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Stress-based fatigue assessment of major component in NPP using modified Green's function approach

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1. Introduction

Recently, 434 nuclear reactors are being operated in the world. Among them, about 40% reactors are being operated beyond their design life or will be approaching their life. During the long term operation, various degradation mechanisms are occurred. Fatigue damage caused by alternating operational stresses in terms of temperature or pressure change is the one of important damage mechanisms in the nuclear power plants (NPPs). Although components important to safety were designed to withstand the fatigue damage, cumulative usage factor (CUF) at some locations can exceed the design limit beyond the design life. So, it is necessary to monitor the fatigue damage of major components during the long term operation. Researches on fatigue monitoring system (FMS) have been widely performed [1-5]. In USA, the FatiguePro was developed by EPRI and was applied to the CE, WEC, B&W and GE type reactors. In Korea, the Kori unit 1 which started commercial operation in 1978 is being operated beyond its design life. At the stage of the license renewal, various plans for degradation mechanisms were established and reviewed. And, in case of fatigue damage, to monitor the fatigue damage of major components, FatiguePro has been installed. Most of FMS have used Green's function approach (GFA) to calculate the thermal stresses rapidly. In this method, thermal stresses can be directly calculated from the convolution integration on the coolant temperature history and Green's function. However, there is a maximum peak stress discrepancy between a conventional GFA and a detailed finite element method (FEM) which temperature- dependent material properties are used. If a conventional method is used in the fatigue evaluation, thermal stresses for various operating cycles may be calculated incorrectly and it may lead to an unreliable CUF estimation [6-8].

So, in this paper, the modified GFA which can consider temperature-dependent material properties is proposed by using a neural network (NN) and weight factor. To verify the modified GFA, thermal stresses by the proposed method are compared with those by FEM. Finally, pros and cons of the new method as well as technical findings from the assessment are discussed to show applicability of them.

2. The modified GFA considering temperature-dependent material properties

The modified GFA which can consider a change of material properties as a temperature variation is proposed by using an NN and weight factor. To define the relationship between time, temperature and stress, an ANN is used. They are usually used to model complex relationships between inputs and outputs [13–15]. Fig. 1 shows the procedure of the proposed method. At the first stage, the maximum and minimum temperature are selected in the whole temperature range of an arbitrary transient. And, also, the triangular transient including the all range of transient is assumed. At the second stage, the maximum and minimum temperature range is divided into n intervals, and the Green's function in the each interval is determined using FEM. When the Green's functions are determined by FEM, temperature-dependent material properties are used. And then, an ANN is trained by using determined Green's functions. The relationship between time, temperature and stress can be modeled as the trained network, G3D(t, T) and it is called 3D-Green's function which can return stress over specific time and temperature. Using the 3D-Green's function, conventional GFA can be modified as Eq. (1).

$$\sigma_{TH}(t) = \int_0^t \alpha \cdot G_{3D}(t-\tau, \Phi(\tau)) \frac{\partial}{\partial \tau} \Phi(\tau) d\tau \qquad (1)$$

where α is the weight factor which is the coefficient calibrating the 3D-Green's function.

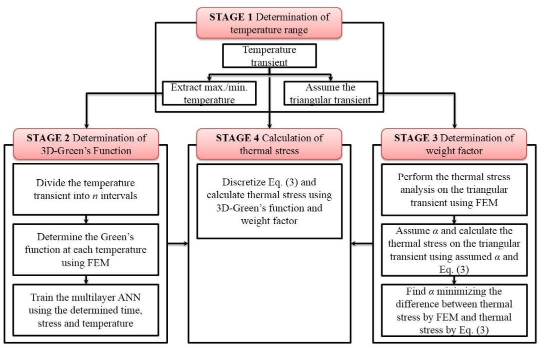

Fig. 1. Procedure to the modified Green's function approach

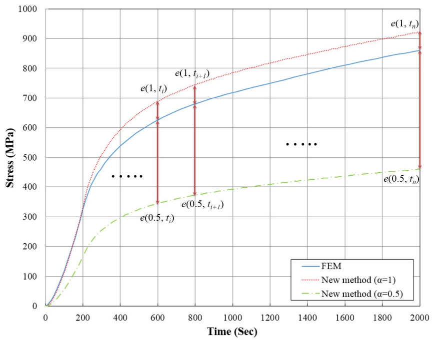

Fig. 2. The thermal stress comparison between FEM and the proposed method

At the third stage, the weight factor is determined. To determine weight factor, the thermal stress on the triangular transient is calculated by two method. One is FEM considering temperature-dependent material properties and the other is the method using an arbitrary weight factor and Eq. (3). As shown in Fig. 5, difference between two methods at any time is defined as follow:

$$e(\alpha,t_i) = \left|\sigma_{FEM}(t_i) - \sigma_{3D}(\alpha,t_i)\right| \qquad (2)$$

where σFEM(ti) is the thermal stress by FEM at ti and σ3D(α, ti) is the thermal stress by Eq. (3) with an arbitrary weight factor at ti.

Therefore, determining the weight factor becomes an optimization problem to find weight factor minimizing the total error (E(α)) indicated in the Eq. (5). If α is determined, the thermal stress for the arbitrary transient at the critical point can be calculated.

$$\text{Min } E(\alpha) = \sum_{i=1}^{n}\left|\sigma_{FEM}(t_i) - \sigma_{3D}(\alpha,t_i)\right| \qquad (3)$$

3. A verification of the proposed method

To verify the modified Green's function approach, thermal stresses by the proposed method are compared with those by FEM at the critical location. A nozzle connected to a spherical head of pressure vessel is selected as the interesting component and Fig. 3 shows the FE model and boundary conditions of the nozzle.

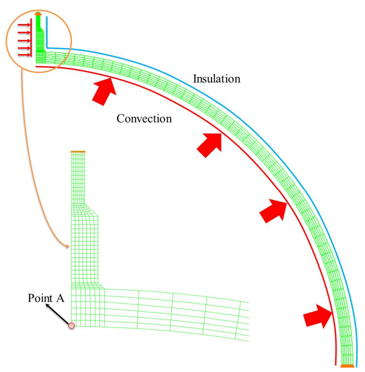

Fig. 3. FE model and boundary conditions

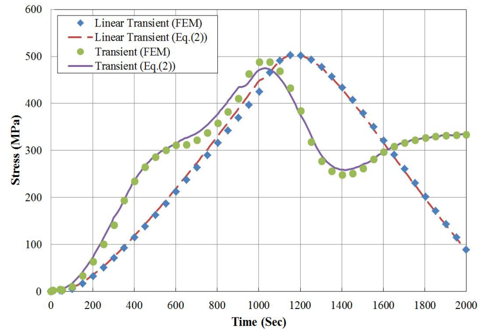

Fig. 4. Thermal stress comparison between the proposed method and FEM

The critical location is the point A because the stresses are concentrated in this point. For the modeling, an axisymmetric element is used and FE model is generated by using ABAQUS. In this model, only y-axis direction of the top and bottom is fixed and the displacement of x-axis direction is allowed. Heat transfer by the convection is occurred at the inner surface of the nozzle and the film coefficient value is 630.5W/(m2℃). And the outer surfaces of the nozzle are assumed to be thermally insulated. Carbon steel is used as the material of the nozzle. And, Fig. 8 presents the assumed linear transient and the temperature. The whole temperature range is from 25℃ to 400℃ and the Green's function at interval of 25℃ is determined. NN is trained using these thermal stress values of each Green's function. As shown in Fig. 10, when thermal stresses on the linear transient by FEM are compared with those by Eq. (2), α minimizing the difference between thermal stress histories is 0.9654. And, as shown in Fig. 10, when results by new method are compared with those by FEM, the results between two methods show a very good agreement.

4. Conclusions

In this paper, the modified GFA considering temperature-dependent material properties is proposed by using NN and weight factor. To verify the proposed method, thermal stresses by the modified Green's function are compared with those by FEM and the results between two methods show a good agreement. Finally, it is anticipated that more precise fatigue evaluation is performed by using the proposed method.

REFERENCES

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