Impact of Multi-Dimensional Thermal and Structural Analyses on Bolted flange in Gas Turbine

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Abstract: ***Bolted flanges play a vital role in aircraft engines as they join components; transmit loads and serves as dismantling joint. Most of the bolted flanges in aircraft turbine engines experiences high mechanical loads, thermal gradients and impartial air leakage as they experience massive pressure difference. Thermal and stress analyses plays significant role in the design of bolted flange components as they are used to estimate temperature distribution, flange stresses, number of life cycles, snap fit tightness, and displacement of the flange assembly. Currently two dimensional thermal analyses are carried out at most of the compressor flanges as it simplifies modelling with a compromise in accuracy. It reduces lead time in generating temperature & mechanical distributions. On the other hand, three dimensional thermal analyses capture local features of geometry, boundary conditions and predict circumferential variation in temperature distribution but increases the computational and turnaround time. An effort has been made in this paper to compare the temperature distribution and stresses for two dimensional and three dimensional thermal analyses with varying flange leakage (via gap b/w flanges). Subsequently through structural analysis, mechanical stresses are compared based on 2D & 3D thermal results. Results presented in this paper will be helpful for the selection of 2D thermal analysis Vs 3D***

Keywords: Bolted flange, 2D, 3D, OD, ID, Bolt hole, Forward flange, Aft flange, FE model

1. Introduction

Bolted flange joints are designed to withstand huge amount of pressure differences, axial blow off loads and temperaturegradients. Flange joints are also needed to ensure less leakage and tighter snaps throughout flight mission for safe operation. Mechanicalstressis an important parameter that decides the durability of the bolted flange which is strongly influenced by thermal gradient within the flange.

M Yousuf [1] presented sensitivity studies on bolted flange 3D thermal analysis by varying amount of leakage, flange height and flange thickness and shown their impact on thermal gradient of the flanges. It was concluded that thermal gradient is highly sensitive to amount of leakage, flange thickness and flange height. It has given insights into critical time point at which max gradient in an acceleration deceleration mission occurs. Steady state and Transient maximum temperature gradients were also monitoredthough these case studies.

It is noted that there arenumerous numbers of papers whichattempt to study the accuracy of bolted flange joint analysis procedures in terms of boltpreload, axial loadand flange opening. However, no information is available in public domain to understand the thermal distribution difference between 2D and 3D thermal analysis and its effect on mechanical stresses.

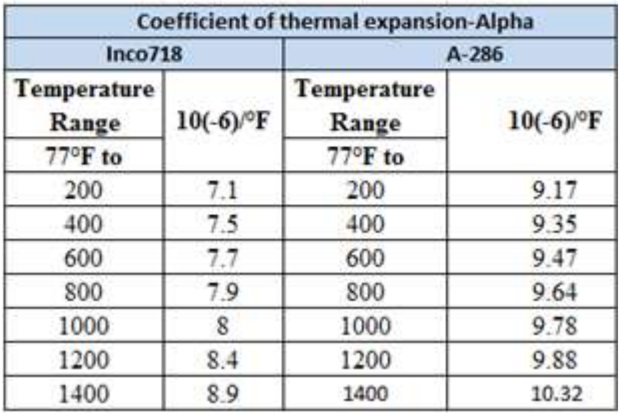
Hence thispaper attempted to predict temperature distribution of the bolted flange through two dimensional and three dimensional transient thermal analysis approaches and their corresponding impact on stress through three dimensional static structural analyses. Flange leakages are varied using both 2D & 3D thermal models and their effect on stresses are presented.

Flange, bolt and nut materials are made up of nickel alloy which can bear temperatures up to 1200° F. Flange material properties variation with temperature is accounted in the analysis.

2. Assumptions

Bolted flange is assumed to be a static structure. Inco 718 and A-286 material properties are used for case and bolt/nut respectively. Alpha values for both materialsare tabulated in table 1 taken from [4]. No transient's effects are considered in structural analysis. Friction coefficient of 0.15 is used at all contact interfaces in structural analysis. Bolt Preload is assumed to be 65% of the material's yield strength. Radiation heat transfer is neglected for this study. Leakage is assumed to be uniform thought the circumference.

Table 1: Coefficient of Thermal Expansion



Coefficient of thermal expansion-Alpha			
Inco718		A-286	
Temperature Range 77°F to	10(-6)/°F	Temperature Range 77°F to	10(-6)/°F
200	7.1	200	9.17
400	7.5	400	9.35
600	7.7	600	9.47
800	7.9	800	9.64
1000	8	1000	9.78
1200	8.4	1200	9.88
1400	8.9	1400	10.32

Finite Element Models- Thermal

Two dimensional finite element thermal model is created using ANSYS 14.5 as shown in Figure 1. 90 bolts are considered for the analysis. PlANE55 elements are used for meshing(total of 2035nodes). PlANE55 elements have an option to capture axi symmetric & non axi symmetric regions. Non axi symmetric regions like flange holes,bolt and nut are treated through real constant approachwhere metal thickness is explicitly calculated and assigned as real constant which is one of the elements attributes. Thermal contact is modelled with LINK34 elements and conduction area is given as real constant. FLUID116 elements are used for air network to simulate the leakage through flange, bolts and nuts. Convective boundary conditions are captured using SURF151 (edge element)& SURF152 (area element) and appropriate thickness is captured through their real constants.

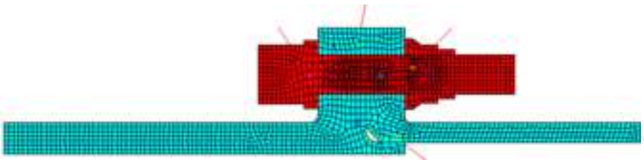


Figure 1: Bolted Flange –2D FE Model (Thermal)

A three dimensional finite element sub model is created using ANSYS 14.5 as shown in Figure 2. 18 Degree sector model is considered which consists of 5 bolts. SOLID70 elements are used for meshing (total of 114228nodes). Heat transfer contact is modelled with TARGE170 and CONTA174 at the flange interface with bolt/nut and across the flanges. FLUID116 elements are used for air network to simulate the leakage through flange, bolts and nuts. Convective boundary conditions are simulated using SURF152 elements.

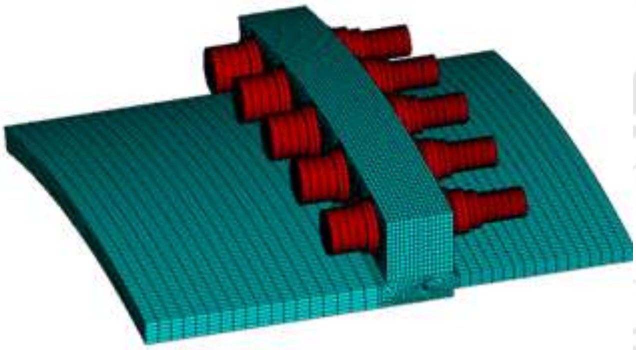


Figure 2: Bolted Flange – 3D Mesh Model (Thermal & Structural)

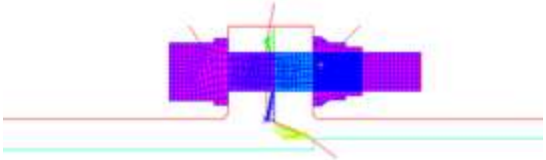


Figure 3: Convection and Fluid Elements (2D)

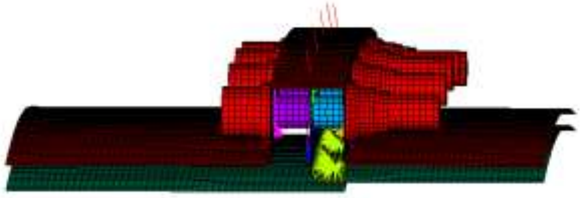


Figure 4: Convection and Fluid Elements (3D)

SURF151, SURF152 elements along with FLUID 116 are shown figures 3 (2D) & figure 4 (3D).

Thermal FE Model Comparision, 2D Vs 3D:

3D thermal sub model captures exact mass of the bolted flange assembly particularly at non axi symmetric features. 2D thermal model captures these features through real constant thickness option. Volume comparison is made between 2D thermal model and 3D thermal model and they are well matched with in 1%. Similar to the volume comparison, Convection area is compared b/w 2D & 3D thermal models and they are in good agreement within 3% variation.

Finite Element Model - Structural:

Three dimensional thermal FE model is used for creating structural model. Solid70 thermal elements are converted to structural 3D solid 45 elements.All interfaces in assembly are simulated using surface to surface, flexible-flexible contact elements. Friction coefficient of 0.15 is used at all contact interfaces. Pretension section is created at each bolt shank to simulate the bolt preload for structural analysis.

Flight Cycle Mission:

Acceleration – Deceleration duty cycle is chosen for steady state and transient thermal analysis.Mission started with stabilized idle condition and accelerated to takeoff in 15 sec. In order to stabilize the temperatures at high power, a dwell of 25 minutes was modelled, then the engine was decelerated to idle condition in 25 sec and then engine was keptto run for a period of 40 minutes at idle condition. The duty cycle is shown in Figure5.

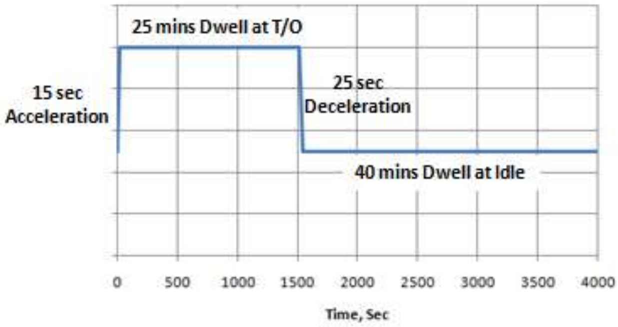


Figure 5: Flight Cycle Mission

Flow Model Approach:

As seen in the Figure1, forward and aft flange are snapped at the ID region. Flow restriction at ID snapgap and gap between flange & bolt head/nut are modelled based on isentropic nozzle relations. The Frictional loss along the radial path b/w flanges is modelled based on compressible fanno loss relations. Leakages are estimated both at low power and high power conditions. It is observed that snap joint at ID region is controlling the leakages through the flange. It is also observed that most of the air is leaking out through the gap between the flange and bolt heads/nuts.

Flange leakage path is shown in figure 6a (2D) and figure 6b (3D). Leakage enters at ID and goes via interface b/w flange and bolt and flange to flange gap. Total leakage is divided by number of bolts when modelling leakage in 3D thermal model

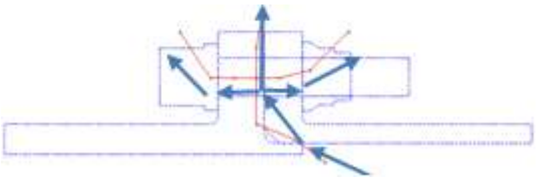


Figure 6a: Flange Leakage Path (2D)

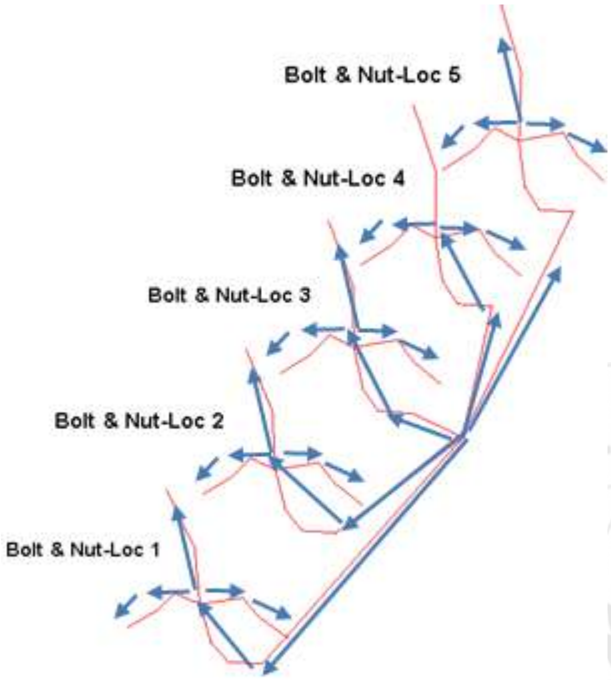


Figure 6b: Flange Leakage Path (3D)

Flange leakage distribution is shown in figure 7 (2D). As seen from the figure that most of leakages escapes through gaps b/w flange and bolt head/nuts. Small amount of leakage scrubs through flange to flange interface.

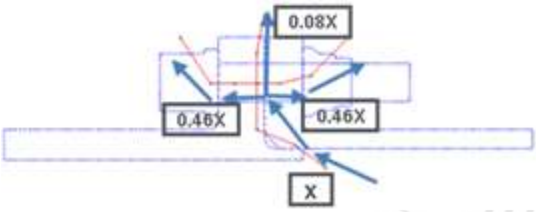


Figure 7: Flange Leakage Distribution (2D)

Thermal Boundary Conditions

Flange inner side is exposed to high temperature and high pressure zone and outer side experiences cold environment with low pressure i.e. flange is leaking from ID to OD void. The bulk air temperatures are applied with transient response for both inner and outer sides of flange to simulate the actual delay in air temperature response compared to that of rotor speed response.

Forced convective heat transfer coefficient on the ID of the flanges is estimated using the empirical correlation for flow over a flat plate,taken from [2] and is replicated below:

$$Nu=0.0296\ Re^{0.8}Pr^{0.333} \qquad (1)$$

On the OD of the flange, conditions for natural convection exist, so the following correlation to model free convection is used, which is taken from [2] and is replicated below:

$$Nu=0.15\ Ra^{0.33} \qquad (2)$$

For modelling convection due to leakage between the flanges and between bolts and nuts, the well-knownDittus-Boelter correlation is used. It is reproduced below from [2].

$$Nu= 0.023Re_D^{0.8}Pr^{0.3} \qquad (3)$$

Structures Boundary Conditions

Sector model is constrained in hoop direction at hoop cut faces to account for symmetry. Mid-layer of nodes at one end of the case shell is constrained in axial direction simulating pinned boundary conditions. Bolt and nut thread engagement region is coupledin all degrees of freedom.Temperatures from thermal analysis, cavity pressures and axial load at other end of case shell are applied.Figure 8 shows the schematic diagram of loads and boundary conditions for the sector model.

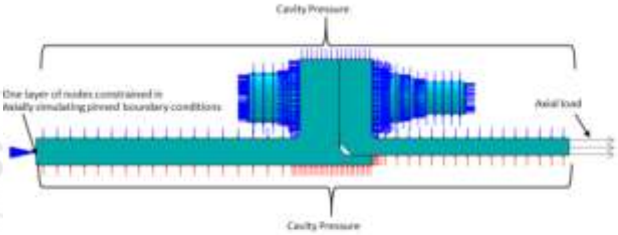


Figure 8: Structural Model Loads

Applied bolt Preload is assumed to be 65% of the material's yield strength. For analysis purpose, axial load is applied as a function of total bolt preload. Max axial load applied is at take-off, which is 30% of total preload in sector [3].

Flange Gap Simulation

Contact gaps are estimated fromstructural analysis results and flange to flange opening is estimated. These gaps are used to modify contact conductance and convection heat transfer coefficient values used in thermal analysis. Contact gaps are shown in below Figure9. Red contoured region which is from OD to mid of bolt hole shows that contact gap is zero hence more axial conduction and less leakage though top of the flange.

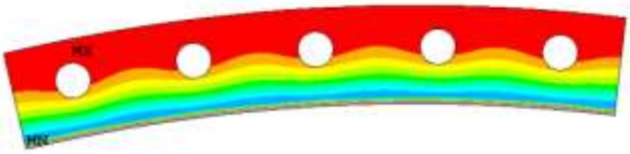


Figure 9: Contact Gap

3. Thermal Analysis Results & Discussion

Transient thermal analysis is carried out for acceleration / deceleration mission with 2D and 3D thermal model. Thermal gradients are processed for forward and aft flange and max gradients occurs at 47 seconds into transient accel in both 2D and 3D thermals. Bolt and nut temperatures are hotter in 2D model compared to 3D thermal model due to the averaging effect in 2D model. 2D & 3D thermal contours are plotted in Figure10 for max gradient time point & Steady state take off condition.

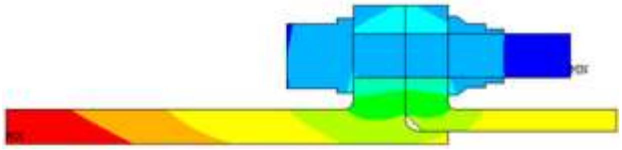


Figure 10a: 2D Temperature Contour at Max Gradeint Time Point (47 Seconds)

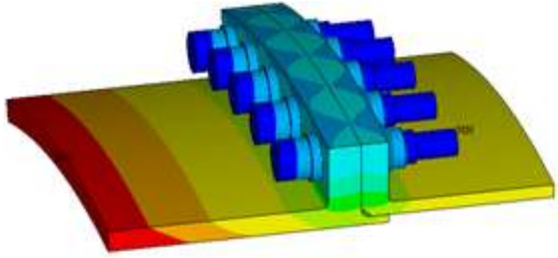


Figure 10b: 3D Temperature Contour At Max Gradeint Time Point (47 Seconds)

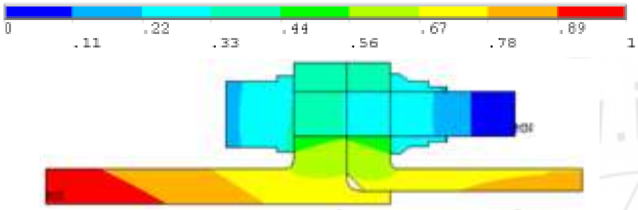


Figure 10c: 2D Temperature Contour At Ss Take Off Time Point (1515 Seconds)

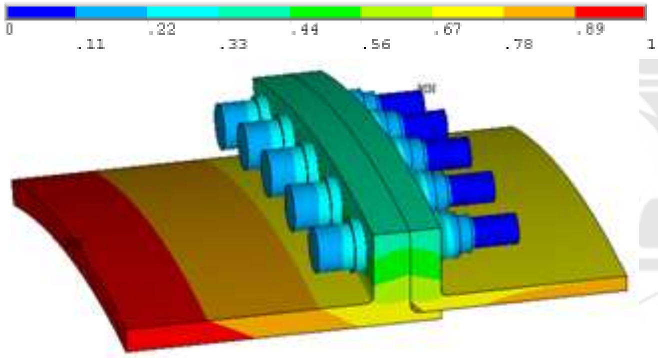


Figure 10d: 3D Temperature Contour at SS Take Off Time Point (1515 Seconds)

Thermal gradients are plotted for both forward and aft flanges throughout the mission cycle from 2D and 3D thermal analysis as shown in Figures11&12.As the engine is throttled to take-off, the inner side of flange gets heated up more compared to outer side, due to forced convection boundary conditions with higher heat transfer coefficient&hotter environment. This causes the temperature gradient to increase transiently in the initial phase. Over a period of time, the gradient decreases and finally stabilizes asouter side gets heated up due to conduction.Heat is transferred from theID to OD.Temperature gradients are extracted at bolt hole section in 3D thermal model.

It is observed that flange max temperature gradient between 2D and 3D thermal model is very close. Maximum gradient is 298/305 ^{o}F (2D/3D) in forward flange and 269/275^{o}F (2D/3D) in aft flange at 47 sec during acceleration.Flange gradients are summarized in tables 2&3. Longer conduction path in forward flange is the reason for higher gradient compared to that of aft flange.

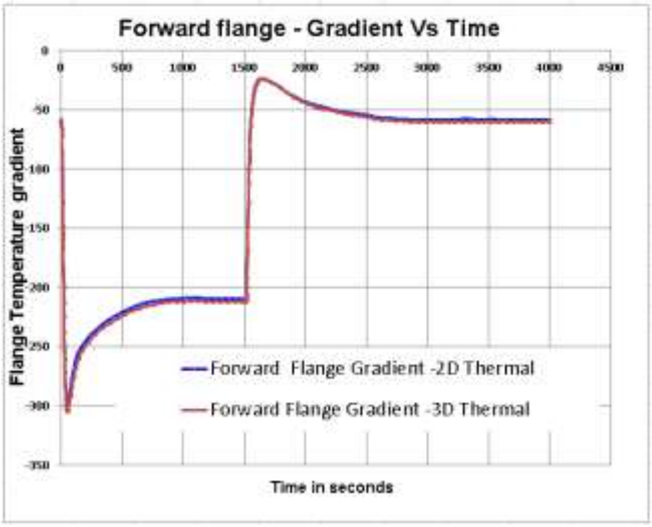


Figure 11: Forward flange Temperature Gradient

Table 2: Forward Flange Gradient Summary

FORWARD FLANGE GRADIENT SIMMARY			
Condition	Time in seconds	2D-GRADEINT	3D - GRADIENT
SS IDLE	0	-58	-61
SS Take off	1515	-208	-212
Max gradient	47	-298	-305

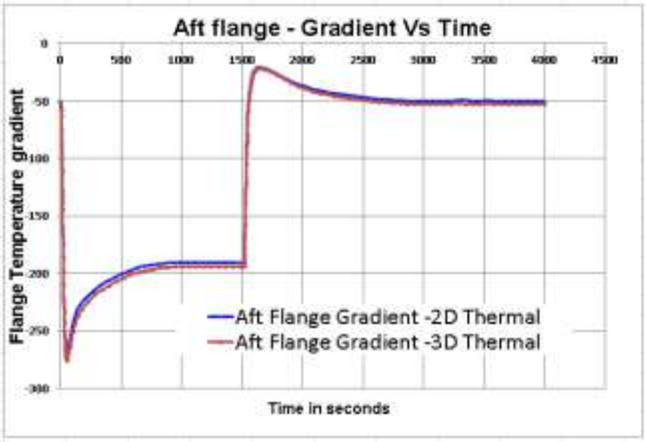


Figure 12: Aft Flange Temperature Gradient

Table 3: Aft Flange Gradient Summary

AFT FLANGE GRADIENT SIMMARY			
Condition	Time in seconds	2D GRADEINT	3D GRADIENT
SS IDLE	0	-50	-52
SS Take off	1515	-189	-193
Max gradient	47	-269	-275

2D & 3D path line temperatures are plotted along radial height of the flange at max gradient time point (Figure13). It is noted that3D non bolt hole (between bolt to bolt) temperature are hotter than2D averaged temperatureswhereas 3D bolt hole location temperature is cooler than 2D temperature particular at flange hole OD location.

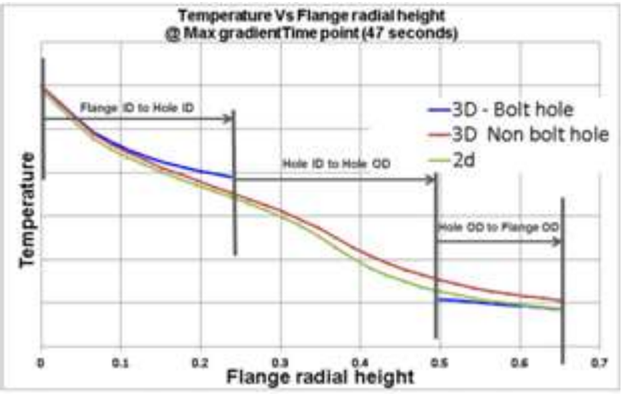


Figure 13: Forward Flange, ID to OD Temperature Profile

Discontinuity in blue curve (3D- Bolt hole) is real and represents 3D flange hole location

Stress Analysis Results & Discussion

Temperatures, cavity pressures, bolt preload & axial load are used as loads to structures model and static structural analysis is carried out at 6 conditions namely Assembly, SS IDLE, Snap Accel (15 seconds), Max gradient (47 seconds), SS take off (1515 seconds), Snap Decel (1540 seconds).

As evident from thermal mapping pictures, (Figures 14& 15) 3D thermal model temperatures at bolt hole location are cooler compared to non-bolt hole location. This is due to the fact that heat is getting conducted from ID to OD and there is conduction break at the bolt hole location. Hence flange hole temperature at bolt hole location in 3D model is cooler compared to non-bolt hole location. This could not be captured using 2D thermal model. This would explain stress differences b/w 2D thermals Vs 3D thermals.

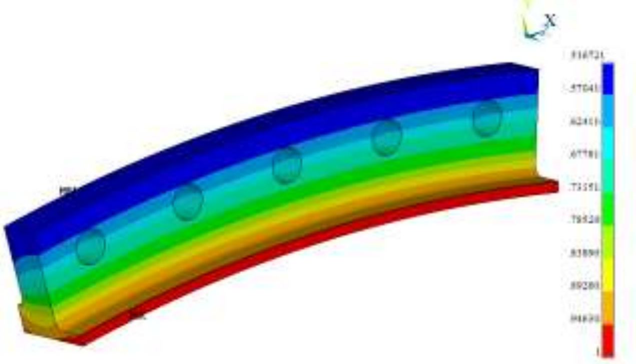


Figure14a: Forward Flange temperature Mapping from 2D Thermals

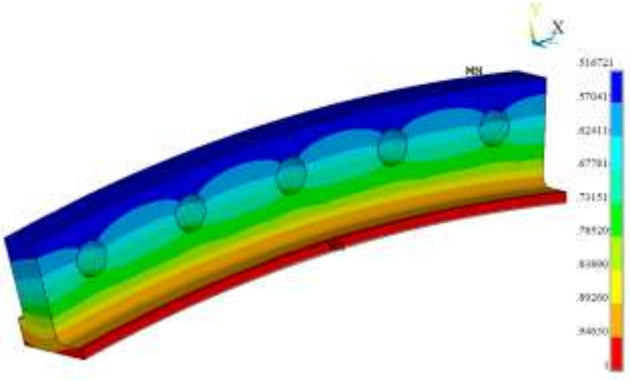


Figure14b: Forward Flange temperature Mapping From 3D Thermals

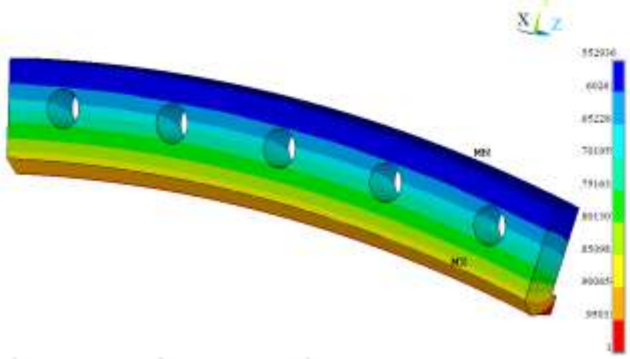


Figure15a: Aft flange temperature Mapping from 2D Thermals

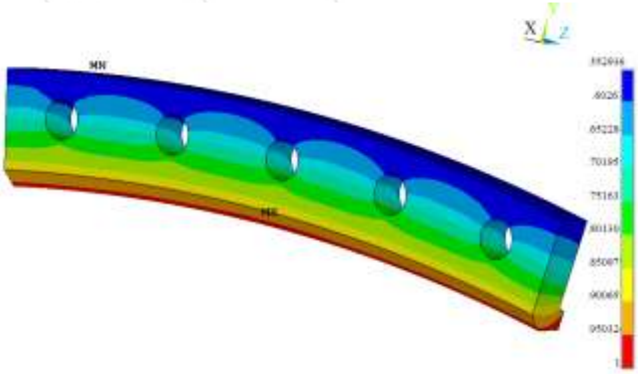


Figure15b: Aft Flange temperature Mapping From 3D Thermals

It is observed that max gradient time point is turning out to be max stress condition. Max stress contour is shown with both 2D thermals and 3D thermals in Figures 16&17.Max stress is observed at flange hole OD location.

Structure analysis based on 2D thermals produces17% higher stress than based on 2D thermals. Irrespective of the mesh density, 2D vs 3D stress differencesremainssame.

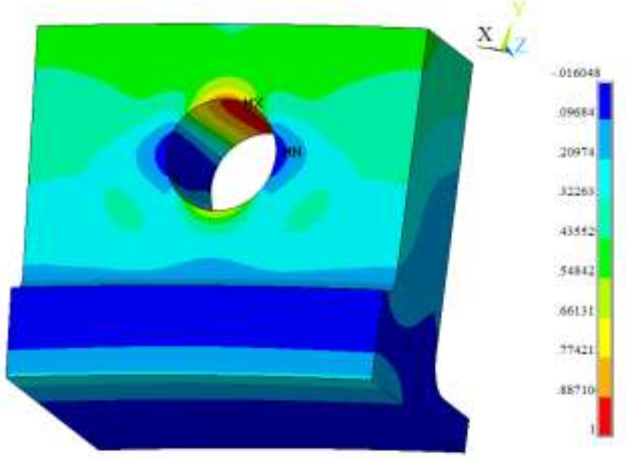


Figure16a: Forward Flange Hoop Stress Based on 2D Thermals

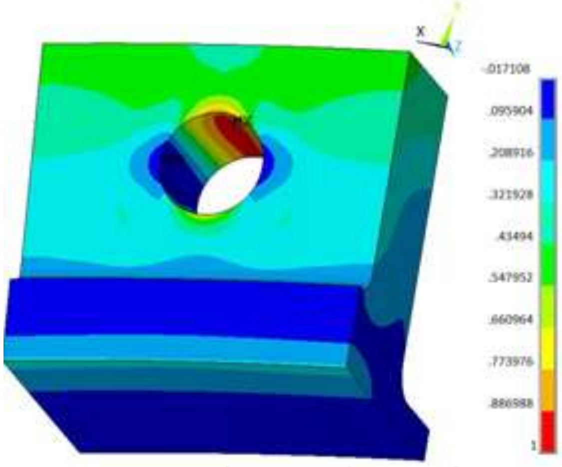


Figure16b: Forward Flange Hoop Stress Based on 3D Thermals

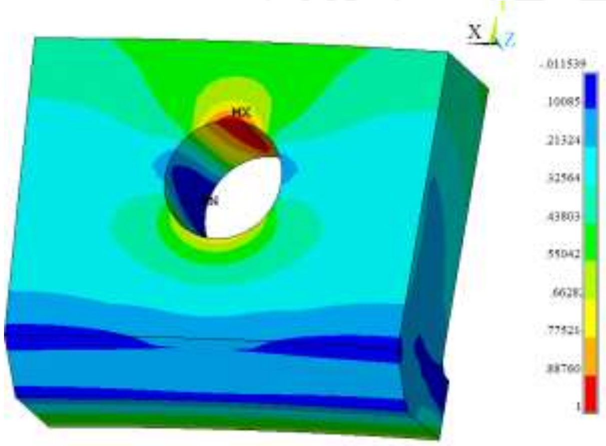


Figure17a: Aft Flange Hoop Stress Based on 2D Thermals

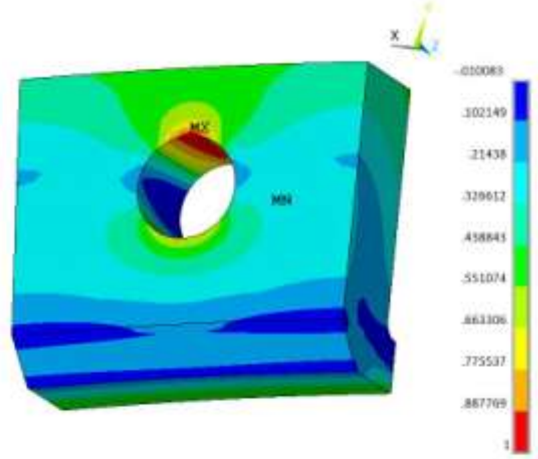


Figure17b: AFT Flange Hoop Stress Based on 3D Thermals

Impact of Mesh Density:

Effect of mesh density on the bolt hole stresses is analysed by changing elements types at bolt hole regions form SOLID45/SOLID70 (8 noded element)to SOLID90/SOLID95 (20 noded higher order element with midside nodes) and also by increasing the mesh density at bolt hole regions with minimum element length from 0.0178 inch to 0.006 inch. Stressesdifferences results are summarized in table 4.

Table 4: Stress Difference Due To Mesh Density

Location	Max stress time point	% of Stress difference	
		with 2D thermals	with 3D thermals
Forward Flange hole	47 seconds	2.4	3.69
Aft Flange hole	47 seconds	5.84	6.28

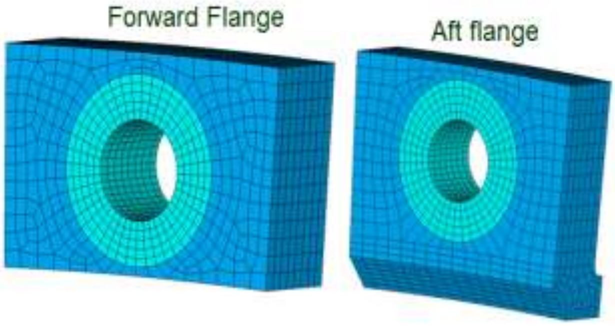


Figure 18: Forward Flange Stress Comparison

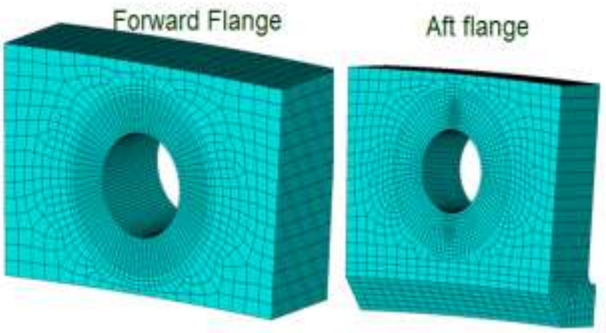


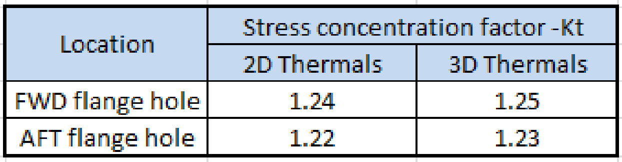
Figure 19: Forward Flange Stress Comparison

Baseline & refined mesh density pictures at flange hole region are shown in figures 18& 19 respectively.

Bolt - Hole Kt Details

Concentrated stress on circular hole patterns often result from presence of combined membrane and bending load. Stress concentration factor Kt is calculated analytically from 3D& 2D structural analysis models for both 2D and 3D thermals through ANSYS stress linearization method(Total stress/membrane+bending). It is important to note that this procedure is solely analytically based with no test substantiation. Kt comparison is shown in table 5.

Table 5: Bolt Hole Kt Summary

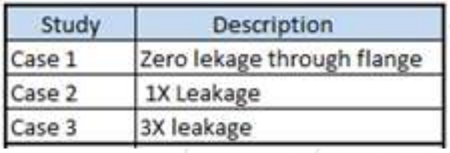


Location	Stress concentration factor -Kt	
	2D Thermals	3D Thermals
FWD flange hole	1.24	1.25
AFT flange hole	1.22	1.23

Case Studies

Sensitivity studies are carried out to assess the impact of leakages on flange bolt hole stresses. Below table6 describes case studies that are performed.

Table 6: Summary Of Case Studies



Study	Description
Case 1	Zero lekage through flange
Case 2	1X Leakage
Case 3	3X leakage

Generated 2D and 3D thermal results for all the above cases and subsequently stresses are evaluated using both 2D & 3D thermals. Stress based on 2D thermals is consistently coming higher than the stress based on 3D thermals as depicted in below Figures 20&21. With increase in flange leakages, stress difference b/w 2D & 3D thermals is increasing as 3D thermal model captures leakage and convection heat transfer accurately than 2D thermals. It is also observed from graphs that leakage increment decreases flange hole stress.

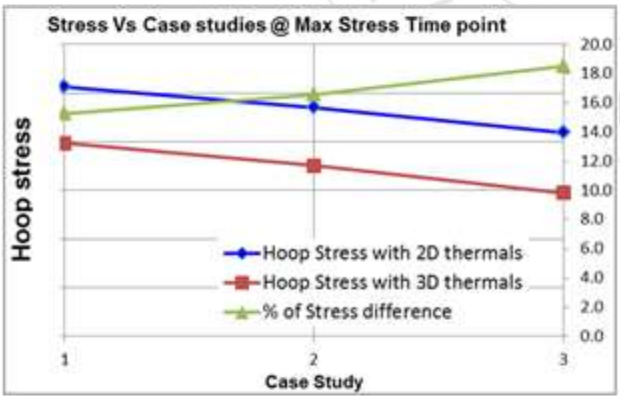


Figure 20: Forward Flange Stress Comparison

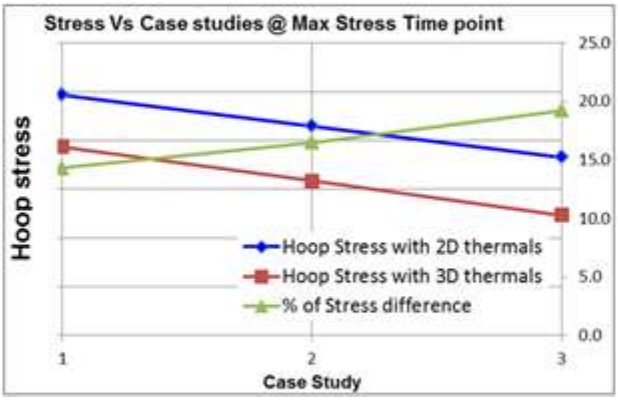


Figure 21: AFT Flange Stress Comparision

4. Conclusions

Impact of two dimensional and three dimensionaltemperaturedistributionson flange bolt hole stresses are studied and the following conclusions are reached.

- 2D thermals yield higher stresses than the 3D thermals at the bolt hole. Stress variance of up to 17% (case2) is observed between 2D &3D thermals.
- With higher leakage (3x), stress difference at forward flange b/w 2D thermals and 3D thermals is increased by 3.2% and stress difference at aft flange b/w 2D thermals and 3D thermals is increased by 4.8%.
- Forward flange hole stress is reduced by 15.4% (3D thermals) and by 12.4% (2D thermals) when flanges leak more by 3x.Aft flange hole stress is reduced by 22% (3D thermals) and by 17.2% (2D thermals) when flanges leak more by 3x.
- Higher order elements& finer mesh density gives up to 6% stress variation compared to lower order elements&comparatively coarse mesh.
- It is recommended to use 2D thermal analysis approach for bolted flange durability assessment as stress generated is on a conservative side and reduces modeling & solution run time (At non critical locations, when there are sufficient life margins).It's suggested to use temperatures from 3D thermal analysis for critical locations where life short falls exist

It is hoped that the results presented in this paper will assistdeciding appropriate thermal analysis procedure in bolted flange durability estimations for static structures. This work can be extended to rotating bolted flange joint.

Nomenclature

Accel:	Acceleration
Decel:	Deceleration
2D:	Two Dimensional
3D:	Three Dimensional
ID:	Inner Diameter
MAX:	Maximum
min:	Minutes
Nu:	Nusselt Number
OD:	Outer Diameter
Pr:	Prandtl Number
Ra:	Rayleigh Number
Re:	Reynolds Number

sec: Seconds
SS: Steady State
FE: Finite Element
Hoop: Circumferential Subscripts
D: Diameter

References

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