FAILURE PRESSURE ESTIMATES FOR HELICAL TUBES CONTAINING WEAR-TYPE DEFECTS UNDER EXTERNAL PRESSURE

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ABSTRACT

Recent designs of nuclear power plant have many dissimilar features comparing with those of existing reactors. Unlike conventional designs, there are differences in not only geometric characteristics but also loading conditions. In this study, a new type of steam generator tube which is helical shaped and pressurized outside is considered. Because of these peculiar aspects, it is not available to apply existing integrity assessment methods directly to the steam generator tubes. Especially, this study is concerned with the effect of volumetric defects on the plastic failure pressure of helical coiled steam generator tube under external pressure. Three kinds of wear-type defects are taken into account and relevant failure pressures are examined by changing defect depth, defect length and wrap angle through three-dimensional nonlinear finite element analyses. From the extensive parametric study, the failure pressures according to diverse geometric parameters were estimated.

INTRODUCTION

Nowadays, small modular reactors (SMRs) are developed or under development for various needs such as small power generation, reduced site cost and improved safety. To meet these objectivities, SMRs need to change their structural design to be more compactly. For instance, steam generator tubes of System-integrated Modular Advanced ReacTor (SMART) which is being developed by the Korea Atomic Energy Research Institute (KAERI) [1] are designed to have helical shape for securing large heat transfer area in confined space. Furthermore, since the primary fluid flows outside of the tubes and secondary fluid flows inside of them, it is subjected to external pressure difference. Because of these specific features, applicability of existing integrity assessment methods for steam generator tubes is limited.

Most of previous studies for steam generator tube were confined to cracks [2] and internal local wall thinning [3], and relatively fewer researches have been carried out on material loss or removal caused by flow-induced vibration (FIV) and contact between tubes and support structures [4, 5]. Since these studies dealt with conventional steam generator tubes, internal pressure or bending moment were only considered as applied loading condition. Also, studies related to worn or corroded pipelines have been performed within offshore engineering field. Fatt [6] and Xue et al. [7] proposed an analytical solution for the non-uniform cylindrical shells subjected to uniform external pressure and investigated the failure mode. Furthermore, some experiments and finite element (FE) analyses were performed to investigate collapse of tubes containing wear-type defect or corrosion under external pressure [8, 9]. Although, they considered external pressure as the loading condition, offshore pipelines have relatively thin wall thickness (D/t>15) compared to that of newly developing steam generator tubes. Consequently, it is necessary to investigate systematically failure condition of helical and moderate thick tubes with wear-type defects under external pressure.

The objective of the present study is to estimate the structural integrity of helical coiled steam generator tubes with a specific wear-type defect under external pressure. To achieve this goal, three types of defects are idealized and then the failure pressures of helical tubes containing wear-type defects are evaluated by detailed three-dimensional finite element analyses.

MODELING OF HELICAL TUBES WITH WEAR-TYPE DEFECT FOR COMPUTATIONAL ASSESSMENT

Geometry of Wear-type Defect on Helical Tubes

Fig. 1 represents a schematic of helical tube considered in the present study. The geometry can be defined by outer diameter, thickness, bend radius and pitch which were denoted as D_o, t, R_b, h, respectively. The steam generator tubes of SMART consist of a number of layers, so each pipe has another bend radius. Accordingly, the

pitch also has various values with respect to bend radius to maintain the same helical angle. In this study, the conservative pitch value is selected through preliminary analyses. Also, the outer diameter and tube thickness are fixed to 17 mm and 2.5 mm and the resulting dimension is shown Table 1. Three wear-type defects which were typically found in operating condition or assumed are employed by referring to existing study [10]. However, since the previous study was intended for just straight pipes, the defect shape was slightly modified by considering that the tube shape is helical in the present work. Fig. 2 illustrates schematics of these wear-type defects contained in the helical tube. The first type of defect is elliptical wear which is commonly generated by flow-induced vibration in steam generator tubes. To define geometry of this defect, defect depth, defect length and wrap angle which were denoted as d, l and θ, respectively, were selected. The second one is rectangular wear that is simplified model of elliptical wear. It was considered to compare the failure pressure with that of elliptical wear. Thus, it has the identical parameters to the elliptical wear-type defect to define its geometry. The third one is tapered wear which is usually formed in the free span of the tube at the nominal axial location of the batwing [11]. Only two parameters, defect depth and defect length, are considered in this defect and its depth is always facing the center of the spiral.

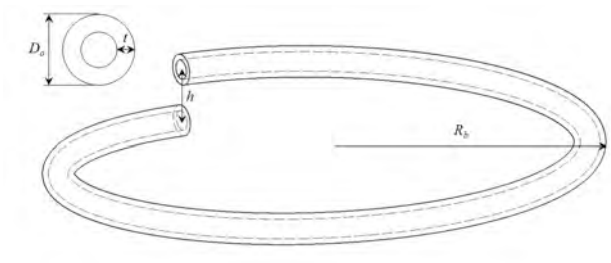
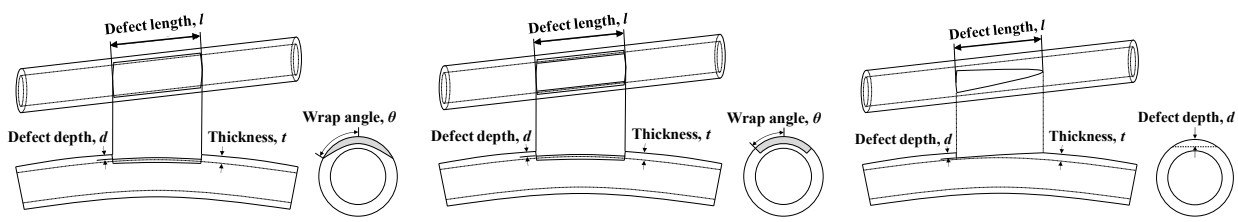


Fig. 1: Schematic of helical tube

Table 1: Dimension of helical tube model

D_o (mm)	t (mm)	R_b (mm)	h (mm)
17	2.5	577	20



(a) Elliptical wear (b) Rectangular wear (c) Tapered wear

Fig. 2: Schematic of wear-type defects

Finite Element Models and Analysis Method

In order to investigate failure pressure of the helical tubes with wear-type defect, three-dimensional FE models were made by using the general purpose FE program, ABAQUS [12]. Fig. 3 depicts typical meshes for the FE model. Since the tube has a non symmetric feature due to helical shape, full-model was adopted. The model was generated long enough as rotating 360 degrees around the bend radius. The initial geometric imperfection like out-of roundness (ovality) or thickness variation (eccentricity) was neglected in the present work. To avoid problems associated with incompressibility, the reduced integration element within ABAQUS (C3D20R) was used. The number of elements and nodes ranges from 34,768 elements-120,320 nodes to 54,618 elements-172,213 nodes depending on wear types. The mesh of numerical analysis model is refined enough to ensure convergence satisfaction. Consequently, the mesh size at the deepest point of wear region was fixed 0.5~1.5 mm approximately. The tube was fabricated by Alloy 690 and its mechanical properties at room temperature (25°C) and operating temperature (360°C) were summarized in Table 2. In the present work, the mechanical properties at operating temperature were used for conservative analyses. Materials were assumed to be elastic-perfectly plastic governed by von-Mises condition and hardening was neglected. Moreover to avoid problems associated with convergence in

elastic-perfectly plastic conditions, the modified RIKS option within ABAQUS was invoked, so that the corresponding fully plastic limit loads could be easily obtained from the FE analyses. As the loading condition, external pressure was applied to the outer surface of FE model as a distributed load. The magnitude of external pressure was large enough to cause failure of wear area. The effective axial tensile stress due to the external pressure, which is usually applied to the cross section at the end of FE model (End-cap load), was disregarded because sufficiently long tube was modeled. As the boundary condition, both ends of the tube were fixed.

Table 2: Mechanical properties at room and operating temperatures

Material	E (GPa)	σ_y (MPa)	σ_u (MPa)
Alloy 690 (25 ^{o}C)	266.3	284	672
Alloy 690 (360 ^{o}C)	143.5	210	549

(a) Elliptical wear (b) Rectangular wear (c) Tapered wear

Fig. 3: Typical FE models employed in the present study

PARAMETRIC FINITE ELEMENT ANALYSES

A detailed parametric study was performed to investigate the effect of key parameters (d, l, θ) on maximum load-carrying capacity of helical tubes with wear-type defects. For each wear-type defect, relevant parameters influencing the plastic limit load were systematically changed to quantify their effects. Firstly, for the elliptical wear-type defect, five different wear depths, four different wear lengths and three different wrap angles were considered. Accordingly, total of 60 cases were investigated in the parametric study. For the rectangular wear-type defect, which is a simplified model of elliptical wear, five different wear depths, four different wear lengths and five different wrap angles were considered. Total of 100 cases were investigated in the parametric study and the analyses results were compared with those of elliptical wear-type defect to verify applicability of the simplified model. In the case of the tapered wear-type defect, four defect depths and four defect lengths were considered to investigate failure pressure. Detailed analyses matrix is listed in Table 3.

Table 3: Analysis matrix for parametric study

Defect	Normalized defect depth d/t	Defect length l (mm)	Wrap angle 2θ (deg)
Elliptical wear	0.1, 0.3, 0.5, 0.7, 0.9	15, 25, 35, 50	90, 135, 180
Rectangular wear	0.1, 0.3, 0.5, 0.7, 0.9	15, 25, 35, 50	10, 45, 90, 135, 180
Tapered wear	0.25, 0.5, 0.75, 0.9	15, 25, 35, 50	-

Elliptical and Rectangular wear-type defects

Failure pressures obtained from the elliptical model and rectangular model with the same geometric parameters are summarized in Table 4 for comparison. The failure pressure of rectangular model ($P_f^{\ rec}$) is normalized to that of elliptical model ($P_f^{\ ellip}$). In most cases, the failure pressure of rectangular model had low value compared to that of elliptical model because the amount of volumetric loss of rectangular wear is slightly more than that of elliptical wear with the same geometric parameters. Especially, if the crack depth is deep and wrap angle is narrow ($d/t \geq 0.7$, $2\theta = 90^o$) the differences are high. However, except for these a few cases, each failure pressure

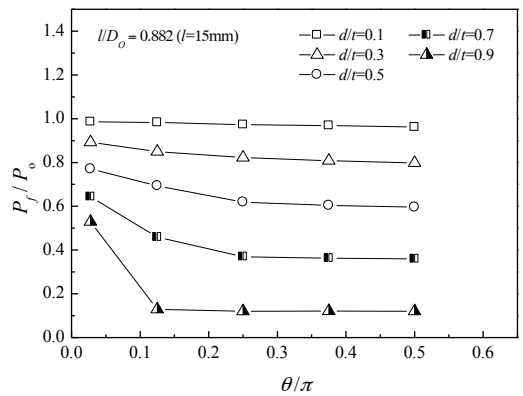
correlated very well ($P_f^{rec}/P_f^{ellip} \approx 1$) within 7% of differences even if the failure pressure of rectangular wear was slightly low. Therefore, the use of rectangular one which is easier to model than elliptical one is valid to investigate the failure pressure of elliptical model.

Table 4: Comparison of failure pressures between elliptical wear and rectangular wear

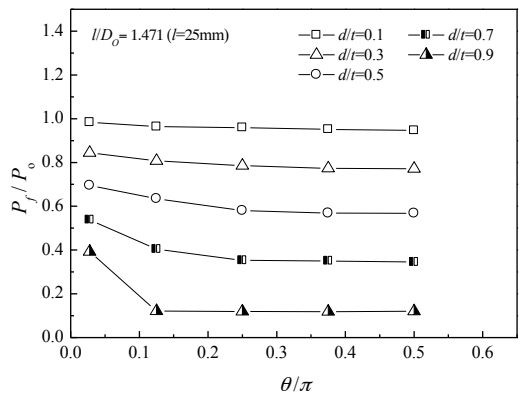
l	d/t	2θ	P_f^{rec}/P_f^{ellip}	l	d/t	2θ	P_f^{rec}/P_f^{ellip}
15	0.1	90	0.980	35	0.1	90	0.992
15	0.1	135	0.990	35	0.1	135	0.990
15	0.1	180	0.983	35	0.1	180	0.988
15	0.3	90	0.965	35	0.3	90	0.971
15	0.3	135	0.970	35	0.3	135	0.980
15	0.3	180	0.965	35	0.3	180	0.986
15	0.5	90	0.901	35	0.5	90	0.925
15	0.5	135	0.929	35	0.5	135	0.956
15	0.5	180	0.944	35	0.5	180	0.976
15	0.7	90	0.786	35	0.7	90	0.831
15	0.7	135	0.887	35	0.7	135	0.935
15	0.7	180	0.928	35	0.7	180	0.978
15	0.9	90	0.667	35	0.9	90	0.731
15	0.9	135	0.880	35	0.9	135	0.949
15	0.9	180	0.949	35	0.9	180	1.022
25	0.1	90	0.988	50	0.1	90	0.991
25	0.1	135	0.988	50	0.1	135	0.992
25	0.1	180	0.982	50	0.1	180	0.985
25	0.3	90	0.968	50	0.3	90	0.977
25	0.3	135	0.971	50	0.3	135	0.984
25	0.3	180	0.981	50	0.3	180	0.991
25	0.5	90	0.913	50	0.5	90	0.937
25	0.5	135	0.942	50	0.5	135	0.960
25	0.5	180	0.970	50	0.5	180	0.982
25	0.7	90	0.809	50	0.7	90	0.855
25	0.7	135	0.929	50	0.7	135	0.937
25	0.7	180	0.950	50	0.7	180	1.014
25	0.9	90	0.725	50	0.9	90	0.747
25	0.9	135	0.935	50	0.9	135	0.933
25	0.9	180	0.991	50	0.9	180	1.003

Based on the FE analysis results, failure pressures for elliptical and rectangular wear-type defects were calculated and the influence of defect depth, defect length and defect angle were investigated. Fig. 4 shows the effect of wrap angle for each defect depth in case of rectangular wear-type defects. The failure pressures of defected tubes and un-defected tube are denoted as P_f and P_o, respectively, and the P_f is normalized to P_o. Also, the defect depth (d), wrap angle (θ) and defect length (l) are normalized to wall thickness (t), outer diameter (D_o) and π, respectively. Among three variables, the defect depth was the most influential on failure pressure. As expected, as the defect depth becomes deeper, the failure pressure severely down according to the decrease of load-carrying capacity caused by reduction of volumetric wear. For small defect angle and length, the decrease rate of failure pressure by the increase of defect depth was relatively small but this rate increased as the defect angle and length became larger and longer. The wrap angle also had a considerable effect on the failure pressure. In all cases, the failure pressure decreased as the increase of wrap angle due to buckling. However, after the increase of wrap angle to a certain extent, the effect of buckling became negligible and the failure pressure converged to a constant value. Furthermore, the wrap angle effect rose as the increase of defect depth. For shallow defect depth (d/t=0.1), the failure pressure had no change with varying wrap angles. For deep defect depth (d/t=0.9), the failure pressure rapidly decreased until $2\theta=45^{o}$ (θ/π <0.112) and then converged to a constant value. On the other hand, the wrap angle effect fell as the

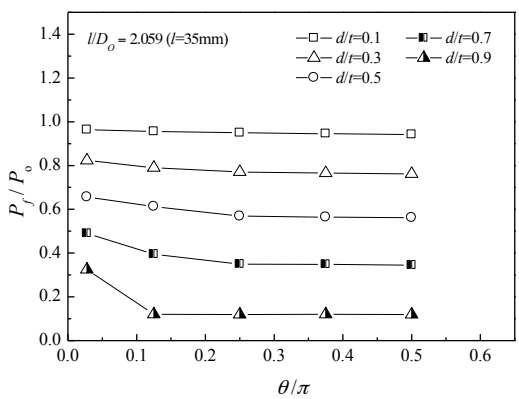
increase of defect length. When the defect length becomes longer, the decrease rate of failure pressure becomes small with the increase of wrap angle. The failure pressure also decreased as the increase of defect length and then converged to a constant value. However, the defect length had minor effects on the failure pressure compared to defect depth and wrap angle. Except for the cases with $2\theta=10^{o}$ (θ/π = 0.028), the effect of decrease rate on the failure pressure became small as the increase of defect length because the range of considered defect lengths was belong to convergence domain.



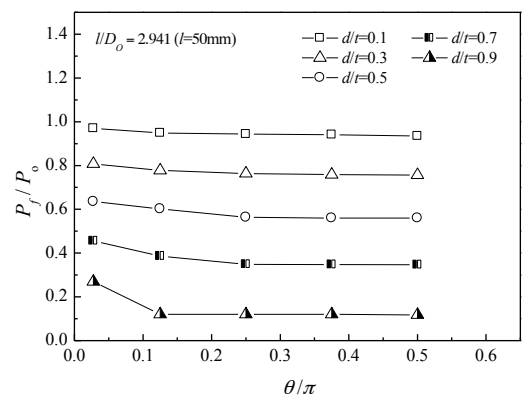
(a) l/D_o=0.882 (l=15mm)



(b) l/D_o=1.471 (l=25mm)



(c) l/D_o=2.059 (l=35mm)



(d) l/D_o=2.941 (l=50mm)

Fig. 4: Geometric parameter effects on the failure pressure for rectangular wear defects

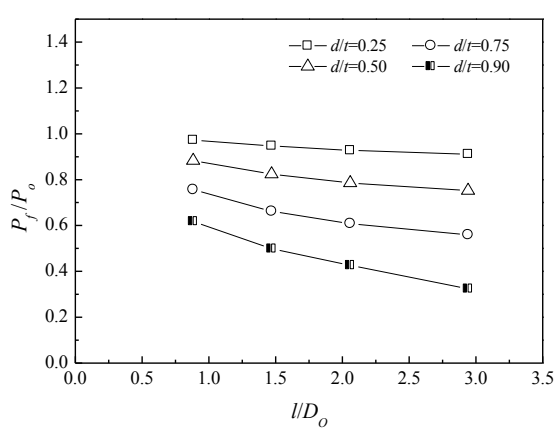


Fig. 5: Geometric parameter effects on the failure pressure for tapered wear defect

Tapered wear-type defect

In case of tapered wear-type defect, the influence of defect depth and defect length were investigated based on the FE results. Fig. 5 shows the effect of them on failure pressure in case of tapered wear-type defect. Like the elliptical and rectangular wear cases, the failure pressure of defected tubes are normalized by that of un-defected tube. Also, the defect depth and defect length are normalized by the wall thickness and outer diameter, respectively. Even though the variation of failure pressure according to the change of defect depth and defect length values showed similar trend to those of elliptical and rectangular wear cases, the effect of defect length on failure pressure became increasingly clear. The decreasing rate of failure pressure with the increase of defect length was larger as the defect depth becomes deeper.

CONCLUSION

In this paper, detailed three-dimensional simulations were performed for the helical tubes containing elliptical wear, rectangular wear and tapered wear-type defects under external pressure. More than hundreds of finite element analyses were performed to investigate the effect of key parameters on failure pressures. In cases of the elliptical and rectangular wear, the defect depth was dominant parameter to estimate the failure pressure while the defect length had a minor effect on failure pressure. Furthermore, even though the defect length and wrap angle continuously increased, the failure pressure temporarily decreased and then converged to a constant value. In case of the tapered wear, the variation tendency of failure pressures was similar to that of rectangular wear, however, the effect of defect length on failure pressure was clearer. These results provide valuable information not only for the estimation of failure pressure but also for the understanding of the failure behavior of helical tubes with a wear-type defect.

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