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Collapse Pressure Evaluation of Helical Steam Generator Tubes Considering Geometric Characteristics and Temperature-Dependent Material Properties

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1. Introduction

In recently proposed Small Modular Reactor (SMR) designs, helical steam generator (SG) tubes have been adopted to provide an efficient heat transfer area within the confined vessel space [1]. Unlike conventional U-tube SGs, helical-coil tubes possess a three-dimensional (3D) geometry with numerous design variables, making it challenging to account for all geometric parameters while ensuring structural integrity [2].

The collapse behavior of helical heat transfer tubes under external pressure varies nonlinearly with changes in operating conditions and geometric parameters [3]. It is also sensitive to the material constitutive model, and an elastic perfectly plastic assumption can cause non-negligible deviations by neglecting strain hardening.

In this study, the effects of geometric variables and collapse pressures of helical tubes were analyzed under external pressure. Governing variables were identified through preliminary finite element (FE) analyses. The material properties of Alloy 690 were quantified, using the master curve method, to reflect the actual material behavior. Based on the FE analysis results, an estimation equation was developed to predict the collapse pressure of helical tubes.

2. Analysis method

2.1 Analysis model and conditions

3D single-turn FE models were constructed to reduce computational cost while preserving the essential structural behavior of actual multi-turn helical tubes. The geometric variables are the helical diameter (D), helical angle (θ), and tube thickness (t), as illustrated in Fig. 1. The inner diameter of 12 mm was used for the tube.

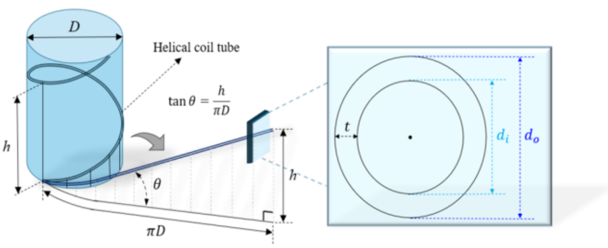

Fig. 1. Schematic of geometric variables.

As a loading condition, external pressure was uniformly applied over the entire outer surface of the tube. The end-cap effect was neglected because the tube was sufficiently long. To approximately represent the displacement-restrained characteristics all directional displacements and rotational degrees of freedom at both end sections were fully constrained. The Riks option was used to calculate the external pressure at the point of structural instability, and the collapse pressure was determined as the pressure corresponding to the maximum load proportional factor.

2.2 Preliminary analyses

The governing geometric variables were identified through a series of preliminary analyses. The results are presented in Fig. 2, where the influence of D on the collapse pressure was found to be insignificant within the examined range. Therefore, in the main analysis, D was fixed as a representative value of 500 mm, and θ and t were selected as the governing variables of the collapse pressure. The ranges of θ and t were 8 to 24° and from 1.5 to 2.5 mm, respectively.

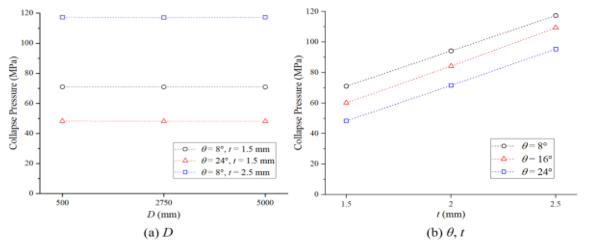

Fig. 2. Preliminary analysis results to identify governing variables.

2.3 Material property

Alloy 690, which is widely employed for helical SG tubes, was selected as the examining material. A master curve approach was adopted to characterize its temperature-dependent mechanical behavior [4]. The master curve was constructed from the available tensile test data, and the corresponding temperature-dependent true stress–strain curves were subsequently generated using interpolated material properties, as shown in Fig. 3. The analysis temperatures (180, 260, and 340 °C) were chosen to envelop the representative operating temperature range of commercial SMR SGs.

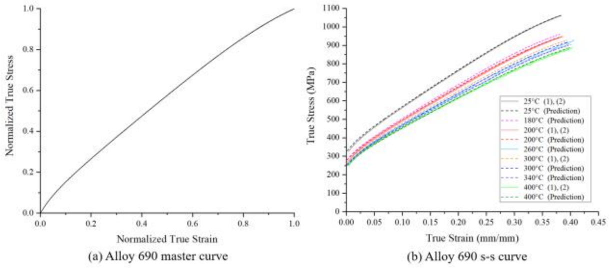

Fig. 3. The mater curve and temperature-dependent stress-strain curves of Alloy 690.

3. Analysis results

3.1 Collapse pressure evaluation

Fig. 4 shows the main FE analysis results according to varying θ and t at each temperature condition. As compared in the figure, collapse pressures decreased as the temperature and θ increased, while they increased as t increased.

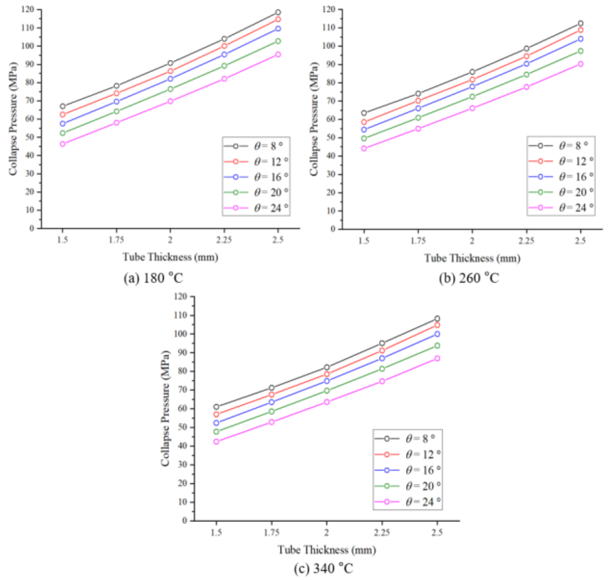

Fig. 4. Variation of collapse pressures with θ and t at the prescribed temperatures.

3.2 Collapse pressure estimation equation

To derive a collapse pressure estimation equation for helical tubes, a stepwise procedure based on the analysis data was employed. Hill's plasticity theory [5] was adopted as the baseline model for evaluating collapse pressure. The plastic collapse pressure of a perfect cylinder is expressed by Eq. (1). For helical tubes, additional correction terms accounting for θ and t were introduced, leading to the modified form given in Eq. (2). These correction terms were determined through regression analysis using collapse pressures obtained from a total of 75 FE analyses, as summarized in Eq. (3).

$$P_c^{Mises} = \frac{2}{\sqrt{3}}\sigma_y \ln\left(\frac{d_o}{d_i}\right) \quad (1)$$

$$P_c = P_c^{Mises} f(\theta, t) \quad (2)$$

$$f(\theta, t) = 0.79896 + 0.11462t - 0.87208\sin^2(2\theta) + 0.18793t\sin^2(2\theta) \quad (3)$$

The predictive performance of the proposed equation was assessed by comparison with FE analysis results. The maximum relative error of 1.18% and an R^2 of 0.999 indicate a high level of agreement between the prediction and numerical results.

4. Conclusions

In this study, the collapse pressure under external pressure was evaluated through finite element (FE) analysis considering the temperature-dependent material properties of Alloy 690 and the geometric variables of helical tubes. The main conclusions are summarized as follows:

(1) The preliminary FE results indicate that θ and t are the dominant parameters governing the collapse pressure within the examined range, whereas the influence of D is negligible.
(2) When temperature dependence was incorporated using the master curve approach for Alloy 690, the collapse pressure decreased with increasing temperature.
(3) A collapse pressure estimation equation was derived through regression analysis of the FE results, based on a modified Hill-type plastic collapse formulation.

ACKNOWLEDGMENTS

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