International Journal of Pressure Vessels and Piping 117-118 (2014) 25–32

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

Determination of interaction effect between cracked tube and eggcrate support plate on the burst pressure

Hyun-Su Kim [a], Chang-Kyun Oh [a], Hee-Jin Shim [a], Yoon-Suk Chang [b,*]

[a] KEPCO Engineering and Construction Company, Inc., M-Tower, 188 Gumi, Bundang, Sungnam, Gyeonggi 463-870, South Korea
[b] Department of Nuclear Engineering, Kyung Hee University, 1732 Deokyoungdaero, Giheung, Yongin, Gyeonggi 446-701, South Korea

Keywords:
Axial crack
Burst pressure
Contact condition
Finite element analysis
Interaction effect

ABSTRACTS

Steam generator is one of the major components in the nuclear power plant comprising pressure-retaining boundary. Typically, there are thousands of thin-walled tubes as well as several support plates in a steam generator. According to the operating experience of the steam generators, a lot of cracks have been found in the tubes. Therefore, an accurate integrity assessment of the tubes is crucial for maintaining safety as well as reliability of a nuclear power plant. The steam generator tubes are supported by several support plates, and deformations of the tubes are partially restrained depending on the crack location and the gap between the tube and the support plate. In the authors' previous study, it has been reported that burst pressures for circumferentially cracked tubes are significantly affected by the support plate and existing solutions differ from the actual burst pressure. However, this interaction effect for axially cracked tubes has not been fully investigated while those are frequently occurred during operation. In this paper, therefore, a number of elastic-perfectly plastic finite element analyses were performed considering the contact interaction between the tube and the support plate. The burst pressure is then evaluated in accordance with the lower bounding limit theorem and the support-induced interaction effects on the burst pressure were determined.

1. Introduction

The steam generator in the nuclear power plants is a kind of heat exchanger and comprises over 50% of the total primary pressure-retaining boundary. In general, there are thousands of thin-walled tubes as well as several eggcrate support plates in a steam generator, as shown in Fig. 1. According to the operating experience of the steam generators, lots of cracks due to stress corrosion cracking (SCC) have been found at top of tube sheet (TTS) region and near the eggcrate support plate (SP) region of the tubes [1,2]. In particular, outside diameter stress corrosion cracking (ODSCC) has been a critical issue for the steam generators with the eggcrate SPs [2]. Failure of the steam generator tubes can result in release of the radioactivity into the environment. Therefore, an accurate integrity assessment of the tubes is crucial for maintaining the safety as well as the reliability of a nuclear power plant.

Typical failure phenomenon of the tube subjected to internal pressure is so called burst, which is defined as the gross structural failure of the tube [3]. With regard to the prediction of the burst for a cracked tube, most of the preceding researches have been focused on the limit load (LL) approach and many LL solutions for the cracked tube have been proposed up to date [4,5]. Noting that typical tube material such as Alloy 600 is very ductile, an application of the LL approach seems plausible [5,6].

The steam generator tubes are supported by disposed support plates, and deformations of the tubes are partially restrained depending on the crack location and the gap between the tube and the support plate. In the authors' previous study [7], it was reported that the burst pressures for the circumferentially cracked tubes are affected by the interaction of the support plates and existing LL solutions significantly under-predict the actual burst pressure. However, the interaction effects by the eggcrate support plate on the burst pressures of axially through-wall and surface cracked tubes have not been fully investigated while those are frequently occurred during operation [1,2].

In this paper, therefore, a series of elastic-perfectly plastic finite element (FE) analyses were carried out for the tubes with axial through-wall crack (TWC) and surface crack (SC) considering contact interaction between the tube and the eggcrate support plate. The burst pressure is then evaluated by using the LL approach adopting the lower bounding limit theorem [8,9]. Being based on these FE analyses results, the support-induced interaction effects

* Corresponding author. Tel.: +82 31 201 3323.
E-mail address: yschang@khu.ac.kr (Y.-S. Chang).

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http://dx.doi.org/10.1016/j.ijpvp.2013.10.006

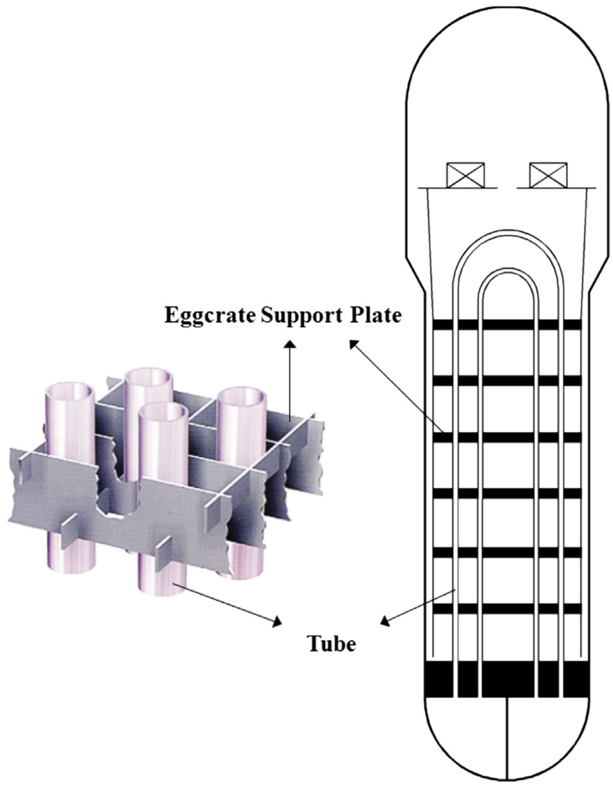

Fig. 1. Schematic of the stream generator and eggcrate support plate.

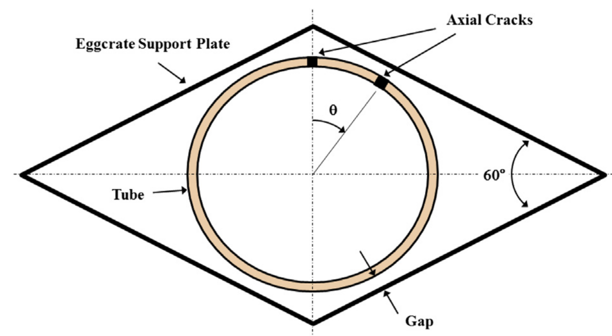

Fig. 2. Schematic of crack locations in the tube.

on the burst pressure are determined for the tubes with axial TWCs and SCs of various sizes and effects of friction on the burst pressure are investigated.

2. Finite element analysis

Global limit load can be defined as the maximum load that a given structure can sustain and when this load is reached, deformation of the structure increases without bound [8]. One way to estimate the global LL for the given structure is experimental approach. Another popular way to determine the global LL, other than the experimental approach, is numerical approach, which is based on the FE analysis. The LL of the given structure can be estimated from the direct FE limit analysis based on the lower bounding theorem assuming a small strain and an elastic-perfectly plastic material behaviour [4,8]. Since stress equilibrium and yield criterion are satisfied simultaneously in each element in the FE analysis, the results obtained from this method can be regarded as the most accurate or reliable global LL solution [6,8].

The geometry and dimensions of the tubes with axial through-wall and surface cracks are described in Table 1 and Fig. 2, respectively. The mechanical properties of the tube material, Alloy 600, adopted in this study are summarized in Table 2. These mechanical properties were determined from the tensile tests performed by some of the authors in accordance with ASTM E8. In addition, the properties of the support plate material, SA176 TP409 stainless steel, are also summarized in Table 2. Fig. 3 shows typical FE models with an axial TWC and SC. These FE models were developed by using twenty-node isoparametric solid element (C3D20R) in ABAQUS code [10] for the tube and rigid element (R3D4) for the support plate. Numbers of nodes and elements in the FE model were about 70,000 and 16,000, respectively. Considering the geometric symmetry, only a half of the tube was modelled. Also, the crack tip was modelled by using collapsed elements and $1/r$ singularity was imposed by allowing the three nodes on the collapsed face to displace independently and keeping the midside nodes at the midpoints, as illustrated in Fig. 3(a) and (b).

In this study, the axial cracks were located at $\theta = 0°$ and $\theta = 30°$, respectively. The reason is that most of the stress corrosion cracks were detected around $\theta = 30°$ region [1,2], where the harsh corrosive environment was formed during operation due to small gap, as shown in Fig. 2. Both the minimum design gap of 0.4 mm between the tube and the support plate at $\theta = 30°$ and maximum one of 1.1 mm at the same location were considered in the FE models. Elastic-perfectly plastic FE analyses for the various cases described in Table 1 were performed being based on the incremental plasticity theory with the small deformation assumption. Materials were assumed to be elastic-perfectly plastic based on the flow stress of the material. In order to avoid the numerical convergence problems associated with incompressibility, reduced integration elements were utilized for the tube. In the FE analyses, internal pressure was applied as a distributed load to the inner surface of the tube and an axial tension load which is equivalent to the internal pressure was applied at the end of the tube. As the boundary condition, a surface-to-surface contact condition was imposed between outer surface of tube and inner surface of the eggcrate support plate. The burst pressure was evaluated from the direct FE limit analysis based on the lower bounding limit theorem assuming a small strain [4,8]. In this study, the burst pressure was defined as the maximum applied pressure at which the stress equilibrium and the von Mises yield criterion are satisfied simultaneously in each element.

Table 1
Geometry and dimensions of the tube with axial cracks.

Mean radius, R_m (mm)	Thickness, t (mm)	Crack length $2c$ (mm)	Crack location, θ (Deg.)	Crack depth ratio, a/t	Gap (mm)
8.99	1.07	0, 5, 10, 20, 30	0, 30	0, 0.25, 0.5, 0.75, 1.0	0.4, 1.1

Table 2
Mechanical properties of the tube and support plate materials.

Component	Young's modulus, E (GPa)	Yield strength, σ_{YS} (MPa)	Tensile strength, σ_{TS} (MPa)	Flow stress, σ_f (MPa)
Tube	195.0	246.4	645.1	445.8
Support plate	200.0	240.0	450.0	345.5