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Dynamic Characteristics of Steam Generator Tube Finite Element Models : A Comparative Study of Element Types

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1. Introduction

A pressurized water reactor has two water circuits, primary and secondary circuits. The water in the primary circuit is heated under high pressure, and the heat is transferred to the secondary circuit via a steam generator. Thus, damage to the steam generator tube could result in significant safety problems for the surrounding environment [1, 2]. Therefore, securing the integrity of the steam generator tube is very critical.

Currently, computer simulations, especially finite element (FE) analysis, are widely used to predict the vibration of the steam generator tube induced by the flow and following tube damages. The dynamic characteristics of the FE model of the tube affect its dynamic behaviors against flow-induced forces. Therefore, investigation of the dynamic characteristics of the FE model of the tube is crucial for accurately estimating tube wear. In this study, the dynamic characteristics of the tube FE models with various types of elements were investigated.

2. Materials and Methods

Three-dimensional FE models of the steam generator tubes were developed using four different element types (beam, shell, solid, and incompatible solid) and different numbers of elements. One of the longest tubes in the U-bend region was chosen. The number of elements along the circumferential direction varied from 8 to 20 (Fig. 1). The number of the elements in the curved region of the tube along the longitudinal direction also varied from 8 to 20 while 100 elements were sued in the vertical straight region, and 50 elements were used in the horizontal straight region (Fig. 2). For the FE model with beam element, 20 elements used for the curved region.

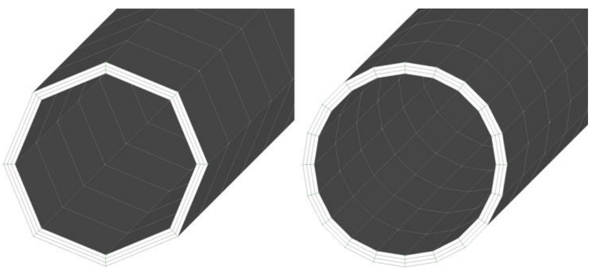
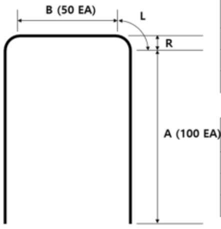


Fig. 1. Difference in the geometry of the FE model of steam generator tube according to the number of elements along the circumferential direction.

For the FE models using solid elements, three layers of elements were used along the thickness direction. Because the dynamic characteristics including natural frequency and mode shape are determined by its stiffness and mass. Thus, the volumes of the FE models were calculated and compared to those in the CAD model. Both ends of the tubes were rigidly fixed in all directions, then the dynamic characteristics of the FE models of the tubes with various element types were predicted and compared with each other. Abaqus/Standard (Dassault Systèmes, Waltham, MA, USA) was used for FE analysis.



No. of elements along the circumferential direction	8	12	16	20
No. element	6384	9864	13536	17400
Volume (mm³)	1488621	1579085	1611497	1626633
Accuracy of the volume	90%	95%	97%	98%

(a) Solid element

No. of elements along the circumferential direction	8	12	16	20
No. element	2128	3288	4512	19600
Volume (mm³)	1611385	1634840	1643097	1652020
Accuracy of the volume	90%	95%	97%	98%

(b) Shell element

Fig. 2. The number of elements used in developing FE models of steam generator tubes and the volume accuracy according to the numbers.

3. Results

The volume of the longest tube in the steam generator for the APR-type reactor, which is used in this study, was calculated as 1653751 mm3 using the CAD model of the tube. The FE model of the tube with solid elements with 20 elements along the circumferential direction showed 98% of the volume of the CAD model. When 12 elements along the circumferential direction were used, the FE model with shell elements showed 99% volume of the CAD model. The number of the elements used in the shell FE model was about 1/5 of the number of elements in the FE model using solid elements showed similar volume accuracy.

All models showed the same deformed shape of the first eigenmode (Fig. 3). The first mode of the FE model using beam element showed about 0.101 Hz. While the predicted 1st mode natural frequency of the FE model with shell element, in which 16 elements were used along the circumferential direction, was 0.100 Hz, 0.156 Hz, and 0.164 Hz were predicted when 8 and 12 elements were used along the circumferential direction.

When the linear solid elements were used, the first mode natural frequencies of 0.336 Hz ~ 0.337 Hz were predicted. However, the first eigenmode's natural frequency of 0.101 Hz was predicted when incompatible solid elements were used.

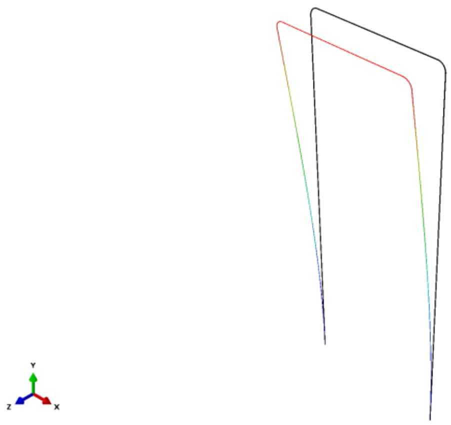


Fig. 3. The deformed shape of the first eigen mode of the steam generator tube FE model with solid elements

Table 1. The first mode natural frequencies of the tube FE models

Element types	No. of elements along the circumferential direction	Natural frequency (Hz)
Beam (B31)	-	0.101
Shell (S4)	8	0.159
	12	0.164
	16	0.100
Solid (C3D9)	8	0.336
	12	0.337
	16	0.337
	20	0.337
Incompatible solid (C3D8I)	16	0.165
	20	0.101

4. Discussions

FE analysis is a powerful tool for predicting the dynamic response of the steam generator tubes against flow-induced forces. Even though steam generator tube wear is estimated using work rate based on the calculated deformation of the tube caused by fluid flow, various approaches are possible to investigate the integrity of the tube, for example fatigue analysis. The beam element is very efficient and accurate for predicting the dynamic response of the steam generator tube. However, it also has limitations in that the element cannot be used for the fatigue analysis.

Solid elements are widely used element for general purposes. However, the element could generate excessive bending stiffness and could result in the prediction of higher natural frequency. Therefore, careful consideration is necessary for choosing the element type in the FE modeling of the tube according to the purpose of the analysis.

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