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Stress Analysis of Surge Line due to Thermal Stratification

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1. Introduction

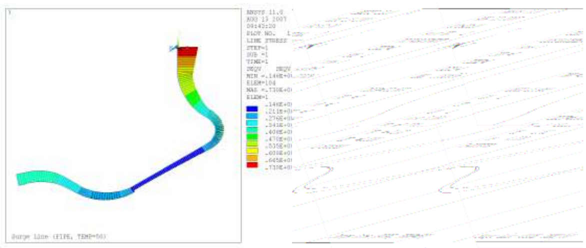
If two media with different densities (i.e. with different temperatures) flow inside a pipe, thermal stratification can occur. Or, warm water is lighter than cool water and therefore tends to float on top of the cooler heavier water, resulting in the upper portion of the pipe being hotter than the lower portion. Under these conditions, differential thermal expansion of the pipe metal can cause the pipe to deflect significantly. Unexpected piping movements are highly undesirable because of potential high piping stress that may exceed design limits for fatigue and stress. The problem can be more acute when the piping expansion is restricted, such as through contact with pipe whip restraints. Plastic deformation can result, which can lead to high local stress, low cycle fatigue and functional impairment of the line.

Therefore in this study, the effect of thermal stratification on the structural integrity of the pressurizer surge line is investigated. Finite element models of the surge line are developed using several element types available in the general purpose structural analysis program and stress analyses are performed to get the response characteristics for the various types of top-to-bottom temperature differential due to the thermal stratification.

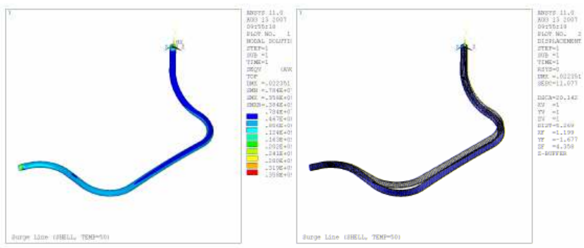
2. Analysis

The stress analysis for the internal pressure of 10 MPa is performed to get the stress distributions in the surge line. The equivalent stress and deflection comparisons between element types showed that there are differences of stress between element types. Comparing results between pipe element and shell or solid elements, large differences of stress and deflection exist for all surge line such as nozzles and elbows. In ANSYS[1], pipe element (PIPE16) is assumed to have “closed ends” so that the axial pressure effect is included. If the endcap effect is included in the analysis, the maximum stress decreases [2]. That’s why the pipe element gives smaller stress than shell or solid element models. When comparing results between shell and solid elements, a little difference of stress and deflection exists for maximum values. In ANSYS, shell element (SHELL63) has six DOFs such as 3 translations and 3 rotations but solid element (SOLID45) has three DOFs such as 3 translations. Therefore, fixed boundary conditions at both ends gives the different boundary conditions for shell and solid models which generate the different stress at the boundary such as nozzles. The stress of the elbows which are located far away from the boundary is almost the same.

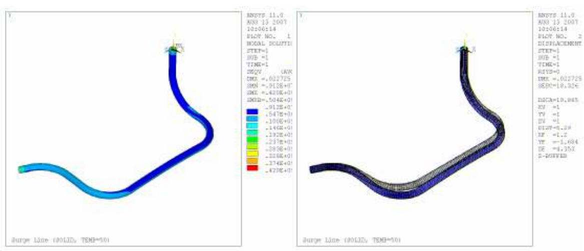
The stress analysis due to the thermal stratification is performed to get the stress distributions in the surge line. Temperature distributions of the surge line are obtained from the thermal hydraulic analysis and they are used as an input to the structural analysis. But in this study, the temperature is taken arbitrarily to be applied to the lower half and upper half of the pipe by top-to-bottom temperature differential ΔT, which shows the temperature distributions of ΔT = 50°C. The equivalent stress and deflection comparisons between element types are shown in Fig. 1 where the maximum stresses are found in the nozzle which connects the surge line with the pressurizer.



(a) pipe element



(b) shell element



(c) solid element

Fig. 1. Equivalent Stresses and Deformations for Thermal Stratification

As shown in Fig. 1, there are differences for stresses between element types. Comparing results between pipe element and shell or solid elements, large differences of stress and deflection exist for all surge line such as nozzles and elbows. In ANSYS, temperature loads for pipe element are input as element body loads at the nodes by only four points along the circumference. Therefore, the temperature is not defined in detail as in shell or solid element. This may lead to the pipe element generating different stresses from shell or solid element models.

3. Results and Discussion

Sensitivity study of temperature loads for pipe element generated large differences according to the temperature application along the circumference. Therefore, care should be taken in pipe element to apply temperatures at four points using T_{avg}, T(90) and T(180) inputs.

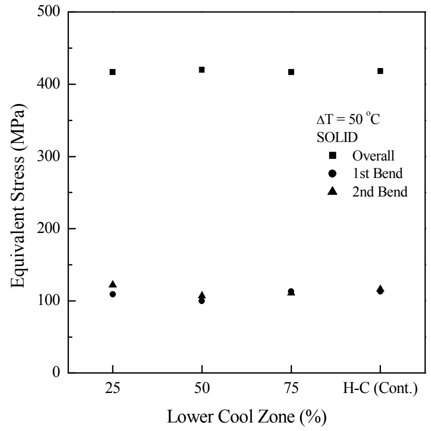
Using the solid model of the surge line, sensitivity study is performed for thermal stratification, where three kinds of temperature distribution in the circumferential direction are considered, and one another case of temperature distribution along the length is considered, where the temperature is continuously changed from the hot leg to the pressurizer with a step change along the length.

Comparisons of equivalent stresses and deflections between temperature loadings are made in Fig. 2. There is little difference in the stress, but much difference in the deflection due to the temperature loading. For all cases, upper half and lower half distribution of the top-to-bottom temperature differential in pipe gives the most conservative results.

Stress analyses are performed to get the pressure and thermal stresses of the surge line. Upper half and lower half distribution of the top-to-bottom temperature differential in pipe which gave the most conservative results are applied along with the internal pressure of 10 MPa to generate the normal operating stresses.

The equivalent stresses and deflections due to thermals stratification of ΔT = 50°C and internal pressure of 10 MPa showed that the stress due to thermal stratification is much higher than that of internal pressure and therefore, thermal stratification is expected to be the major contributor to fatigue life of the surge line.

Assuming top-to-bottom temperature differential ΔT of 30°C from thermal hydraulic analysis for steady state fluctuation, which has the biggest number of cycles 10^6 during the design life and is expected to be the major contributor to the fatigue life, fatigue assessment due to thermal stratification and internal pressure is performed. The maximum alternative stress in this case is $S_a = 324 / 2 = 162$ MPa and from the fatigue curve for austenitic steel, the number of cycles is 2×10^6. Therefore, usage factor (UF) is $10^6 / 2\times10^6 = 0.5$.



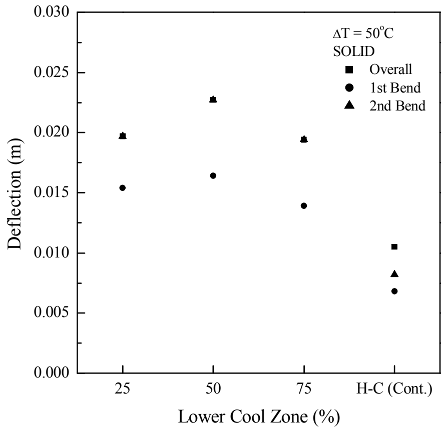


Fig. 2. Comparison of Stresses and Deflections between Various Temperature Distributions due to Thermal Stratification

4. Conclusions

- Pipe element is not proper to calculate the stress of the full model of the surge line due to the application method of the internal pressure.
- Shell and solid elements generate the different stress at the nozzles but the same stress at the elbows due to the different degrees of freedom imposed on the fixed boundary conditions.
- Applying top-to-bottom temperature differential of lower half and upper half in pipe gives the highest stress in the flange but does not give conservative stress in elbows.
- Stress due to thermal stratification is much higher than that due to internal pressure.

REFERENCES

[1] ANSYS, *ANSYS Structural Analysis Guide*, ANSYS, Inc., Houston (2007).

[2] Jhung, M.J., Kang, D.G., and Jo, J.C., "Coupled Thermal Hydraulic and Stress Analysis of Pipe with Two Bends," *Transactions of the Korean Society of Pressure Vessels and Piping*, Vol.3, No.2, pp.65-70 (2007).