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Design, Modelling and Analysis of a Bolted Flange Nozzle

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ABSTRACT

In this exercise, we designed and analyzed the bolted flange nozzle that connected the mid and lower parts of an F1 engine nozzle. We then analyzed this bolted joint by building a non-linear finite element model in ANSYS workbench. Our main objective is to assess and compare hand calculations and results obtained from the ANSYS workbench of the bolted flange nozzle. We also like to determine the gaps that develop between the jointed parts when the assembly is loaded. The Bolted flanged joints are vital mechanisms in all pressurized systems;however, they are similarly one of the most composite parts to design. Numerous features enterinto the finding of an effective design and analysis of a flange joint inoperation. At the entry of the nozzle,the pressure due to the exhaust gas is calculated using 1- D gas thermodynamics. It is assumed to fluctuate linearly along the axis of the nozzle. The pressure at the departure (z=0) is 12.17 psi and the pressure at the entry to the mid-nozzle is 47.72 psi. In the design model, the regeneration channels are removed. In discussion, a free body diagram is used to presume the corresponding forces on the mid and lower nozzle. This force pair is displayed as two separate forces, each of 1000-pound force. The fluid temperature is 700-degree Fahrenheit which causes thermal strain. We adopt that bolt is pre-loaded to 51% of its breaking strength.

KEYWORDS: *Bolted flange joint, ANSYS workbench*

I. INTRODUCTION

Bolted flanged joints with seals are very communal in pressure reservoirs and piping systems, and are manufactured mainly for internal pressure consideration. The major requirement of flanged joints is to prevent fluid leakages. Numerous design constraints affect bolted joint function and it is problematic to predict the performance of linkages in service. A flanged joint could be made with flanges cast vital with the pipes or loose flanges welded. The flange faces are machined to guarantee correct alignment of the pipes. The joint may be made leak proof by placing a seal of soft material, rubber or canvas between the flanges. The flanges are made denser than the pipe walls for strength. The flange is the most indispensable part of Pressure tank or reservoir, Condenser, Heat Exchanger and Storage Reservoir. The usage of flanges is also found in shell of a tank or an exchanger to allow disassembly and cleaning of interior parts. Flanges are also used for production of piping networks and any other nozzle accessory at opening.

II. LITERATURE REVIEW

Adolf E. Blach [1] in one of his pioneering work outlines the two design procedures for bolted flanged linking of noncircular cross-section of round and quadrilateral type. One procedure is valid to unreinforced "almost square" quadrilateral shapes, using a "similar circular flange", and typical flange design steps. The supplementary is based on adisintegration of frame and bolted flange, bending and shear stresses and might also be used for rib-reinforced pressure tank. Calculations, investigational values and finite elementout comes were deduced for flange with disk seals (sealsfully inside the flange bolt axis line) and full-face seals. Comparing numerical values with experimental data, heverified that the method of equivalent circular flanges is appropriate for round and rectangular pressure vessel flanges within firm limits. The outcomes are on the safe side and become increasingly conventional as the length to width ratio increases.

Muhsen Al-Sannaa and Abdulmalik Alghamdi [2] studied the outcomes gained using Finite Element Methods (FEM) of bulky diameter welded neck steel flanges under diverse loading settings. They gave the stress analysis of flanged joint comprised of the flange and the gasket for bulky diameter steel flanges. The parametric study done by them; comprise the effect of clamping pressure, internal pressure, axial end pressure, heat transfer, and gasket solid on the contact pressure. They exhibited that clamping pressure is a determining factor for the sealing condition and that clamping pressure needs to be judiciously selected to get appropriate sealing of the flange-gasket assembly. Increasing the clamping pressure will result in a well contact pressure but at the cost of higher flange stress. Gasket has to be produced of soft material withlow modulus of elasticity to ensure better sealing of the assemblage. Axial end load may rise in gasketseepage if the clamping pressure is not satisfactory.

From the literature review, it is factual that there is an indispensable need for an efficient use of Finite Element Analysis(FEA) technique so that precision of the result could be maintained for the best analytical treatment.

Figure 1: F1 engine (Photography by Mike Peel)

III. BOLTED FLANGE NOZZLE DESCRIPTION

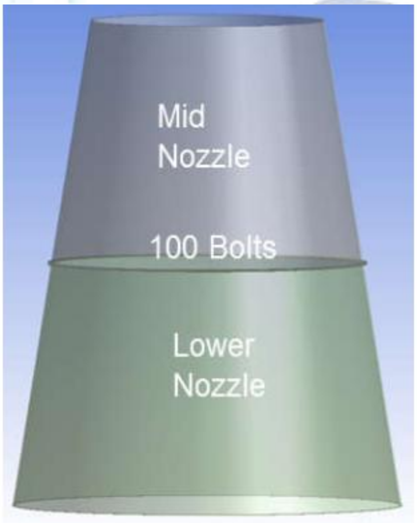


Figure 2: Ansys model of bolted flange nozzle

The above figure 2 shows the complete model in Ansys Workbench and figure 3 shows a close – up view of the bolted flange joint connecting the mid and lower parts of the nozzle.

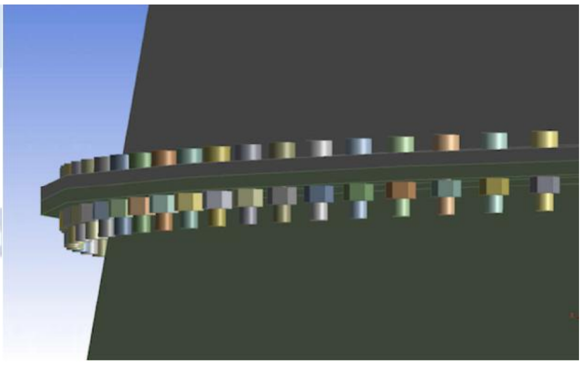


Figure 3: Bolted Ansys model

Table 1: Material Property of Structural Steel

Density	0.2836 lbm in^-3
Isotropic Secant Coefficient of Thermal Expansion	6.6667e-006 F^-1
Specific Heat Constant Pressure	0.10366 BTU lbm^-1 F^-1
Isotropic Thermal Conductivity	8.0917e-004 BTU s^-1 in^-1 F^-1
Isotropic Resistivity	8.5235-ohm cmil in^-1

IV. ANSYS WORKBENCH ANALYSIS OF DESIGN MODEL

For the analysis of the bolted flange nozzle, we used ANSYS workbench 19.0 to analyze and simulate the fluid, thermal and structural analysis by applying finite element method.

Procedures Involved in Ansys Analysis

- Pre-Analyses
- Geometry
- Meshing
- Model Setup
- Numerical Solution
- Results

A. Pre-Analysis

It basically consists of

- Mathematical Model: 3D elasticity
- Numerical solution strategy: Finite – element analysis
- Hand – calculations of expected results

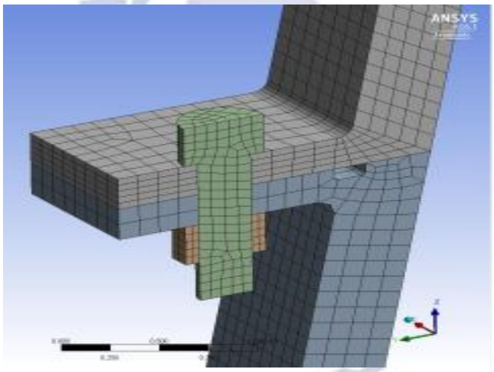


Figure 4: Half section of Design model

The model is a half of a bolt and nut assuming symmetry Four parts namely;

- Mid nozzle
- Lower nozzle
- Bolt
- Nut

B. Mathematical Model: Governing Equations

Physical principle: Equilibrium of infinitesimal element

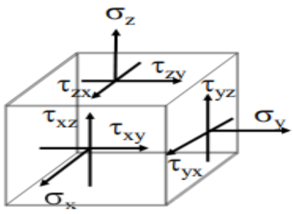


Figure 5: Normal and Shear stresses 3D Differential Equations of Equilibrium

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + f_x = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + f_y = 0$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + f_z = 0$$

3 equations: Force balance in x, y, z with 6 unknowns.

Additional Equations: Constitutive Model

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-2\nu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-2\nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-2\nu \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix}$$

$$- \frac{E}{1-2\nu} \begin{bmatrix} \alpha \Delta T \\ \alpha \Delta T \\ \alpha \Delta T \\ 0 \\ 0 \\ 0 \end{bmatrix} - [Factor] \begin{bmatrix} \varepsilon_{x,bolt} \\ \varepsilon_{y,bolt} \\ \varepsilon_{z,bolt} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Strain – Displacement Relation

$$\varepsilon_x = \frac{\partial u}{\partial x} \qquad \varepsilon_y = \frac{\partial v}{\partial y} \qquad \varepsilon_z = \frac{\partial w}{\partial z}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \qquad \gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \qquad \gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}$$

Mathematical Model: Boundary Conditions

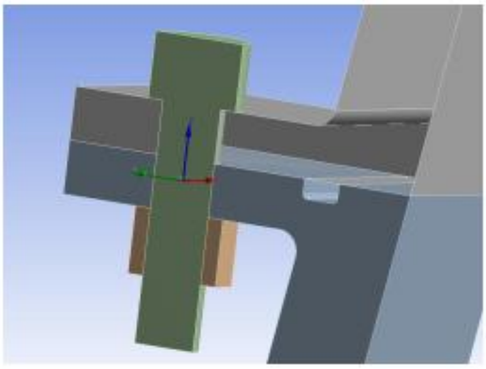


Figure 6: At a given point on the boundary, the displacement has to be defined

C. Essential Boundary Condition

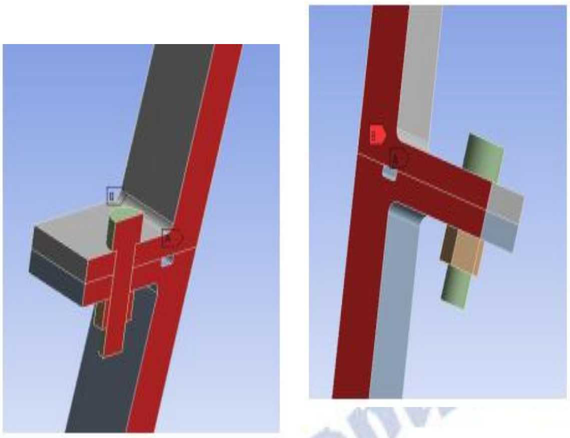


Figure 7: Symmetric condition from periodicity

Traction Conditions: Traction occurring at contact surface is not known prior to where parts coming into contact at the interfaces.
Traction is dependent on the displacement

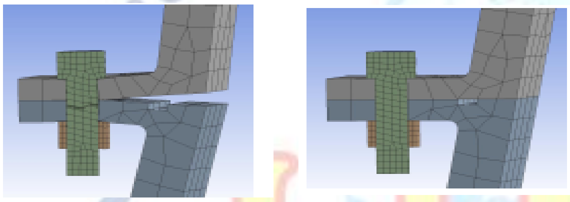


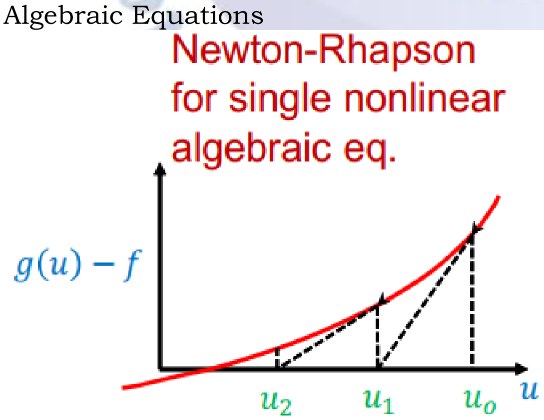
Figure 8: Deformed and Undeformed

D. Numerical Solution Strategy

The numerical solution approach deployed is the Piecewise polynomial approximation

- System of algebraic equations are nonlinear
  {G (d) } = { f }
- Compare to linear case
  [K] { d } = { f }

Newton – Raphson Method for Solving Nonlinear Algebraic Equations



Find the value of $\{d\}$, such that
$\{G(d)\} - \{f\} = 0$
The scalar analog:

- $g(u) - f = 0$
- $Example. u^3 - 20 = 0$
- Updating the given equation

$$g^1(u_0)u_1 = g^1(u^3)u_0 - g(u_0) + f$$

Solving $\{G(d)\} - \{f\} = 0$
Taking an initial guess $\{d^0\}$
Using Newton – Rhapson to get $\{d^1\}$

- Example $[K(d^0)]\{d^1\} = \{f\} + \{f(d^0)\}$
- Calculating the residual:
  $$\{G(d^1)\} - \{f\} = \{f_{residual}\}$$
- If the residual is larger than the tolerance, update guess and repeat
  - New update Example
  - $[K(d^1)]\{d^2\} = \{f\} + \{f(d^1)\}$
  - To calculate $\{d^2\}$

E. Hand Calculations from theoretical Approach

Reaction in Axial (z) direction

- Average gas pressure:

$$\frac{12.17 + 47.72}{2} = 30\ psi$$

- Given the top radius = 41.75 inches
  Bottom radius = 69.50 inches
  Projected area = $\pi(69.50^2 - 41.75^2)$ = 9699 in^2
- The net pressure force in the z direction = 30 * 9699
- Therefore, the net force in the negative z direction on the $1/400^{th}$ model

$$= \frac{30 * 9699}{400} = -720\ lbf$$

(In the negative direction)

Hoop stress:

$$\sigma_\theta = \frac{pr}{t}$$

At exist:
p = 12.17 psi
r = 69.5 in
t = 0.5 in
$\Rightarrow \sigma_\theta \sim 1692\ psi$

Thermal strain
Thermal strain = $\alpha \Delta T = \alpha(700F - 70F)$
This term appears in the constitutive model

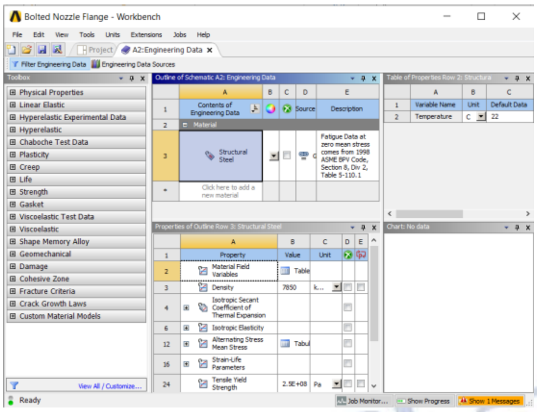


Figure 9: Engineering data of Design model

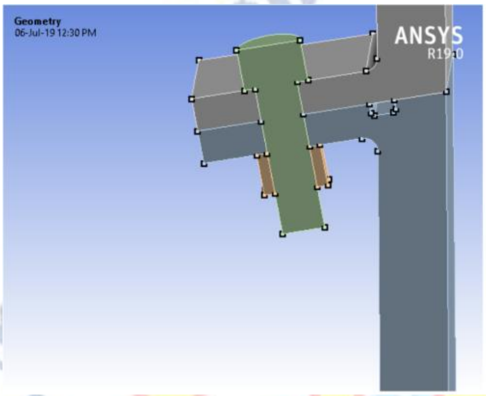


Figure 10: Geometry of Design model

The above figure 8 shows the selection of material, in the analysis of the design model. We applied the structural steel for the mid and lower nozzle and titanium for the bolts and nuts.

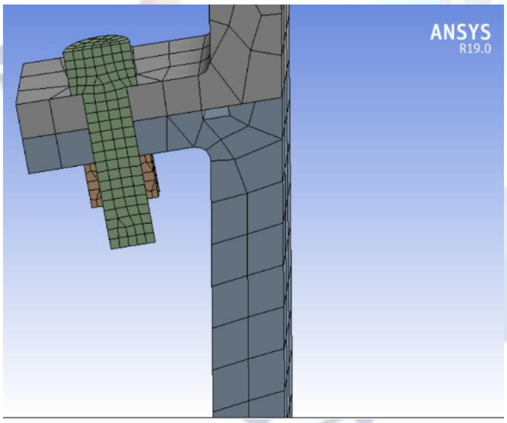


Figure 11: Mesh model in Ansys Mechanical

The above figure is a meshing performed on the sectional bolted flange nozzle. The body sizing of the mid and lower nozzle was 0.3 inches and that of the bolts and nuts was 0.075 inches.

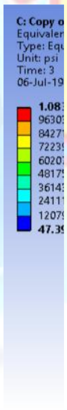
Table 2: Summary of the Mesh Model

Object Name	*Body Sizing*	*Body Sizing 2*	*Hex Dominant Method*
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	2 Bodies		4 Bodies
Definition			
Suppressed	No		
Type	Element Size		
Element Size	0.3 in	7.5e-002 in	
Method			Hex Dominant
Element Order			Use Global Setting
Free Face Mesh Type			Quad/Tri
Control Messages			Yes, Click to Display...
Advanced			
Defeature Size	Default		
Behavior	Soft		

F. *Numerical Solution*

The ANSYS workbench generated the respective mathematical equations to solve the design model

Figure 12: Total deformation at t = 1



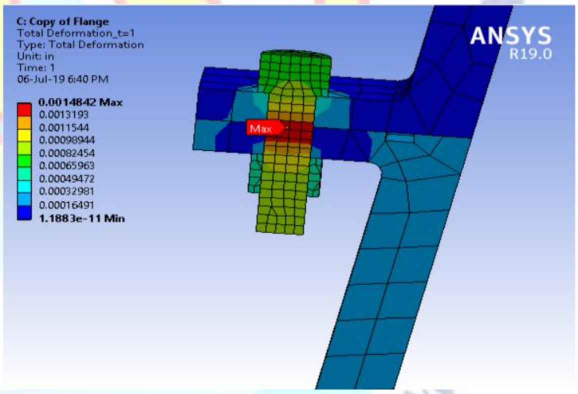


Figure 13: Equivalent (von – mises) stress

Table 3: Force Reactions in all directions

Time [s]	Force Reaction (X) [lbf]	Force Reaction (Y) [lbf]	Force Reaction (Z) [lbf]	Force Reaction (Total) [lbf]
1.	6.2938e-009	2.0336e-008	-8.1272e-006	8.1272e-006
2.	4.2583e-002	0.13091	-683.61	683.61
3.	4.2677e-002	0.13119	-683.69	683.69

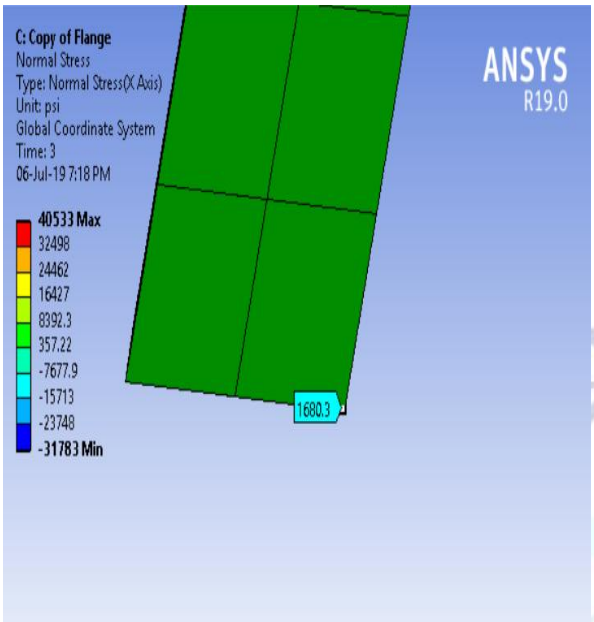


Figure 14: Hoop Stress Probe at 1680.3 psi

V. RESULTS

Table 4: Comparison between Hand Calculations and ANSYS simulation results

	Hand Calculations	ANSYS simulation
Average gas pressure	30	$30\ psi$
Force Reaction in the z direction (lbf)	−7	$-684\ lbf$
Hoop Stress (psi)	169	$1680.3\ psi$

VI. CONCLUSION

The main objective of this paper was to compare the hand calculations and the ANSYS simulation result.

We can further observe that, the results obtained from both sides shows a very close similarity and a small margin of error. The margin of error could be attributed to a lot of factors such as numerical iteration process due to the formation of thousands of mathematical equations.

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