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Fatigue Analysis of Reactor Pressure Vessel using APDL

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1. Introduction

There are many transients considered in the design stage and their effect on the structural integrity should be addressed during licensing documents as a form of design report. Therefore in this study, the analysis procedure for fatigue analysis is suggested including thermal and stress analyses.

For the transient thermal analysis, heat transfer coefficients are determined based on the operating environments and thermal transient data are simplified for preparing an easy input deck. The severest instants are found considering satisfaction of total stress intensity range and stresses at those times are obtained along with pressure application, which are used for the fatigue analysis to give the final cumulative usage factor.

All of these analysis procedures are established using ANSYS Parametric Design Language (APDL). Example analyses are performed for the reactor pressure vessel of SMART for arbitrary transients and two acceptance criteria, primary plus secondary stress intensity and cumulative usage factor, are investigated

2. Analysis

2.1 Finite Element Models

Two finite element models are developed for transient thermal analysis and structural analysis using ANSYS [1]. For the thermal analysis, 2-D thermal solid elements are used in reactor vessel and cladding. This element can be used as an axisymmetric ring element with a 2-D thermal conduction capability and has four nodes with a single degree of freedom, temperature, at each node. Six elements are made in the radial direction of the shell to represent the profile of the result in that direction well enough to generate sufficient information for ensuing analysis.

For the structural analysis, 2-D structural solid elements are used as shown in Figure 1. This element is used for 2-D modeling of solid structures and can be used as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node: translations in the nodal *x* and *y* directions. Symmetric boundary conditions are imposed at the center nodes of the upper and lower heads. In addition, one node is fixed in all directions not to generate a rigid body motion.

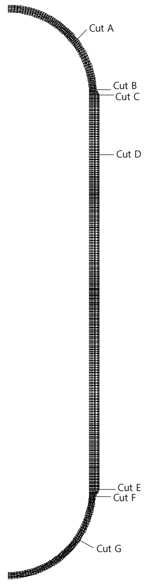


Fig. 1. Finite element model and locations for calculating fatigue usage factor

2.2 Thermal Analysis

To get the temperature distribution in the shell and head of the vessel, transient thermal analyses are performed for each transient defined previously. 2-D thermal surface effect elements for the thermal analysis are used for various surface effect applications such as heat transfer coefficient which may be overlaid onto a face of any 2-D thermal solid element.

2.3 Stress Analysis

Using the temperature distributions determined in thermal analysis, stress analysis is performed with the inclusion of pressure loads. Stresses are not obtained for all time steps used in the thermal analysis. Instead, time point samplings are made according to ASME Section III, Subsection NB-3653.2 [2] to find the severest times.

3. Fatigue Assessment

Cycle counting is used to summarize (often lengthy) irregular load-versus-time histories by providing the number of times cycles of various sizes occur. Rain-flow method is used in this study [3]. The first step in implementing this procedure is to draw the stress-time history so that the time axis is oriented horizontally, with increasing time rightward. One could now imagine that the stress history forms a number of “pagoda roofs”. Cycles are then defined by the manner in which rain is allowed to “drip” or “fall” down the roofs. A number of rules are imposed on the dripping rain so as to identify closed hysteresis loops.

Stress concentration factors of Cuts B and F at outside are calculated and they are used in fatigue evaluation.

The S-N curve, a curve of alternating stress intensity, $S_{alt} = S_p/2$, versus allowable number of cycles, is used [2], and it is adjusted considering design temperature.

The ranges of primary plus secondary stress intensities are summarized in Figure 2, which shows that stresses of all locations investigated in this study are well below the allowables satisfying criteria.

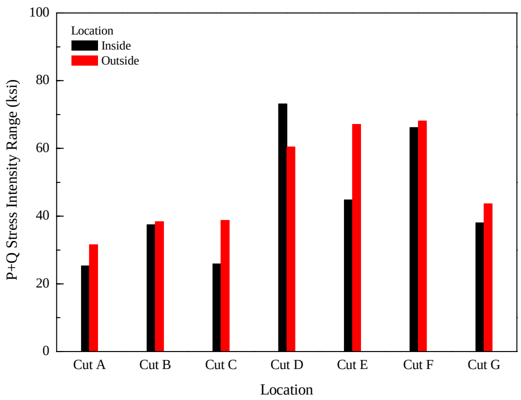
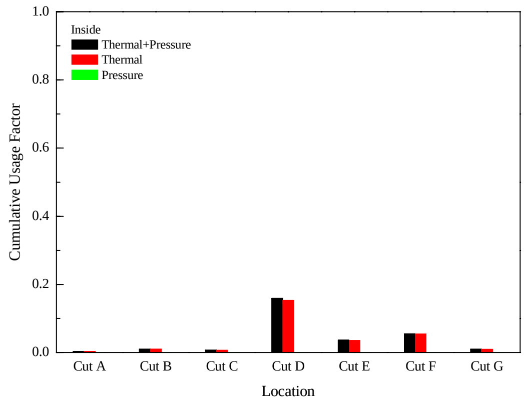


Fig. 2. Primary plus secondary stress intensities

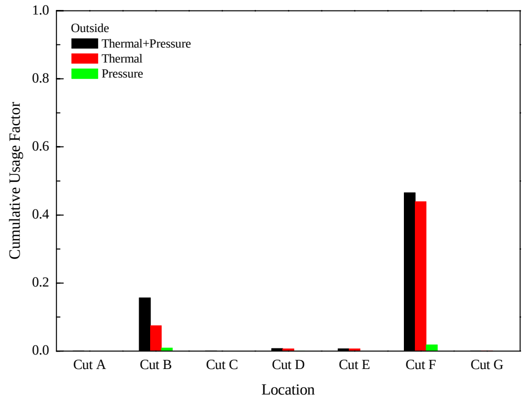
When the stress concentration factors are not considered, the cumulative usage factors at outside of Cut-B and Cut-F are 0.00699 and 0.02676, respectively, which are so small compared with those from considering case. Therefore, the stress concentration factor is found to be one of the most important factors affecting the fatigue usage factor.

Fatigue evaluations are performed when thermal stress and pressure stress only are considered separately, and the ranges of primary plus secondary stress intensities and the cumulative usage factors are investigated.

The cumulative usage factors are well below the allowable, 1.0, as shown in Figure 3, satisfying the requirement. The comparison of cumulative usage factor among pressure + thermal loadings, thermal loading and pressure loading are shown in Figure 10. At the inside of the vessel, pressure load does not affect the fatigue usage factor at all, but a small effect of pressure is shown at the outside. It is found that most fatigue usage factor comes from temperature variations during transient.



(a) Inner surface



(b) Outer surface

Fig. 3. Comparison of cumulative usage factors

4. Conclusions

Example analyses for the reactor pressure vessel are performed for arbitrary transients postulated and two criteria are investigated generating following conclusions:

- The ranges of primary plus secondary stress intensities and cumulative usage factors are well below the allowables satisfying requirement.
- Major contribution for fatigue usage factor is temperature variations during transients.
- No effect of pressure loading on the fatigue factor is found at the inside of the vessel.
- The stress concentration factor is one of the most important factors affecting the fatigue usage factor.

REFERENCES

[1] ANSYS, Inc., *Theory Reference for ANSYS and ANSYS Workbench Release 12.0*, Canonsburg, PA (2009).

[2] ASME, *ASME Boiler and Pressure Vessel Code*, Section III, Division 1, Subsection NB Class 1 Components, The American Society of Mechanical Engineers (2004).

[3] Bannantine, J.A., Comer, J.J., Handrock, J.L., *Fundamentals of Metal Fatigue Analysis*, Prentice Hall, New Jersey (1989).