Development of Green's Functions for Steam Generator Tube of System-integrated Modular Advanced ReacTor

Seung-Hyun Kim[a], Yoon-Suk Chang[a,*] and Tae-Wan Kim[b]
[a] Department of Nuclear Engineering, Kyung Hee University
[b] SMART Design Group, Korea Atomic Energy Research Institute
[*]*Corresponding author: yschang@khu.ac.kr*

1. Introduction

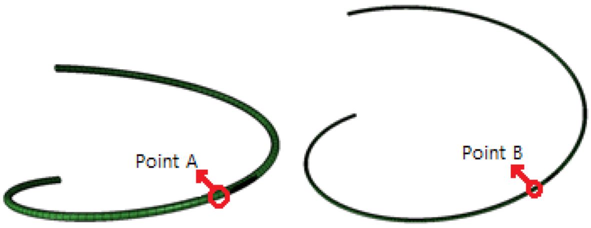
During the recent decade, world-wide efforts have been devoted to secure stable energy source and to encourage CO2 reduction. Although importance of clean energy in use of wind, solar, hydro and other resources has increased, it takes in charge of only small portion of electric output. KAERI has been developing a small and medium-sized multipurpose reactor, SMART (System-integrated Modular Advanced ReacTor), which includes all the main components in a pressure vessel [1]. Due to this characteristic feature, SG(Steam Generator) tubes in SMART system are designed as the shape of once-through helical type to secure large heat transfer area as shown in Fig. 1 [2]. Also, unlike the existing large commercial reactors, the external pressure which is larger than the internal pressure is subjected to the tubes since the primary coolant flow outside of tube and secondary coolant and steam flow inside. Consequently, the SG tubes in SMART system are distinguishable in their shape and boundary conditions with those of existing PWR. The object of this paper is to suggest an effective fatigue evaluation methodology based on prototype FE(Finite Element) analyses and resulting transfer functions.

Fig. 1 Schematic of SMART steam generator [2]

2. Numerical Analysis

2.1 Finite element model

The SG tubes in SMART system are arranged as multi-layer structure with a curved shape due to requirement of high space efficiency in all-in-one NPP systems. Thus, for accurate structural integrity evaluation, the characteristics of complex geometry should be preferentially investigated. By taking into account asymmetric conditions, full-3D tube models were generated for development of stress transfer functions. Systematic elastic FE analyses were carried out by using the general-purpose commercial program, ANSYS [3]. Fig. 2 shows representative FE models. The inner tube(1st layer, R_m=288.5mm) mesh consists of 118,572 nodes and 98,400 elements and outer tube(17th layer, R_m=648.5mm) mesh consists of 136,292 nodes and 115,000 elements. Also, the center point of each helical tube was selected as the critical locations.



(a) 1st layer (b) 17th layer

Fig. 2 Finite element models of SG tubes

2.2Material property

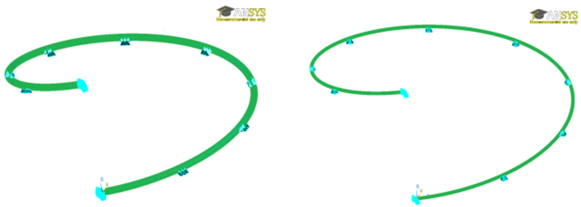
Alloy 690 was considered as the tube material for FE analyses. In relation to the heat transfer analyses, heat convection coefficient of 1.358 W/m^2-℃ was used. Other relevant properties are summarized in Table 1.

Table 1 Material property of alloy 690

Temp. (℃)	Modulus of elasticity (GPa)	Coeff. of thermal expansion (m/m/℃)	Poisson's ratio	Specific heat (W/m^2-℃)	Thermal conductivity (J/kg-℃)
20	215	1.41x10^{-5}	0.289	12	1.807x10^{-4}
100	208	1.43x10^{-5}	0.289	14	1.807x10^{-4}
200	201	1.45x10^{-5}	0.289	16	1.807x10^{-4}
300	195	1.48x10^{-5}	0.289	18	1.807x10^{-4}

2.3 Loading and boundary conditions

As loading conditions, the unit step pressure and temperature variations were applied as a distributed load to the outer surface of the tube. As boundary conditions, the end parts of SG tube were fixed for all direction and strips to support SG tubes were considered by fixing nodes along the y-direction. Fig. 3 shows the boundary conditions assigned in the analysis.



(a)1st layer (b) 17th layer

Fig. 3 Boundary conditions of SG tubes

3. Development of Transfer Function

The stress at a given point can be divided into two terms such as $\sigma_P(t)$ and $\sigma_T(t)$. The latter is a stress vector affected by changing temperature history and the former is a stress vector due to pressure change. By combining the concept of Green's function with well-known Duhamel's theorem, the change of thermal stresses at time τ due to varying temperature history can be expressed as below [4]:

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

where, $G(p, t)$ is the stress transfer Green's function, which can be determined by using the unit thermal step load. In this paper, the Green's function was made of a 6th-order polynomial form at each direction [5]. Tables 2 and 3 summarize resulting coefficients of the mechanical and thermal stress intensity transfer functions at each critical location.

Table 2 Resulting coefficient of mechanical stress intensity transfer function (y=Ht, initial temperature of 24℃)

Location	Constant value (H)
Point A (1st layer)	0.38892
Point B (17th layer)	0.19944

Table 3 Resulting coefficient of thermal stress intensity transfer function (y=at^6+bt^5+ct^4+dt^3+et^2+ft+g, initial temperature of 24℃)

Location	Constant value						
	a	b	c	d	e	f	g
Point A (1st layer)	-6.48 X10^{-12}	2.2 X10^{-9}	-2.91 X10^{-7}	1.89 X10^{-5}	-6.14 X10^{-4}	8.61 X10^{-3}	3.18 X10^{-4}
Point B (17th layer)	-1.63 X10^{-11}	5.51 X10^{-9}	-7.27 X10^{-7}	4.68 X10^{-5}	-1.48 X10^{-3}	1.92 X10^{-2}	8.1 X10^{-4}

4. Verification of Green's Function

Verification analyses of the developed Green's function were conducted for both critical locations of 1st and 17th layers. Due to lack of specific transient data of developing SMART SG, a typical design pressure and temperature histories of Korean PWR as shown in Fig. 4 [4] were adopted. The resulting stress intensities obtained from the Green's functions agreed reasonably well with those of detailed 3-D FE analyses as depicted in Fig. 5.

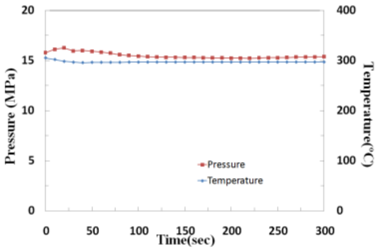
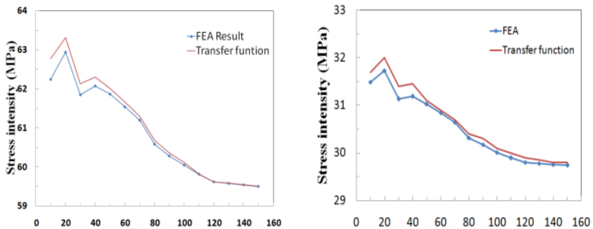


Fig. 4 Typical pressure and temperature time histories used in verification analysis [4]



(a) 1st layer (b)17th layer

Fig. 5 Verification analysis results

5. Conclusion

In the present study, prototype Green's functions at critical locations for SG tubes of SMART system were developed based on systematic FE analyses. For this purpose, specific features of the tube were taken into account such as once-through helical shape, external pressure and strip boundary conditions. The validity of resulting transfer functions was proven by comparing with the corresponding further detailed FE analyses under a typical transient condition. Thus, the proposed approach and prototype results will be useful if incorporated into a practical fatigue life assessment procedure combined with an on-line monitoring system in near future.

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