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Pressure Vessel Engineering Ltd. provides: ASME Vessel Code Calculations - Finite Element Analysis (FEA) - Solid Modeling / Drafting - Canadian Registration Number (CRN) Assistance

Discontinuity Stresses in Flange and Dished Heads

Summary:

In ASME VIII-1 the design of spherical heads and cylindrical shells is based on formulas that calculate the actual stress in the component. The design is acceptable if the calculated stress is less than the allowable material stress.

Stress formulas are also found for flanged and dished (F&D) heads. However these formulas are based on experience and cannot be traced back to theoretical stress equations. The rules are correlations based on physical testing hidden in the form of a stress equation. The results regularly shock theoreticians but work out just fine in practice.

The experience based rules allow stresses in flanged and dished heads higher than other code rules like VIII-2 FEA stress analysis allow. The example head in this article meets VIII-1 code rules but has discontinuity knuckle stresses above 3x allowed by VIII-2 analysis. Experience indicates that it is okay.

VIII-1 code rules:

VIII-1 provides rules for F&D heads in UG-32 and appendix 1-4 that allow for solving for thickness or maximum pressure. The formula is in the same form as the equation for a straight shell, but this equation does not predict the actual stress in the shell. The maximum allowed operating pressure is 88.5 psi.

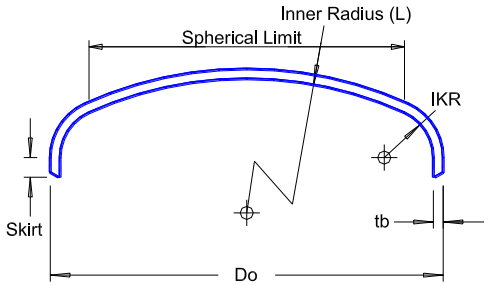
For this article, a sample F&D head with the following properties is used:

S = 20,000 psi
E = 1.00
IKR = 10.440 in

t = 0.652 in
L = 168.00 in
ID = 172.696 in
OD =174 in

PMax = (2*S*E*t) / (L*M + 0.2*t)
= (2*20,000*1*0.652) / (168*1.753 + 0.2*0.652)
= **88.5 psi**

M = 0.25*(3+(L / IKR)^0.5)
= 0.25*(3+(168 / 10.44)^0.5)
= 1.753

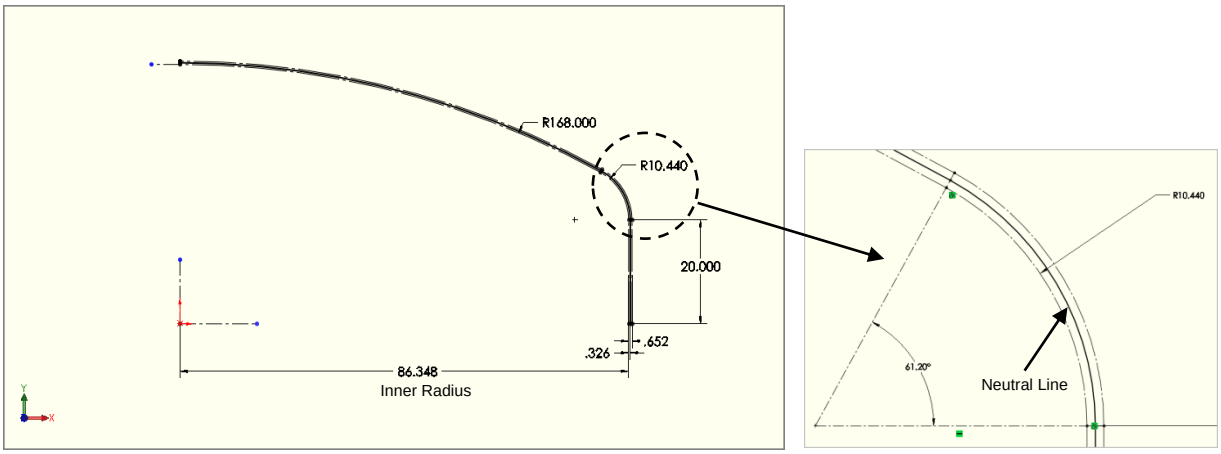


Finite Element Analysis:

The F&D head is comprised of 3 components:

- Dished Crown (168” inside radius)
- Knuckle (10.44” inside radius)
- Straight Flange (174” outside diameter)

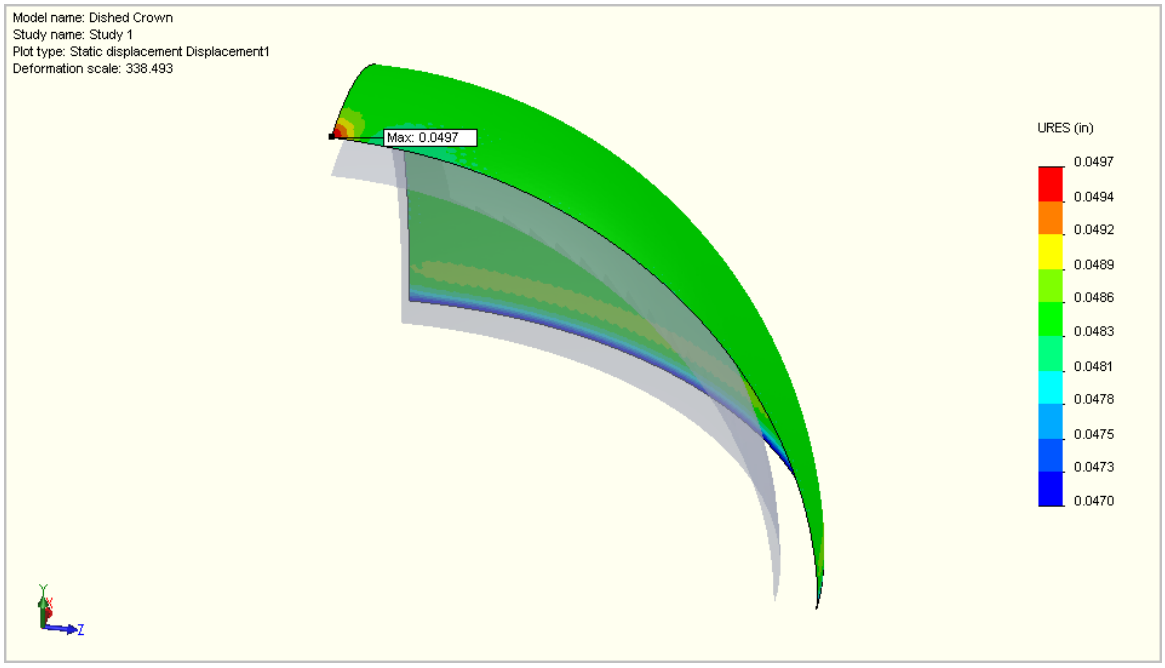
These three components can be seen in the image below.



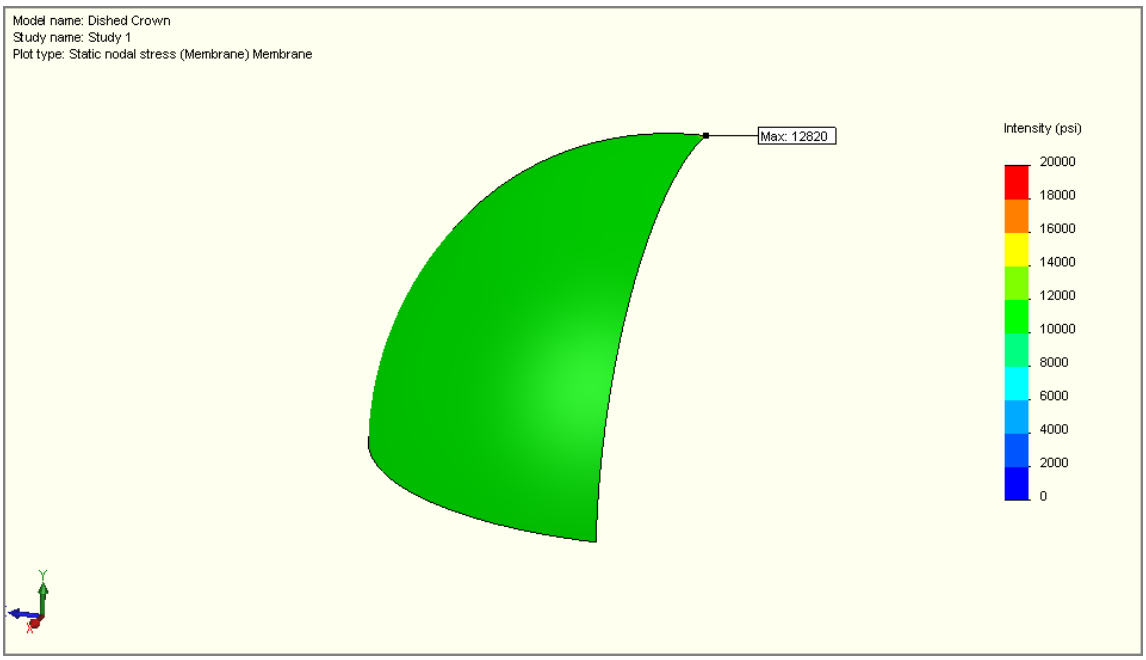
The above image shows all geometry of the F&D head. Note that all dimensions are referenced to the inside surface of the head, however the shell model is created from the neutral line running half way between the inside and outside surfaces.

The three components - dished crown, knuckle and straight flange are analyzed separately to determine their individual displacement and stresses.

Dished Crown:

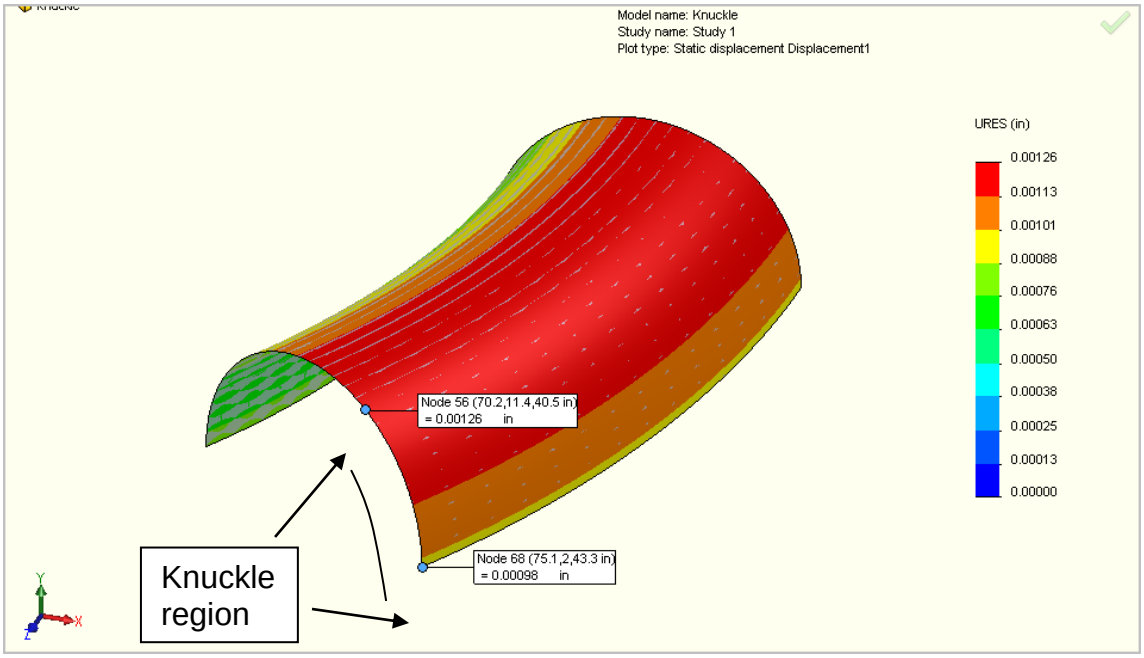


The crown on its own displaces as if it is part of a radially expanding spherical shell. The average displacement is 0.0483".

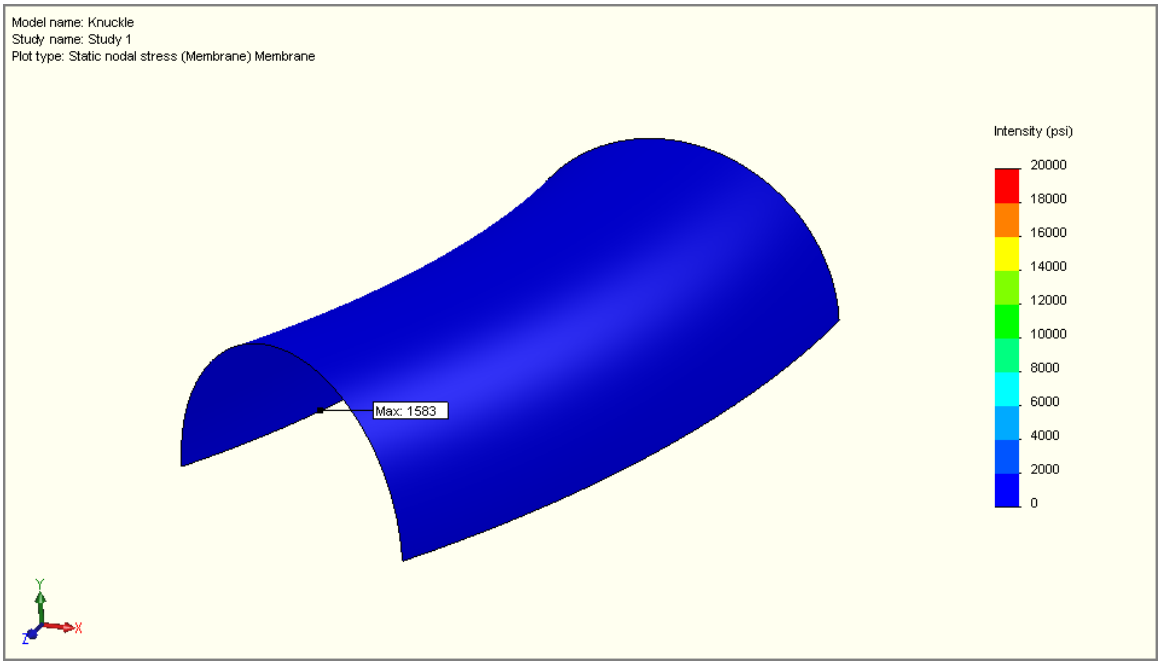


The membrane stresses in the crown are a uniform 12,820 psi - less than the allowable 20,000 psi.

Knuckle:

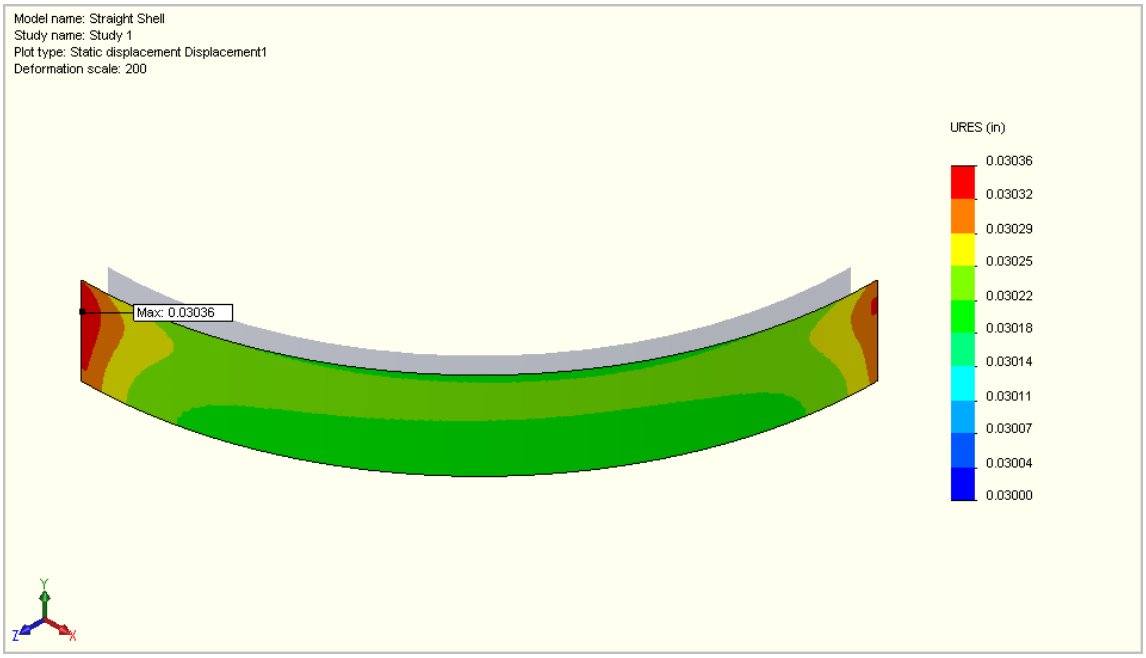


The knuckle is a section of a torus. The maximum displacement is 0.00126", found at the point where the knuckle meets the crown. Results have also been probed at the point which meets the head straight section.

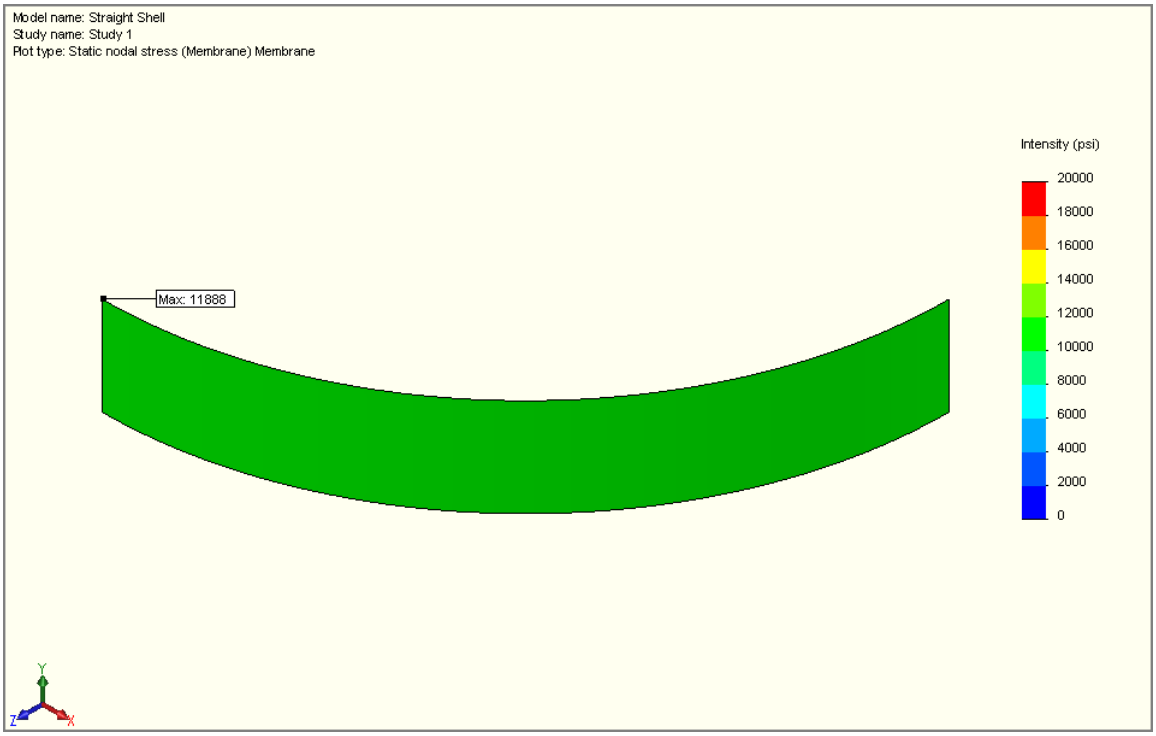


The Membrane Stresses is relatively uniform. The maximum stress is 1583 psi which is below the 20,000 psi allowable.

Straight Pipe:



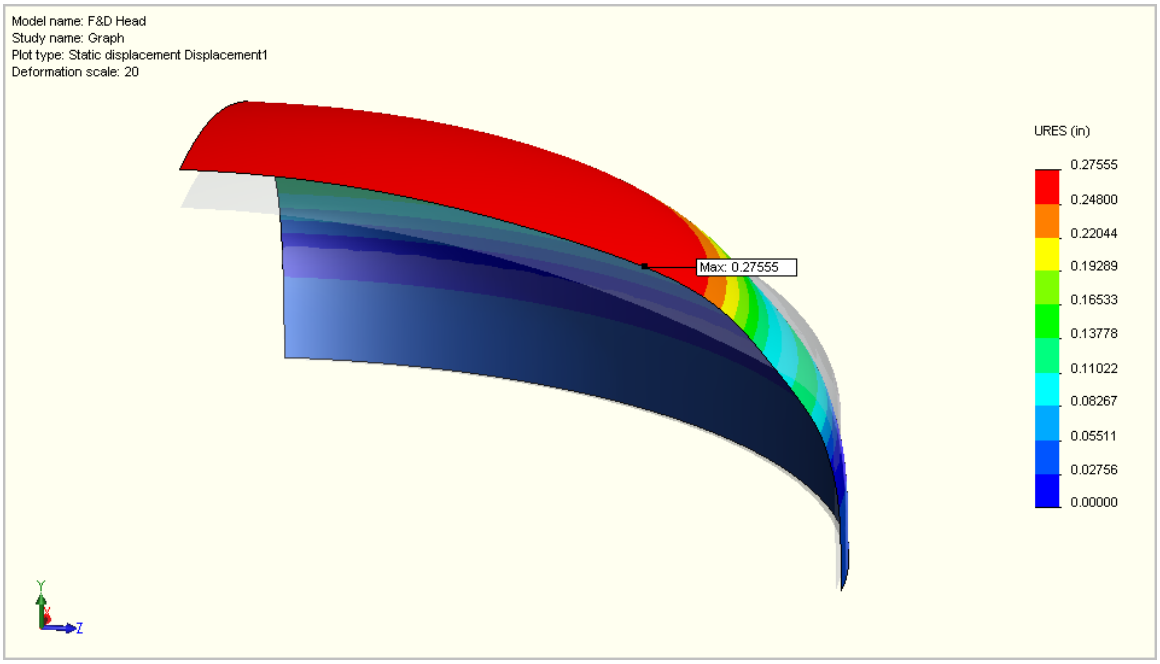
The above image shows a section of the straight pipe component of the head. The displacement in the straight pipe model is relatively uniform. The maximum displacement is 0.0304".



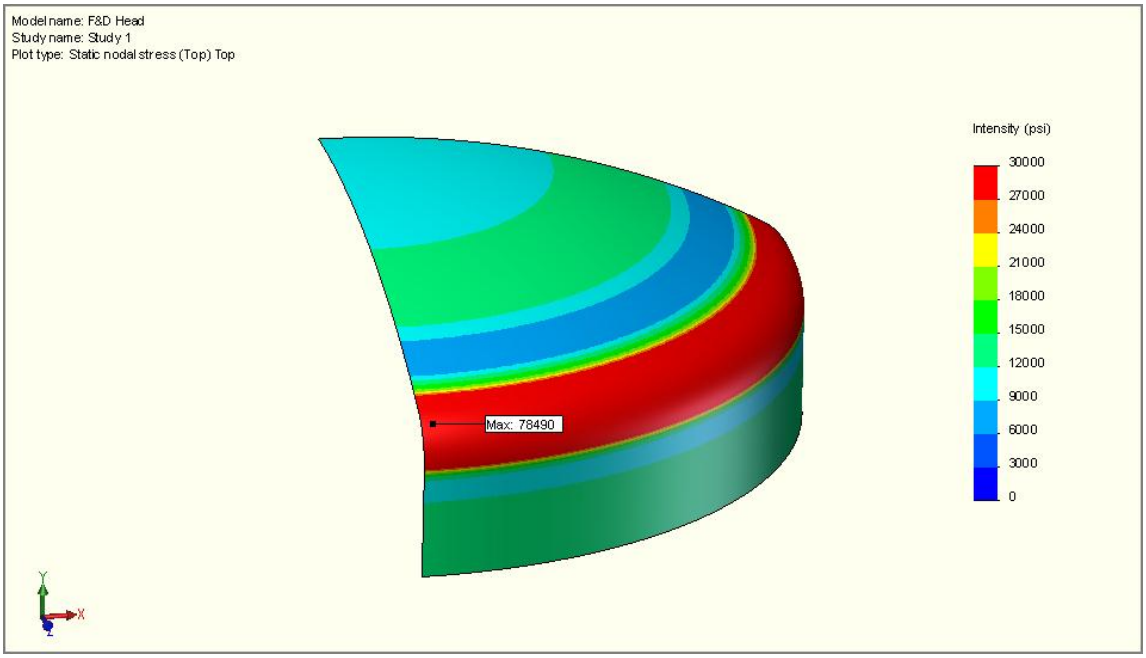
The above image shows the Membrane Stresses in the straight pipe model section. The stress is uniform. The maximum stress is 11,765 psi which is below the 20,000 psi membrane allowable.

Each component on its own has stresses less than the allowed code limit. The spherical crown has the highest stress portion. Combining the 3 components into one analysis we would expect that the highest stresses would be found in the crown and that the VIII-1 code rules are very conservative.

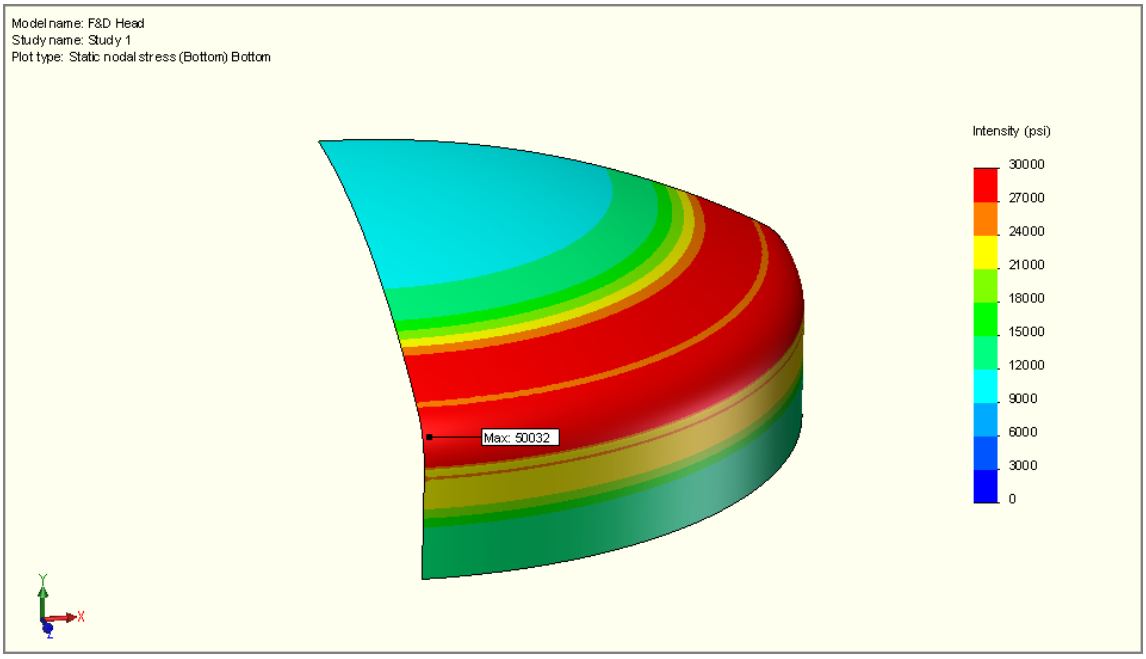
Analysis of the complete head:



The complete F&D head has a maximum displacement is 0.277" much higher than previously found in the individual components. Each component does not displace uniformly as shown in the previous studies.



The top side stress (bending + membrane) is far above the 20,000 psi VIII-1 basic material allowable.



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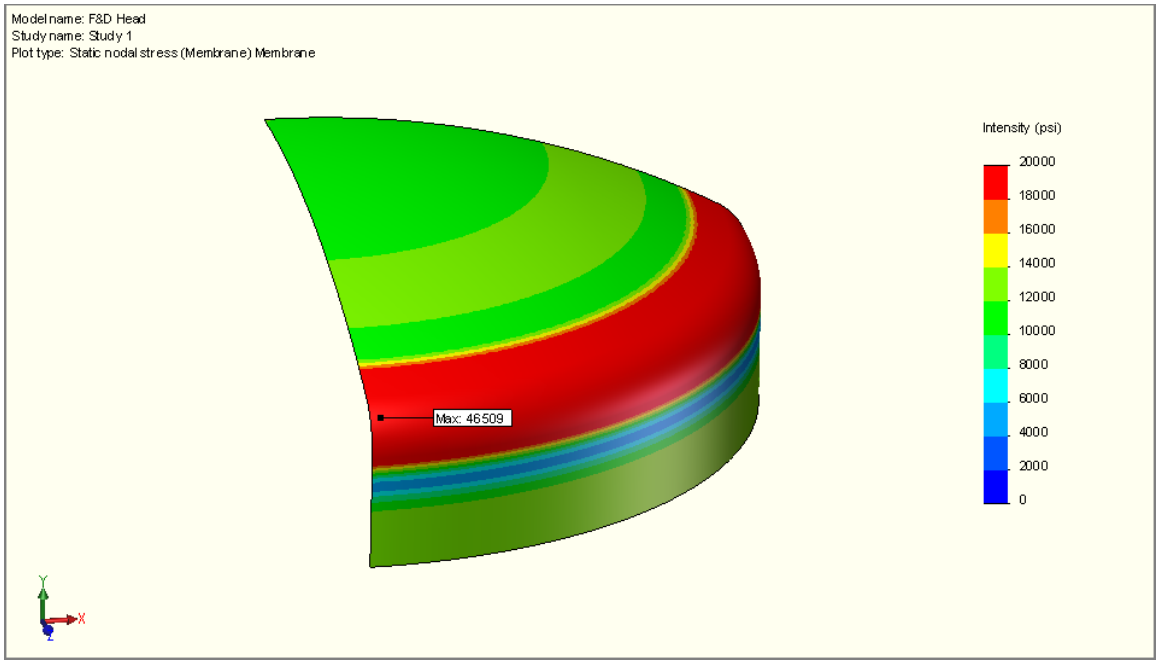
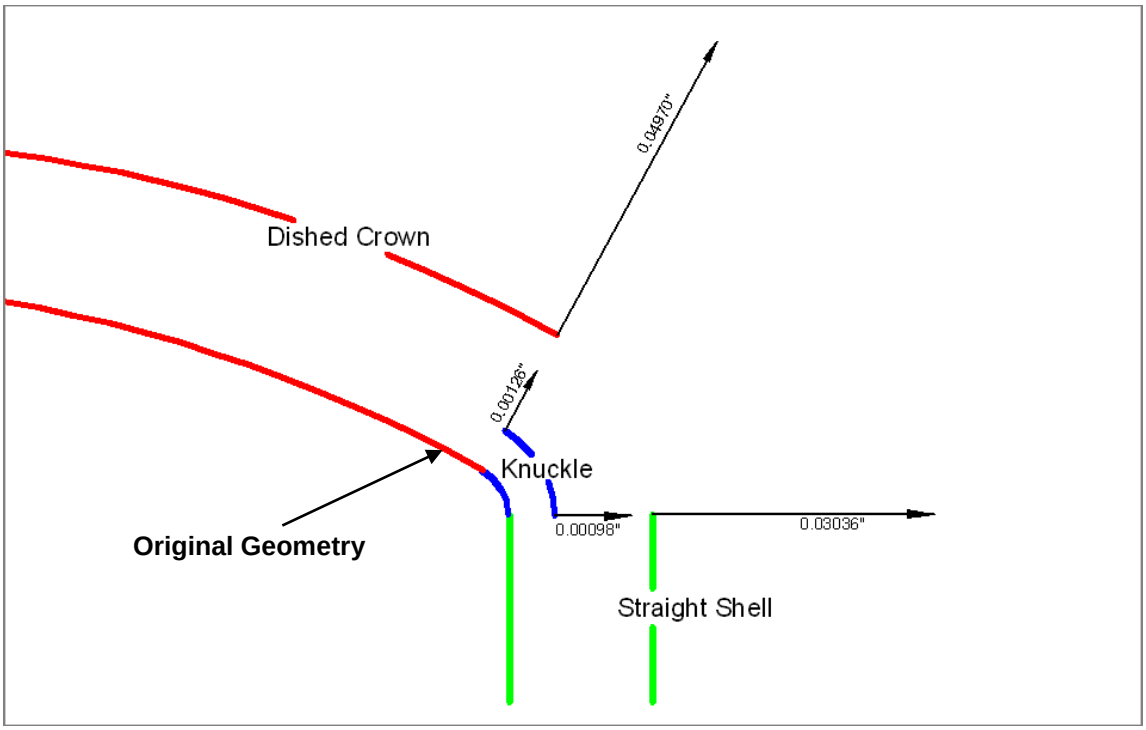


The average (membrane) stresses are also above the VIII-1 basic material allowables.

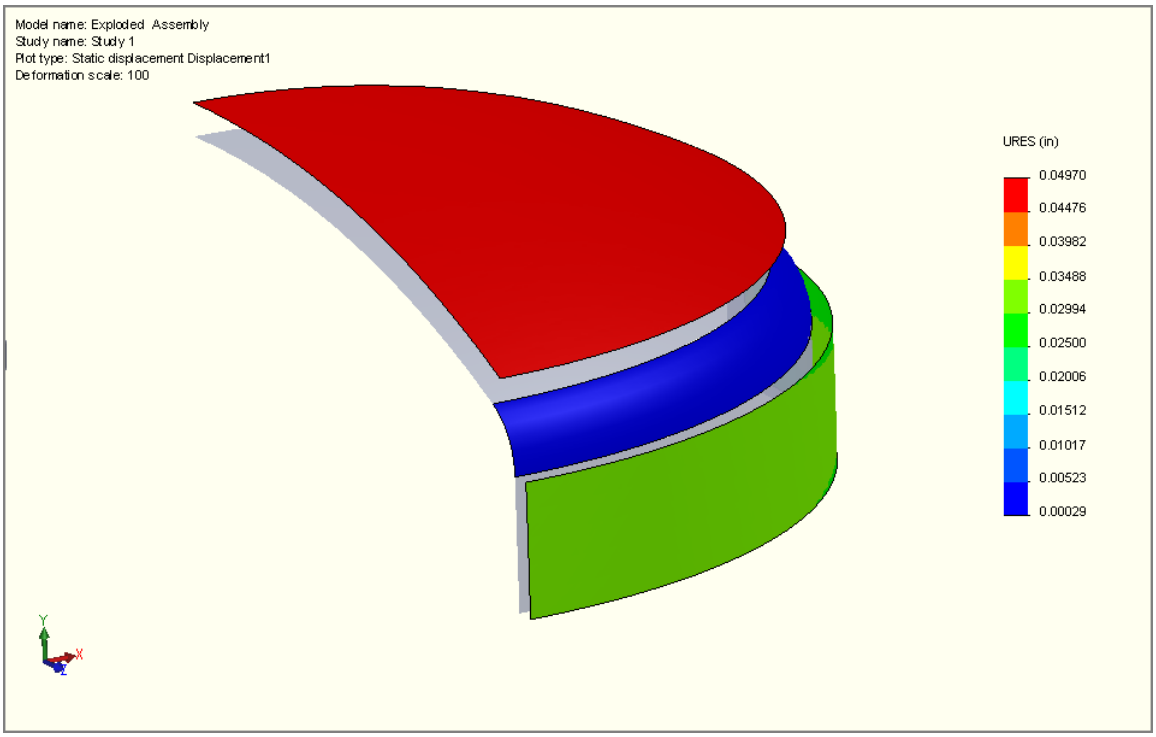
The large stress and displacement originate with the difference in growth of the different head components. This is a discontinuity stress. The allowable stress level used in the VIII-1 design rule was 20,000 psi. The FEA shows an actual stress of 78,490 psi.



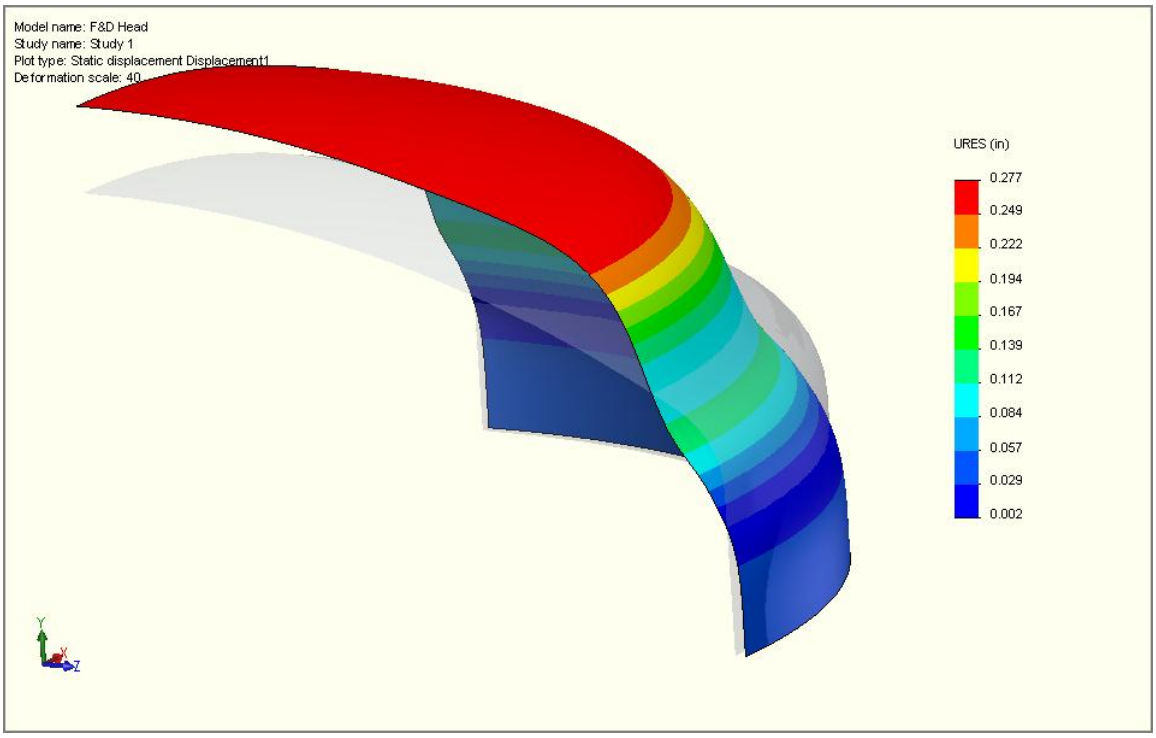
The resulting displacement vectors of each separate head component. The displacements of adjacent components are not equal. This is the source of the high computed stress.

Component	Displacement (in)	Top Stress (psi)	Bottom Stress (psi)	Membrane Stress (psi)
Dished Crown	0.04970	12,967	13,196	12,820
Knuckle	0.00126	1,661	1,573	1,583
Straight Pipe	0.03036	11,974	11,820	11,888
Complete F&D Head	0.27755	78,490	50,032	46,509

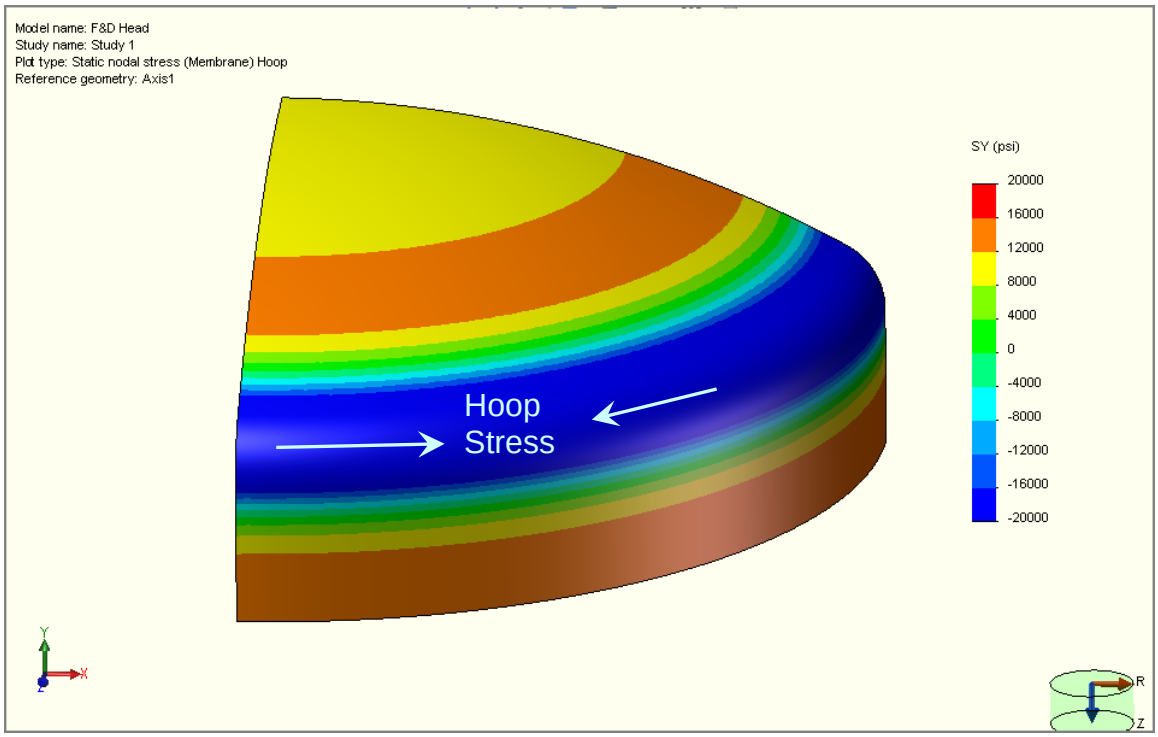
The expected vs actual displacements and stresses



The dished crown and straight flange section need a much greater displacement than the knuckle.



An exaggerated view of the F&D head's displacement shows that the knuckle pushes inward as the crown and straight section deform radially outwards.



The displacement plot shows the knuckle pushing inward. The hoop stress plot shows the region of compressive stress at the knuckle.

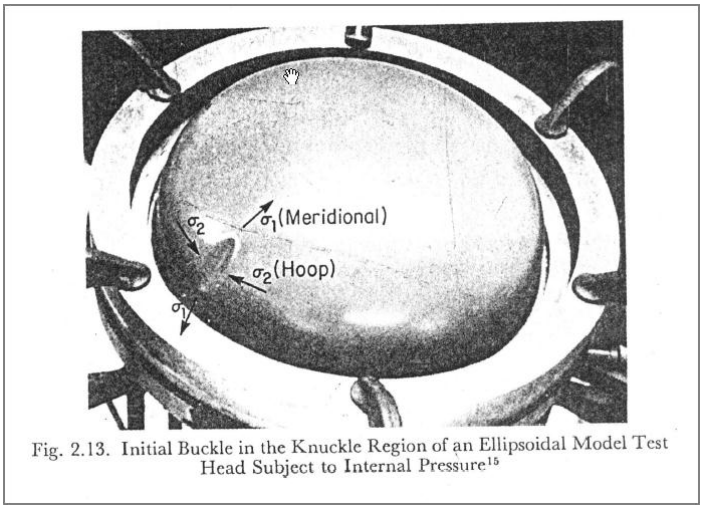


Fig. 2.13. Initial Buckle in the Knuckle Region of an Ellipsoidal Model Test Head Subject to Internal Pressure[15]

Test results from an elliptical head which also has compressive hoop stresses at the knuckle zone.

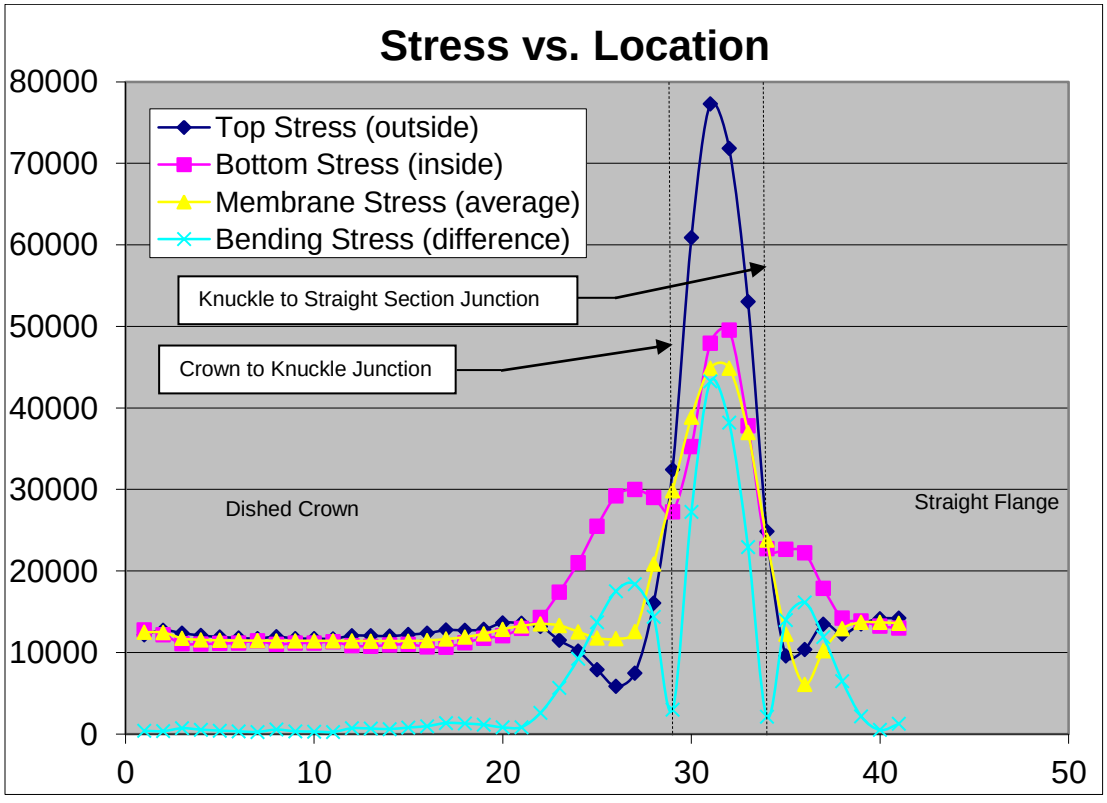
The ASME Code Rules:

The code rules for stress in a F&D head cover more than just tension stresses. The tendency of the heads to buckle at knuckle was considered based on experiment.

Plotting the stress shows why we cannot analyze this head for VIII-1 use using FEA. The stresses are plotted from the crown to the straight flange. VIII-1 allows stresses to be higher in the knuckle (area of discontinuity) than in general areas.

The VIII-1 limits are 20,000psi for general membrane stresses but higher stresses are allowed for bending and local zones (see UG-23(c)-(e)).

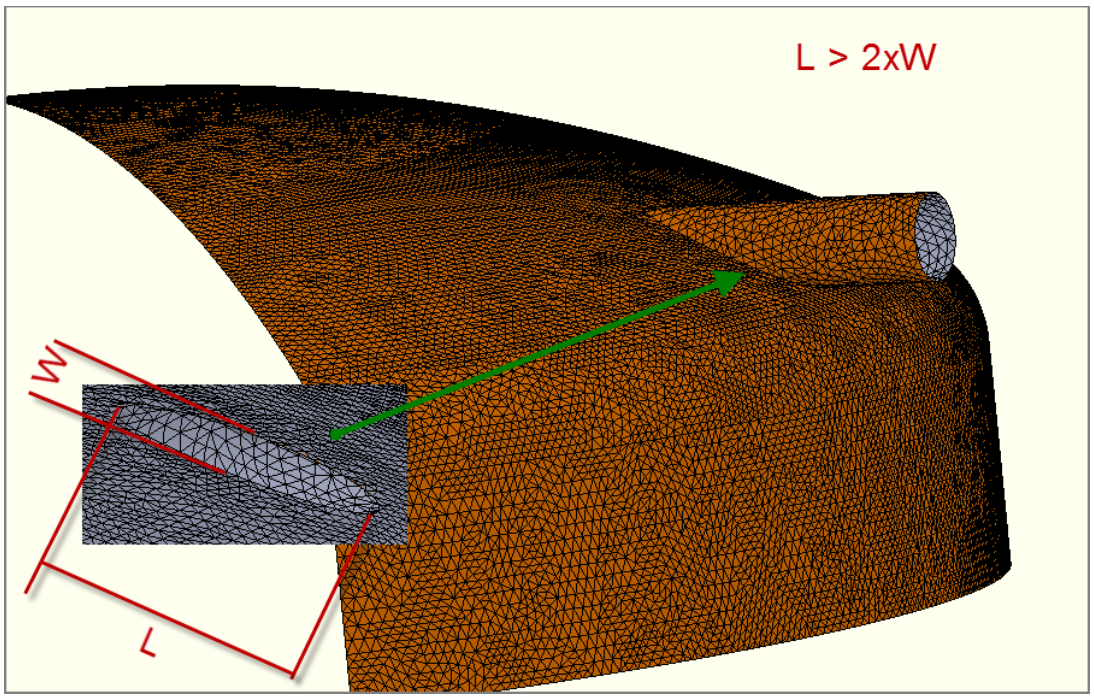
Location	Stress	Type	Value	Limits	
Crown	Top	General M+B	12000	30000	Acceptable
	Average	General M	12000	20000	Acceptable
	Bottom	General M+B	12000	30000	Acceptable
Knuckle	Top	Local M+B	77300	60000	Error
	Average	Local M	46000	30000	Error
	Bottom	Local M+B	49500	60000	Acceptable
Straight Flange	Top	General M+B	14000	30000	Acceptable
	Average	General M	14000	20000	Acceptable
	Bottom	General M+B	14000	30000	Acceptable



This F&D head designed to the VIII-1 rule UG-32 has stress in excess of the amounts allowed in VIII-1 Section UG-23. If F&D heads were invented today we would put a lower allowed pressure rating on them then UG-32 provides, however we have 100 years of experience that indicates that higher stresses can be used in this case.

More about this Head:

This sample head is from a job where our customer wanted to put a nozzle at the sphere to knuckle junction. The nozzle opening length was more than 2x its width so according to UG-36(a)(1) additional analysis is required beyond the standard area replacement rules. NozzlePro was chosen for the analysis, but the head could not be solved because the knuckle stresses were already over the code allowables before any nozzle was added. No matter what nozzle configuration was chosen, a failure was reported.



The simple solution was to relocate the nozzle into the much lower stressed crown area, and have the pipe come in at an angle so that the opening would be less than 2x long to wide. The project could then be finished using regular code rules.

PVE File 3101
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