ASME Section VIII, Div 2 High-Pressure LOX Tank Analysis

Analysis Type:
ASME Pressure vessel, fatigue and thermal-stress analysis, Femap API

Discipline:
Thermal-stress, Transient thermal, fatigue, ASME, stress classification, Femap API, stress analysis, NX Nastran, Femap

Project Overview

The development of the next generation of rocket motors requires extensive testing and that means lots of repetitive live firing. These motors are feed with a standard mixture of high-grade kerosene or RP-1 and liquid oxygen (LOX). The fuel supply system for the rocket motor is fed by two large, high-pressure tanks, with one containing RP-1 and the other LOX. These tanks were the subject of a detailed thermal-stress and fatigue analysis. Results from this analysis were classified under the ASME Section VIII, Division 2 code for pressure vessels. From an engineering perspective, these thick-walled tanks had to withstand cyclic loading of filling and emptying in support of the test program along with thermal shock loading due to the LOX filling cycle at -355 F and then high-pressure evacuation loading via an inert gas.

The biggest challenge in this work was the simulation of the LOX filling cycle where the tank is considered to be at room temperature and -355 F LOX rapidly enters the tank. A standard tank for this type of work is given in Figure 1. To illustrate the thermal gradient during LOX filling, please see Figure 2.

The filling simulation was done by setting up a customized program within Femap using their Application Programming Interface or API. As the fluid entered the tank, the thermal gradient was mimicked by a film coefficient that would be activated over time. As the liquid filled the tank, elements would become sequentially activated. The API ended up generating a couple thousand film coefficient curves, that is, one curve for each element having an interior face. The transient thermal analysis.

Results from the transient thermal analysis were then processed as thermal-stress analyses. This step was likewise automated using the Femap API. Transient thermal temperature results were mapped into individual load steps and then ganged up and solved as a NX Nastran multi-case solution. Since only one constraint set was needed, the stiffness matrix was decomposed once and the hundreds of thermal steps were quickly solved using one inverted stiffness matrix. An example of the thermal-stress results is given in Figure 3.

The thermal-stress results were then interrogated under ASME Section VIII, Division 2 fatigue classification. Miner's rule was used to sum the damage between the various thermal loading conditions. Some of the intricacies of doing an ASME type classification analysis are shown in Figure 4 where stress classification lines are defined.

Both vessels were shown to pass ASME classification and per Division 2 requirements, the engineering report was sent out stamped by a Professional Engineer.
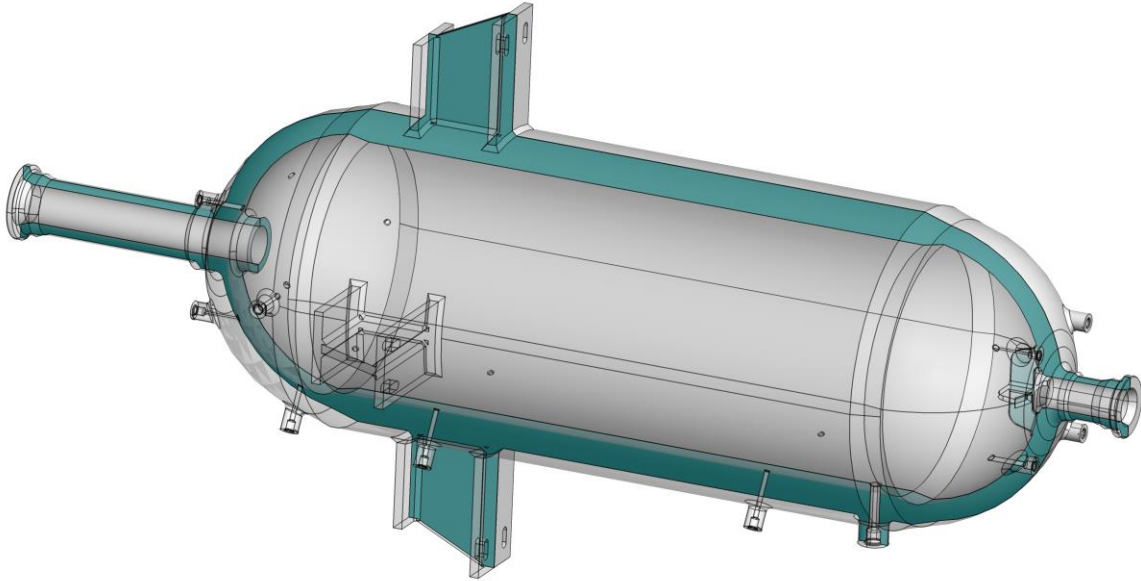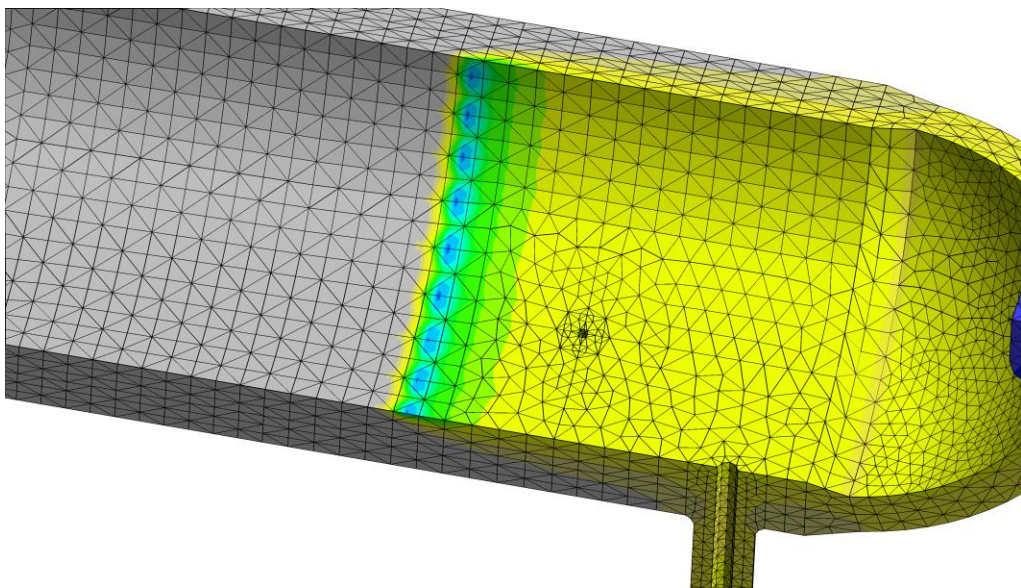
Figure 1: Thick-wall, high-pressure tank

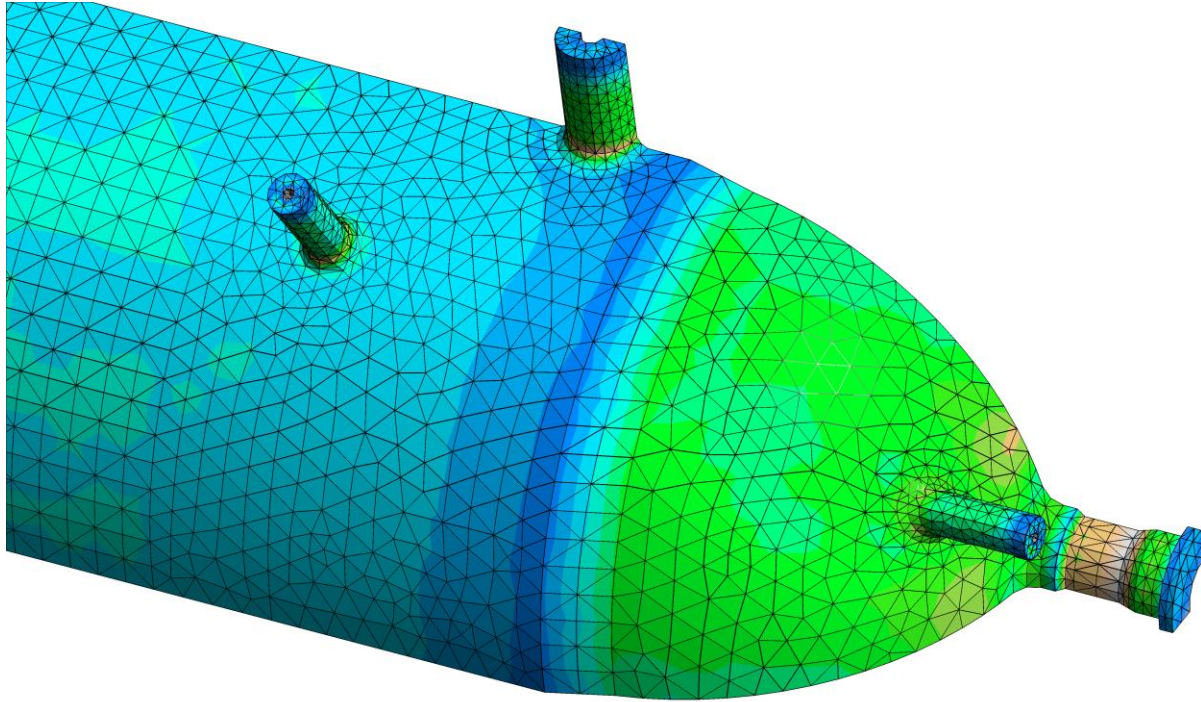**Figure 2:** Transient thermal results during simulated filling operation

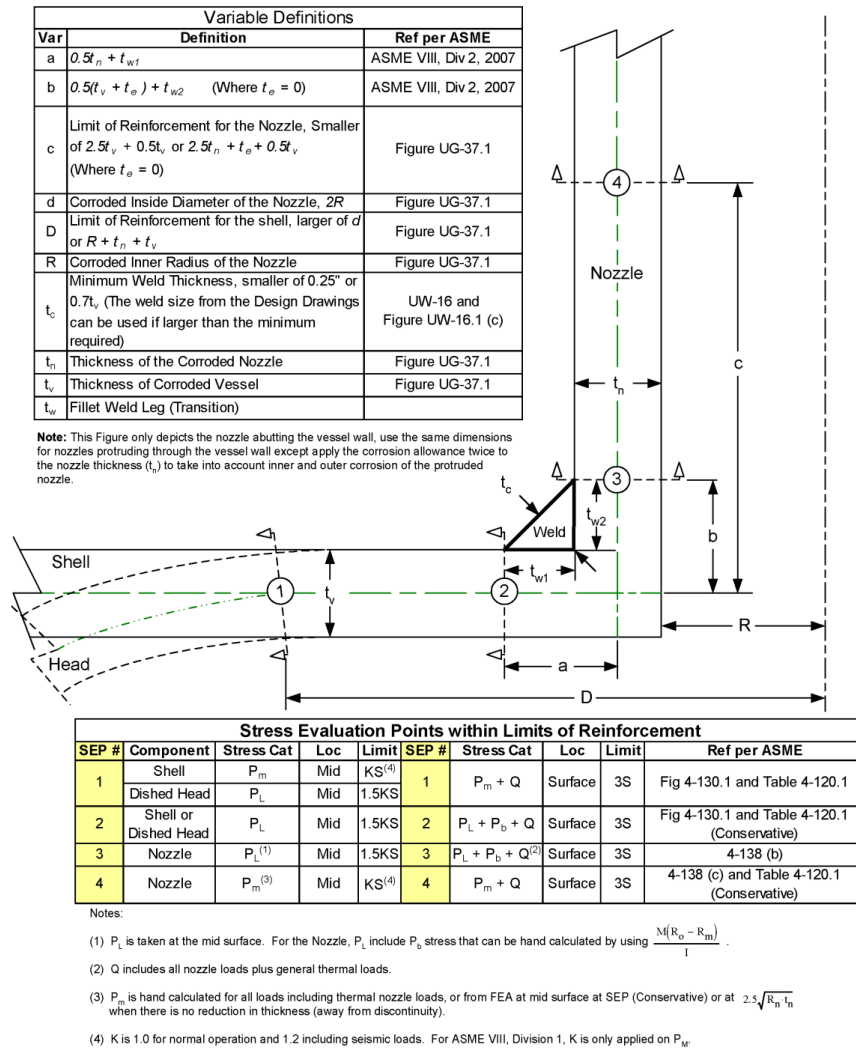**Figure 3:** Thermal-stress results from transient thermal analysis from LOX filling

Variable Definitions		
Var	Definition	Ref per ASME
a	$0.5t_n + t_{w1}$	ASME VIII, Div 2, 2007
b	$0.5(t_v + t_e) + t_{w2}$ (Where $t_e = 0$)	ASME VIII, Div 2, 2007
c	Limit of Reinforcement for the Nozzle, Smaller of $2.5t_v + 0.5t_v$ or $2.5t_n + t_e + 0.5t_v$ (Where $t_e = 0$)	Figure UG-37.1
d	Corroded Inside Diameter of the Nozzle, $2R$	Figure UG-37.1
D	Limit of Reinforcement for the shell, larger of d or $R + t_n + t_v$	Figure UG-37.1
R	Corroded Inner Radius of the Nozzle	Figure UG-37.1
t_c	Minimum Weld Thickness, smaller of 0.25" or $0.7t_v$ (The weld size from the Design Drawings can be used if larger than the minimum required)	UW-16 and Figure UW-16.1 (c)
t_n	Thickness of the Corroded Nozzle	Figure UG-37.1
t_v	Thickness of Corroded Vessel	Figure UG-37.1
t_w	Fillet Weld Leg (Transition)	

Note: This Figure only depicts the nozzle abutting the vessel wall, use the same dimensions for nozzles protruding through the vessel wall except apply the corrosion allowance twice to the nozzle thickness (t_n) to take into account inner and outer corrosion of the protruded nozzle.

Stress Evaluation Points within Limits of Reinforcement									
SEP #	Component	Stress Cat	Loc	Limit	SEP #	Stress Cat	Loc	Limit	Ref per ASME
1	Shell	P_m	Mid	$KS^{(4)}$	1	$P_m + Q$	Surface	3S	Fig 4-130.1 and Table 4-120.1
1	Dished Head	P_L	Mid	1.5KS	1	$P_m + Q$	Surface	3S	Fig 4-130.1 and Table 4-120.1
2	Shell or Dished Head	P_L	Mid	1.5KS	2	$P_L + P_b + Q$	Surface	3S	Fig 4-130.1 and Table 4-120.1 (Conservative)
3	Nozzle	$P_L^{(1)}$	Mid	1.5KS	3	$P_L + P_b + Q^{(2)}$	Surface	3S	4-138 (b)
4	Nozzle	$P_m^{(3)}$	Mid	$KS^{(4)}$	4	$P_m + Q$	Surface	3S	4-138 (c) and Table 4-120.1 (Conservative)

Notes:

(1) P_L is taken at the mid surface. For the Nozzle, P_L include P_b stress that can be hand calculated by using $\dfrac{M(R_o - R_m)}{I}$.

(2) Q includes all nozzle loads plus general thermal loads.

(3) P_m is hand calculated for all loads including thermal nozzle loads, or from FEA at mid surface at SEP (Conservative) or at $2.5\sqrt{R_n \cdot t_n}$ when there is no reduction in thickness (away from discontinuity).

(4) K is 1.0 for normal operation and 1.2 including seismic loads. For ASME VIII, Division 1, K is only applied on P_M.

Figure 4: ASME stress classification line requirement around nozzles.

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