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Development of Green Functions of Steam Generator Shells using Real Operating Data

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1. Introduction

Major components of nuclear power plants have been designed conservatively, in general, based on design transients and 2-D analysis models. However, to ensure the continued operation of nuclear power plant, more accurate evaluation of major components is needed [1]. In this context, stress analyses and fatigue life evaluation employing real operating data and 3-D geometry are recommended. Recently, Green's function -based monitoring systems have been installed also to measure real-time data and to detect damages of primary components [2~4] while most of them were developed using 2-D models. In this paper, temperature and mechanical stress transfer functions, called as Green's functions, are derived from 3-D finite element analyses at critical points of a steam generator. The resulting functions are compared with those obtained from detailed 3-D FEA and prototype of fatigue life evaluation is carried out using real operating data.

2. 3-D Finite Element Analysis

2.1Finite element model

The finite element model was prepared to get the stress histories at critical locations in steam generator. Elastic finite element analyses were performed by using the general-purpose finite element program, ANSYS [5]. Fig. 1 shows a 3-D finite element model. The mesh consists of 103,499 nodes and 73,114 elements. Three critical locations, the end point of steam outlet nozzle (Point A), shell transition region (Point B) and complicated geometry (Point C), were used for developing Green's function.

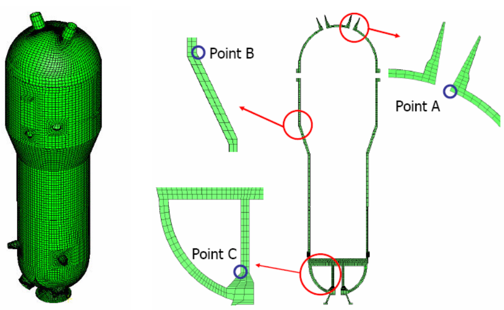


Fig. 1 The finite element model and three critical locations

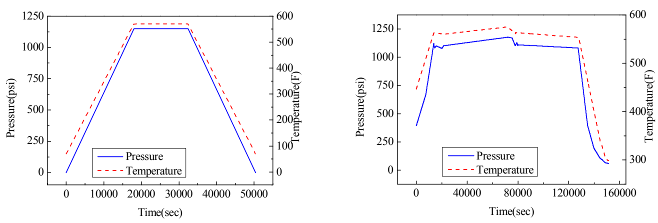
In order to check whether the finite element models are optimum or not, hoop stress distributions at outer surface of shell is compared with theoretical solution [6]. The average differences were less than 3%. This result shows finite element model was optimized.

2.2 Design transient

For 3-D FEA to develop and verify Green's functions, heat-up & cool-down conditions was selected. Fig. 2(a) shows the pressure and temperature histories.

2.3 Real operating data

To prevent unexpected emergency situation in nuclear power plants, the Korea Institute of Nuclear Safety (KINS) developed a monitoring system. It was called as Computerized technical Advisory system for the Radiological Emergency (CARE) [7]. The CARE system provides about 2,000 parameters for maintaining the safety. Among the parameters, SGPr (Steam Generator Pressure), RCHLTp (Reactor Coolant Hot Leg Temperature) were used for stress analyses and fatigue life evaluation of steam generator. Fig. 2(b) is shown real operating data of heat-up & cool-down.



(a) Design transient (b) Operating data
Fig. 2 Heat-up and cool-down condition of steam generator

3. Development of 3-D Green's Function

The stress at a point of component can be divided into two parameters such as $\sigma_P(t)$ and $\sigma_T(t)$. $\sigma_P(t)$ is the stress vector of pressure. It is calculated directly by stress transfer function. And $\sigma_T(t)$ is the stress vector of temperature. It is affected by changing temperature history. So this term can be obtained by applying a Green's function according to the transient history. The Green's function is defined as the response of a system to a step input. Combining Green's function with

Duhamel's theorem, the change of thermal stresses at time τ due to a small change of the temperature boundary at time τ can be expressed as below:

$$\sigma(t)=\int_0^t G(p,t-\tau)\frac{\partial}{\partial\tau}\varphi(\tau)d\tau \qquad (1)$$

where, *G(p, t)* is the stress transfer Green's function, which can be determined by using the thermal step load. In this paper, the Green's function was made of a quadratic form at each direction. Table 1 summarize coefficient of the quadratic Green's function at each critical location.

Table 1 Coefficient of Green's function ($\sigma(t)=at^2+bt+c$)

Location	Direction	*a*	*b*	*c*
Point A	X	0.0001	-0.0112	-0.004
	Y	0.0007	-0.5377	-0.0186
	Z	0.0003	-0.1644	-0.0085
	XY	0.1×10^{-6}	-0.3×10^{-5}	-0.3×10^{-5}
	YZ	-0.2×10^{-8}	0.4×10^{-5}	0.5×10^{-5}
	ZX	-0.0001	0.1364	0.0027
Point B	X	0.0002	-0.355	-0.0126
	Y	0.0002	-0.3272	-0.0018
	Z	0.00002	-0.01596	-0.00079
	XY	-0.4×10^{-7}	0.2×10^{-5}	-0.3×10^{-4}
	YZ	0.5×10^{-8}	-0.2×10^{-5}	0.7×10^{-5}
	ZX	-0.00003	0.04175	0.00153
Point C	X	-0.00001	-0.03496	-0.00121
	Y	-0.00001	-0.07301	-0.00130
	Z	-0.00003	-0.03091	-0.00159
	XY	-0.1×10^{-6}	0.00036	-0.9×10^{-6}
	YZ	0.4×10^{-6}	-0.0016	0.000028
	ZX	-0.00002	0.03457	-0.00072

4. Verification of Green's Function

A verification of the developed Green's function was conducted at three critical locations. For verification, the resulting stress obtained from Green's functions were compared with those from 3-D finite element analysis using design transient and real operating data about heat-up & cool-down. At three critical locations, it showed a good agreement as depicted in Figs. 3 and 4.

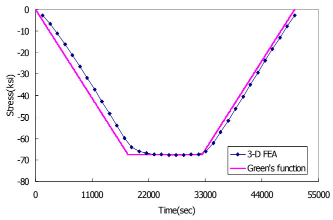


Fig. 3 Verification result of design transient

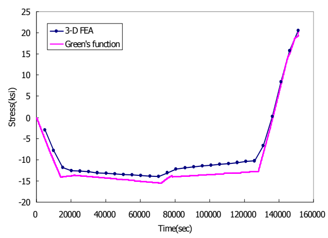


Fig. 4 Verification result of operating data

5. Fatigue Life Evaluation

The fatigue life evaluation by using Green's functions was carried out at three critical locations under both design transient and real operating data of heat-up & cool-down conditions. S-N curve of carbon and low alloy steel designated in ASME Sec. III, was used for evaluation. The resulting maximum alternating stress, allowable number of cycles and usage factor (UF) under heat-up & cool-down condition are summarized in Tables 2 and 3. The number of design cycle regarding the heat-up & cool-down condition was 500. Usage factor of design transient has a more conservatism than real operating data.

Table 2 Fatigue life evaluation results under design transient

Variable	Point A	Point B	Point C
S_a (*ksi*)	42.75	57.5	37.91
$N_{allowable}$ (cycles)	6000	3500	13000
Usage Factor	0.083	0.14	0.038

Table 3 Fatigue life evaluation results under operating data

Variable	Point A	Point B	Point C
S_a (*ksi*)	11.95	18.07	12.22
$N_{allowable}$ (cycles)	1000000	120000	1000000
Usage Factor	0.0005	0.0042	0.0005

6. Concluding Remarks

In this paper, 3-D Green's functions were developed at three critical locations of a steam generator. The validity of resulting Green's functions was proven by comparing the stresses with those obtained from detailed finite element analyses under both design and operating transients. Since the real operating data contributed to a reduced CUF, as anticipated, it is expected that the proposed method is applicable to determine realistic fatigue lives of major components.

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