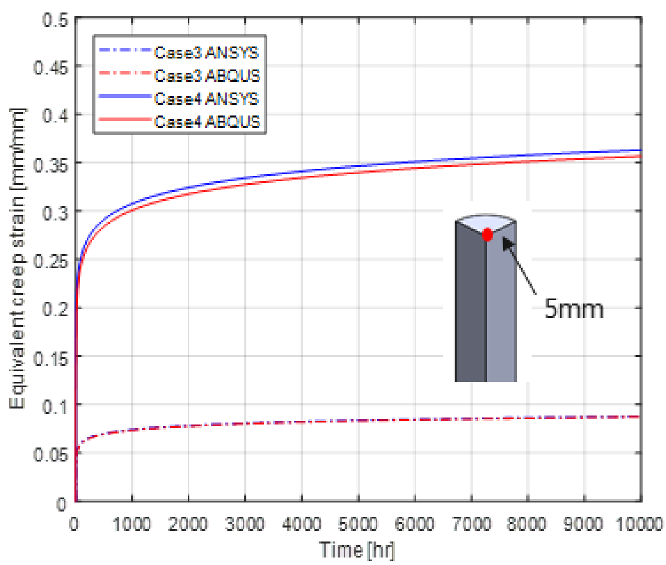

Figure 5. Equivalent creep strain of Case 3, 4 at center of specimen

It can be seen that equivalent creep strain occurs with maximum error rate of about 2%. It can be confirmed that the creep material behavior equation based on the neutron irradiation is applied to the developed subroutine.

The analysis to confirm the void swelling strain by neutron irradiation was applied to cases 5 and 6 separately. In Case 5, the dose increases uniformly linearly over time from 0 dpa to 3dpa. In Case 6, the dose increases linearly from 0 dpa to 10 dpa over time. In both cases, there is no working pressure, and the irradiation time is the same as 10,000 hours. The analysis results show an error rate of about 0.1% and it can be seen that the void swelling strain occurs with time. It can be seen that the equation of motion of the void swelling material by the neutron irradiation of the developed subroutine is applied correctly.

In Case 1~6, the analysis results were confirmed by using subroutine to realize material behavior by neutron irradiation. Finally, the analysis of the neutron irradiation was carried out by dividing into 7, 8 using subroutine that applied the hardening, creep, and void swelling. In Case 7, the working pressure of the specimen is 650 MPa, and the dose is linearly increased over the time from 0 dpa to 3dpa. In case 8, the working pressure of the specimen is 790 MPa and the dose is 0 dpa to 10 dpa in linearly increase over the entire specimen.

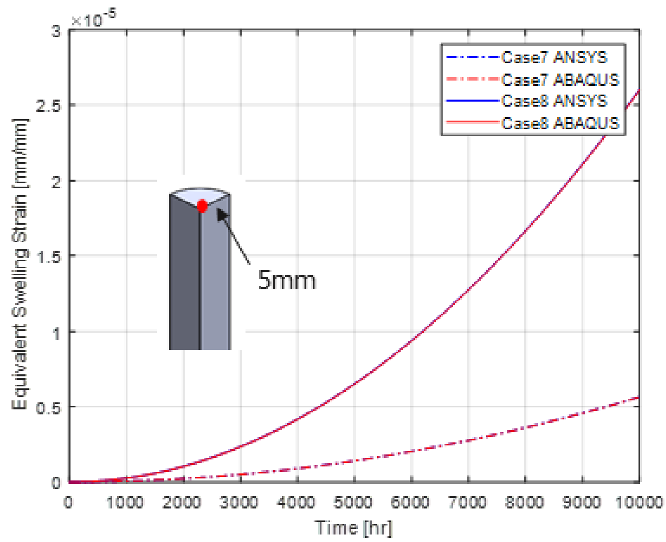

Figure 7. Equivalent swelling strain curve over time of Case 5, 6

The numerical results of the specimen center are shown in Figure 8. Errors of hardning, creep, and void swelling were found to be about 1%. Through the analysis of Case 7 and Case 8, It was confirmed that the three phenomena can be applied simultaneously, as well as the independent application to the hardening, the creep and the void swelling, which are the neutron irradiator.

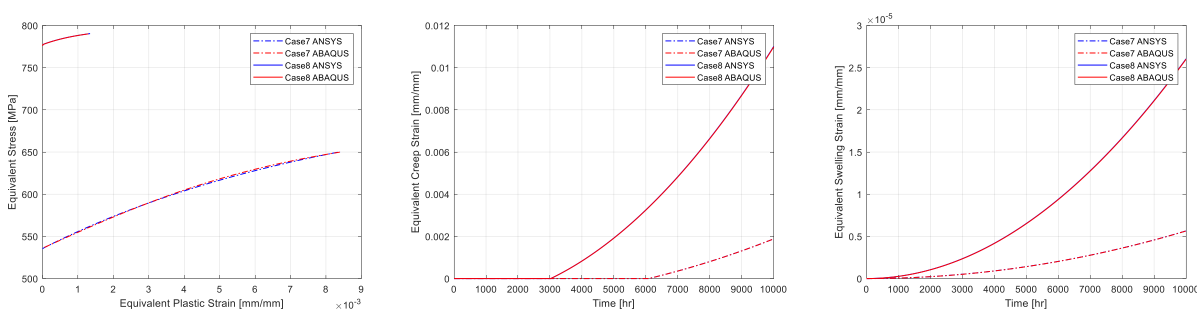

Figure 8. Stress-strain curve (left), equivalent creep strain (middle) and equivalent swelling strain curve (right) over time of Case 7, 8 at center of specimen

CONCLUSION

This study has the ultimate goal of evaluating the structural integrity of reactor vessels and internals considering neutron irradiation effects. For this, preliminary research was carried out in this paper. The analysis methods for aging degradation such as hardening, creep, and void swelling of materials by neutron irradiation were established by developing subroutines applicable to the finite element analysis model.

In the next research project, we develop finite element models for reactor vessels and internals considering plastic deformation. The subroutines considering the effect of neutron irradiation developed in this paper are used to analyze the structure response to the seismic load exceeding the design standard. This will be the basis for the analysis of the design seismic response considering the effect of neutron irradiation.

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