Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 01, January-2016

Studies on Behavior of Conventional Back-to-Back and Stepped Flange Bolted Joints

Kondaiah Bommisetty
Deputy General Manager
Cyient Limited
Bangalore, India

Mahendra Kenchegowda
Senior Design Engineer
Cyient Limited
Bangalore, India

***Abstract* - Structures in aerospace are often connected by different types of bolted flange joints. A basic function of bolted joint is to provide adequate joint strength, stiffness and sealing to minimize leakages. The capability of the joints is determined by analysis, augmented by testing. Therefore accurate evaluation of bolt force in a bolted joint under external loads is a fundamental requirement in bolted joint design. Different types of bolted joints such as conventional back to back flange, stepped flange (Dogleg flange), triple stack flange are generally used to connect casings, bearing housings, rotors of gas turbine aero engine. Bolted joints are complex to design and difference in behavior is expected for different design configuration of bolted joints. While hand calculations are used for simple bolted joint design, finite element analysis found to be effective for complex geometry and loading conditions.**

The objective of present study is to assess the flange separation, contact pressure distribution between flanges, flange stress and load sharing of bolt for back-to-back and stepped flange bolted joints. The nonlinear contact analyses have been carried out for these two bolted joints using FEA software ANSYSver14.0. Analyses were performed for external axial load with assembly preloading. Finite element analysis results indicate different flange separation, contact and load sharing behavior between back-to-back and stepped flange bolted joint. The flange separation starts at the inner radius of flange and grows towards outer diameter of flange, as the axial load is increased in the back-to-back flange joint. The bolt hole zone is critical compare to between bolts for leakage point of view. In the case of stepped flange, no significant flange separation is observed at the interface of flanges as the entire stack pivots about bolt axis with flange corners taking the bending load. The contact pressure between the two flanges is much higher at the bolt position than between bolts. The flange stress induced in the stepped flange is higher compare to convention flange joint. The major portion of the external load is shared by the flanges in case of stepped flange joint, while the bolt shares major portion of the load in back-to-back flange joint. These critical observations provide insight for selecting appropriate joint to ensure structural integrity or to design bolts for failure for worst load case like fan blade off in case of aero engine to reduce load transfer to Airframe.

Keywords: Finite element analysis, Bolted flange joint, Back-to-back flange joint, Stepped flange joint, Load transfer, Contact pressure distribution

I. INTRODUCTION

Bolted joints are the most widely used machine elements because they can repeatedly be assembled and disassembled by an easy operation. Structures in aerospace, energy and industrial applications are often connected by bolted flange joints. A basic function of bolted joint is to provide adequate clamping force, joint strength, stiffness and sealing to minimize leakages. Fatigue is one of the critical failure modes in the bolted joint. Bolted joint with preloading minimizes the fatigue damage as the preload reduces the fluctuating stress in the bolt induced by variable external loads. Accurate calculation of stresses, contact pressure, bolt force in a bolted joint under external loads is a fundamental requirement in many industries. Mechanical behaviour parameters of the bolted joints such as the strength and the stiffness have been analysed experimentally, theoretically based on elasticity theory, and using numerical method. Finite element method (FEM) is found to be the most powerful numerical method for solving the problems of bolted joints. The development of FEM has made it possible to evaluate joint stiffness, contact pressure distribution, bolt force and the stress concentration with high accuracy in bolted joints under external loads with pretension.

The objective of this paper is to assess the flange separation, contact pressure distribution between flanges, flange stress and load sharing of bolt for back-to-back and stepped flange bolted joints. 3D FE model of bolted joint was created with high quality hexahedral elements. The structural analysis was carried out for external axial load with pretension for both the configurations.

II. LITERATURE REVIEW

Before the advent of digital methods, a multitude of approaches, theories, and experimental studies had been conducted in order to analyze the behavior of bolted flange joints with metal to-metal contact beyond the bolt circle. Schneider [1] used a beam theory model to solve flanges with metal-to-metal contact. His method was quickly adopted by the American Society of Mechanical Engineers (ASME) Code. Galai[2] developed analytical method to analyze flanged joints with metal-to-metal contact beyond the bolt circle based on plate theory. This method provides additional considerations comparatively to the current method when designing such flanges. Besides being more comprehensive, the method based on the plate theory gives more confidence on its ability to predict flange separation and the bolt load

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 01, January-2016

increase during operation. Czachor[3] provided an insight to the bolted joint design requirements for both normal and extreme gas turbine operating conditions.

Most of the papers in the literature simulate the behavior of the bolted flange assembly using three-dimensional solid elements in order to capture realistic bolted joint behavior. Montgomery [4] explained different methods of simulating bolted joints using ANSYS, FEA commercial software. He proposed and reviewed six different methods for simulating bolted joints, no bolt, coupled bolt, rigid body element (RBE) bolt, spider bolt, hybrid bolt and solid bolt. He has used half bolt sector to review all different simulation methods. He discussed merits and demerits of each type of simulation and left it to the designer to decide the options based on task specific requirements.

Hyde et al. [5] simulated bolted joints using 3D finite element method. They observed that with increase in axial load, bolt load increases nonlinearly. This non-linearity was attributed to loss of contact area of the flanges as load increases and the eccentricity between load and bolt axis. Fessler et al. [6] further continued the work and measured the leakage at different internal pressure and axial loading conditions. It was observed that initial gap at the inside edge of the flange was increased by all loads and the gap at the outside edge of the flange is increased with axial pressure on the front faces, but decreased by radial pressure on the inside surface and by axial tension. It was opinioned that for all practical loading conditions, the gap is likely to be smaller at the outside than at the inside. For the cases analyzed, they observed significant leakage through the bolt hole when the axial load increased more than 20% of the bolt preload.

Several authors covered the complexities associated with the conventional back-to-back flange bolted joints. But no literature is available on stepped flange bolted joints which are also used in gas turbine aero engine. Present work is focused to carry comparative studies on behavior of conventional back-to-back and stepped flange bolted joints.

III. PROBLEM DESCRIPTION

Most of the papers in the literature simulate the behavior of the conventional back-to-back flange bolted joints using three-dimensional solid elements in order to capture realistic bolted joint behavior. In case of gas turbine aero engine, stepped flange bolted joints are also used for connecting components apart from conventional flange bolted joints because of space constraints. In the present work, both types of bolted flanges are considered to analyse for specific characteristics of flange separation, contact pressure distribution, stress concentrations and bolt load sharing which are the primary concerns when designing bolted joints. The comparative studies have been carried out on both the types of flanges for different types of external loads with preload. A steel bolt-nut set joining two flanged shells is analysed to study joint behavior.

IV. FINITE ELEMENT MODELING AND ANALYSIS

A. Modelling

The design considered here is a steel bolt-nut set joining two flanged shells in a circular pattern. Because of symmetry half bolt sector model is considered for modeling and analysis. Since 90 bolts are used to connect two shell structures, two degree sector models are considered for study. 3/8-inch steel bolt (UNF threads) is used to clamp two 0.5 inch thick titanium flanges. The length of the shell is considered such that, it will not have any effect on joint behavior. Typical conventional back to back and stepped flange bolted joints are shown in figures1&2

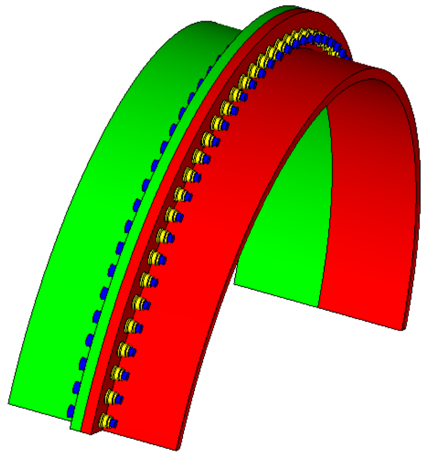

Fig.1. Conventional back to back flange bolted joint

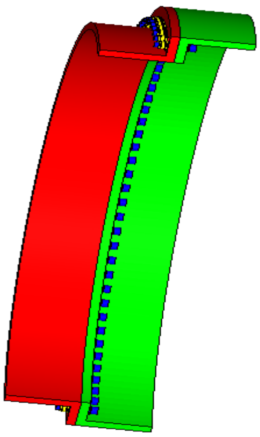

Fig.2. Stepped flange bolted joint

B. Meshing

FE modeling of the entire joint is usually neither practical nor necessary and would detract from the basic insights. It is sufficient to model a half bolt sector with boundary conditions carefully chosen to replicate the constraint existing in the actual joint and to load the fastener with a force representing the half bolt force. Three dimensional 8-node solid brick elements SOLID185 of ANSYS with three degrees of freedom per node are used to build the half bolt sector assembly. The assembly comprises of two flanges, half bolt and nut. Both bolt and nut without threads are modeled

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 01, January-2016

as separate components. The solid element that is unrestricted as to the shape, loading, material properties and boundary conditions. A consequence of this, generality is that all six possible stresses (three normal and three shear) must be taken in to account. Also the displacement filed involves all three possible components (three translations). The finite element softwares HyperMesh and ANSYS are used for meshing and analysis respectively.

In studying the contact between two bodies, the surface of one body is taken conventionally as a contact surface and the surface of the other body as a target surface. For flexible-flexible contact, both contact and target surfaces are associated with deformable bodies. The contact and target surfaces constitute a contact pair. The CONTA174 contact element is associated with the 3D target segment elements TARGE170 using a shared real constant set number. The interfaces between flanges, bolt head & flange, Nut & flange are simulated by using surface to surface, flexible-flexible contact elements. The nodes between bolt & nut are coupled in three directions. The coefficient of friction between mating components considered as 0.15 for analysis.

Preload in the bolt is simulated by using PRET179 element. This element internally creates set of constraint equations to calculate the strain required to generate the applied preload in to the assembly. Model is constrained in hoop direction to account for half sector symmetry. One end of the case shell is constrained in all directions. The other end of the case is subjected to external load.The finite element models of conventional and stepped flange bolted joints are shown in figures3 &4.

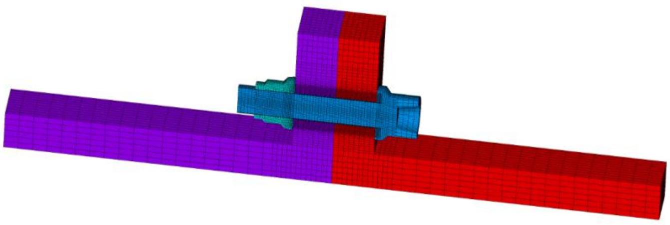

Fig.3. F.E. model of conventional bolted flange joint

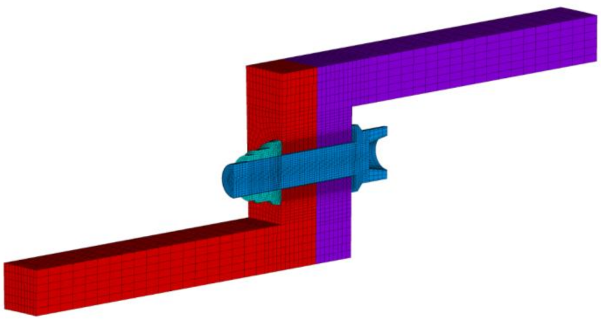

Fig.4. F.E. model of stepped flange bolted joint

C. Material properties

The two casings (shells) are assumed to be made of Titanium material. The bolt and nut are made of high-strength SAE Grade 8, 120 ksi proof stress with yield at 130 ksi. The ultimate strength is 150 ksi at 12% total elongation. The material properties are shown in below table1.

Table 1: Material properties of the joint parts

S.No	Part name	Material	Young's modulus (psi)	Poison's ratio
1	Flanges	Titanium	16.9 × 106	0.31
2	Bolt & nut	High-strength steel	30.0 × 106	0.30

D. Boundary conditions

One end of the shell is constrained in all directions. The other end is subjected to axial load of 7900 lbf (per sector). The sector face nodes have been constrained in a tangential direction. The pretension value of 7900 lbf (per bolt) is applied at the middle of the bolt using pretension element. The boundary conditions plot is shown below figure5.

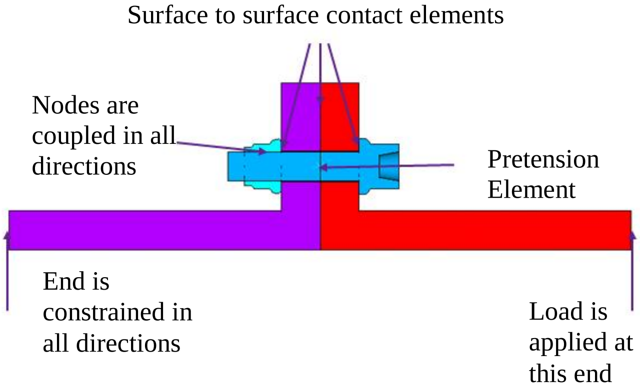

Fig.5. Typical Boundary conditions plot

V. RESULTS & DISCUSSIONS

Nonlinear contact structural analyses have been carried out for two different bolted flange joints to study joint behavior using ANSYSver14.5. The contact problem is essentially nonlinear and solution is obtained iteratively (Newton Raphson). Loads are applied in small increments. The default contact algorithm, augmented lagrangian (AM) method was used for analysis.

The proof tension for the 120 ksi (proof stress) bolt, using the tensile stress area is 10500lbf. Bolts are ordinarily tightened to 75% of the proof load i.e around 7900 lbf. The pretension values of 7900 lbf is considered for analysis. Elastic contact analyses have been carried out for external axial load of 7900 lbf with pretension. Sub step options are specified such a way that results of intermediate loads are also written in results file. Conventional and stepped flange bolted joints are compared for flange opening, contact pressure, stresses in the flanges and bolt loads,. When the joint is subjected to only

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 01, January-2016

preload of 7900lbf, bolt undergoes elongation and flanges are subjected to compression.

A. Flange Separation

Flange separation is calculated by measuring the gap between two flanges. The radial distribution of flange separation from the heel to toe of the flange at bolt hole center and between bolts for different external loads (ie 30% preload & 80 % preload) are shown in figures6&7. It is observed that the separation is very minimal in case of stepped flange bolted joint compare to conventional bolted joint. There is no leakage in case of conventional bolted joint for the axial load equal to 30% preload (Fig.6). But the leakage occurs when external load equal to 40% preload at the edge of the bolt hole. The bolt hole zone is critical compare to between bolts for leakage point of view. There is no leakage in case of stepped flange bolt joint for the axial load equal to total preload because flanges are not subjected significant bending about bolt . As the external load increase, always contact exists at the heel and toe of the flanges.

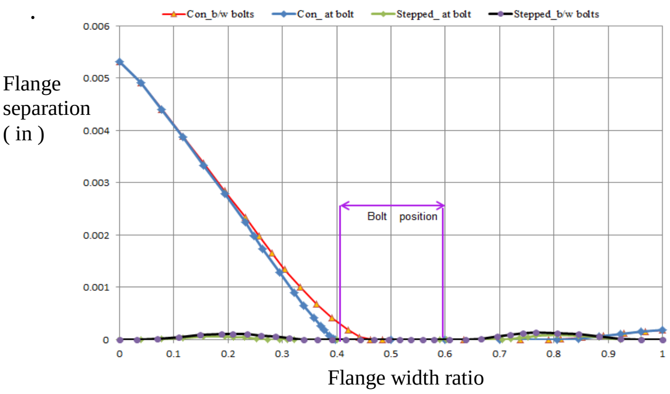

Fig. 6 : Flange separation – Axial load equal to 30% preload

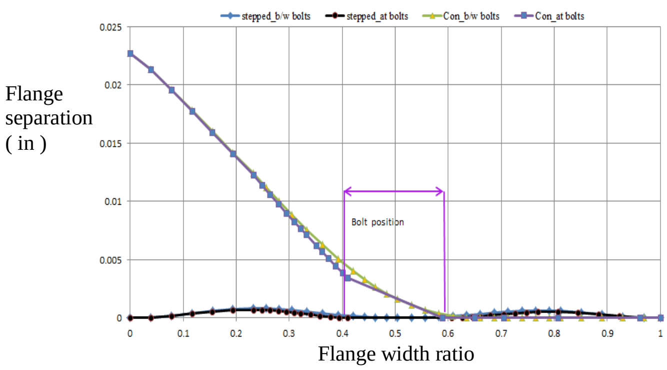

Fig.7: Flange separation – Axial load equal to 80% preload

B. Contact pressure distribution

Figure8 shows contact pressure plots between two flanges of conventional bolted flange joint for pretension alone, pretension with external load equal to 30% and 40% of preload conditions. The contact pressure between two flanges is much higher at the bolt position than between bolts. As the load increases the contact pressure around the bolt hole decreases and at the instance it reached the edge of the hole, leakage sets in. The bolted joint is in leakage condition at external axial load equal to 40% of preload. At this condition there is no contact pressure at the inner edge below the flange hole resulting in leakage.

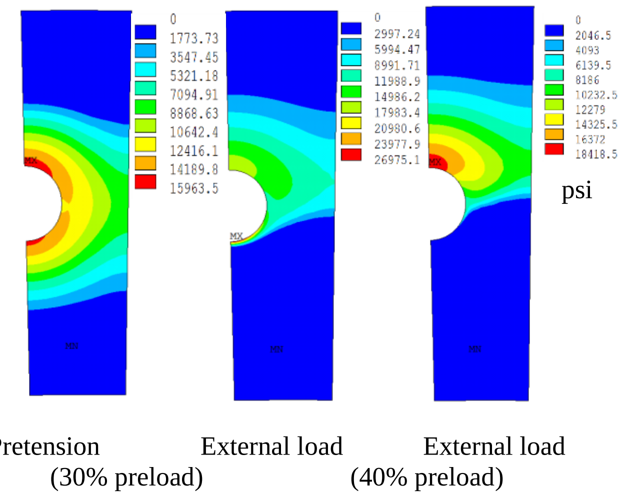

Fig.8 : Contact pressure (psi) distribution Conventional bolted flange joint

Figure9 shows contact pressure plots between two flanges of stepped flange bolted joint for pretension alone, pretension with external load equal to 30% and 80% of preload conditions. The contact pressure between two flanges is much higher at the bolt position than between bolts. As the load increases the contact pressure around the bolt hole decreases and increasing at heel and toe of flange. There is no leakage for external load equal to 100% preload because flanges are not subjected to significant bending about bolt pitch circle.

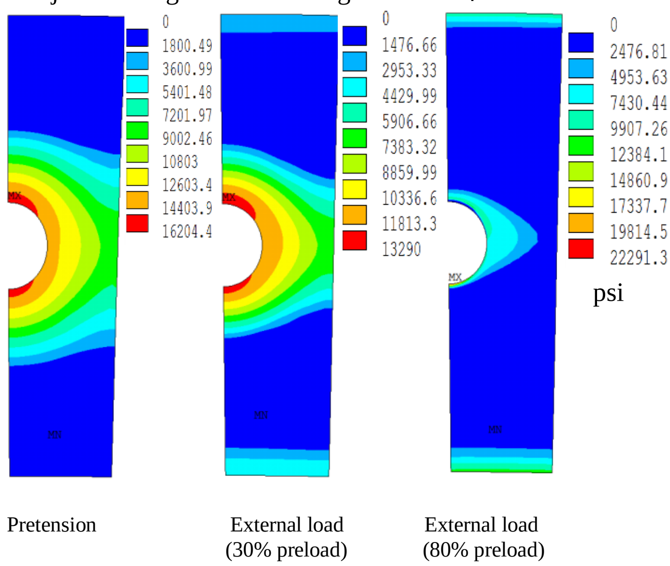

Fig.9: Contact pressure (psi) distribution Stepped flange joint

The contact state at flange interface consists near contact, sliding and sticking. ‘Near contact’’ is a transitional contact state which is between the contact and open state. When the contact interfaces are in near contact state, only heat can be transferred between the contact interfaces. Both ‘‘sliding’’ and ‘‘sticking’’ are closed contact state, but different in style of friction. Figure10 shows contact status plots of conventional bolted flange joint for pretension alone, pretension with external load equal to 30% and 40% of preload conditions. The zone around bolt hole is in sticking state during pretension. As the external load increase the contact state of sticking is reduced and near contact state is increasing.

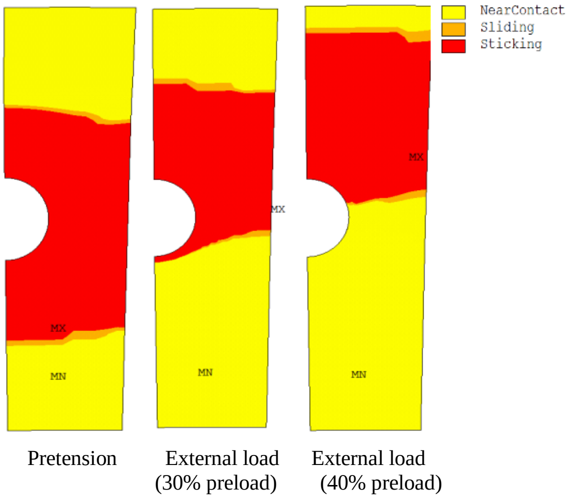

Fig.10. Contact status at flange interface Conventional bolted flange joint

Figure11 shows contact status plots of stepped flange bolted joint for pretension alone, pretension with external load equal to 30% and 40% of preload conditions. The zone around bolt hole is in sticking state during pretension. The contact state of sticking vanishes at bolt hole, sliding and near contact state increasing when the external load is increased

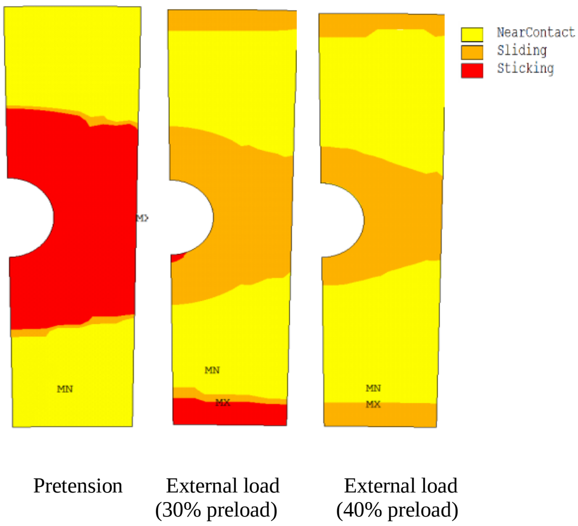

Fig.11. Contact status at flange interface Stepped flange bolted joint

C. Stresses in the flange

The max.first principal stress induced in the flange due to different external loads is shown in Table2. Figure12 shows first principal stress plot for external axial load equal to 40% of preload for conventional joint. The maximum stress is 53.6 ksi and occurring at bolt hole location. Figure13 shows first principal stress plot at external axial load equal to 40% of preload for stepped joint. The maximum stress is 74.4 ksi and occurring at flange shell junction locations. This is due to bending of the flange about flange - shell junction. The flange stress induced in the stepped flange is higher compare to convention flange joint

Table2 : Max.Principal stress (ksi)of flanges due to axial load with pretension

External axial load	Max.First principal stress	
	Conventional flange joint	Stepped flange joint
20% Preload	20.0	38.0
30% Preload	34.0	56.0
40% Preload	53.6	74.0
50% Preload	70.0	93.0

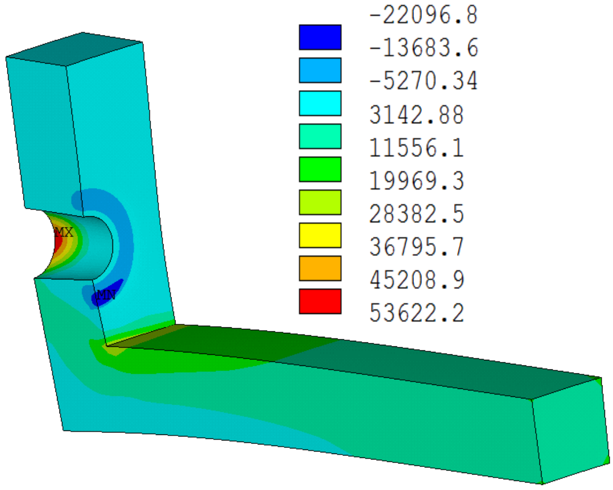

Fig. 12: First principal stress (ksi) in flange Conventional bolted flange joint

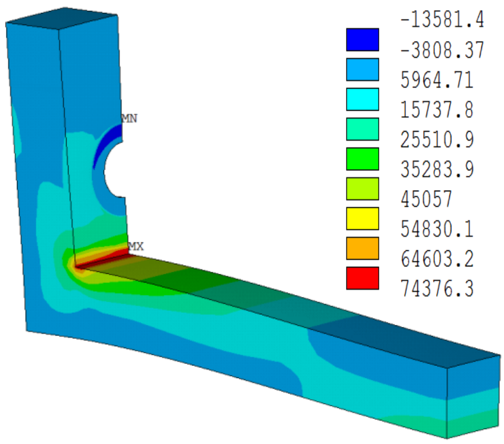

Fig.13 : First principal stress(ksi) in flange Stepped flange bolted joint

D. Load sharing of the bolt

Another parameter worth investigating is the bolt load variation with external load. Figure14 shows the load sharing of the bolt when the joint is subjected to axial load for both the configurations. It is observed from the analysis that in case of convention flange joint, most of the load is shared by flanges when the external applied axial load equal to 20% of the preload and beyond this, bolt starts sharing external load. In case of stepped flange joint, the load shared by bolt is very less compare to the external applied axial load. It is observed that the load shared by bolt is 20% of external applied load when the applied load equal to 100% preload. Hence bolts are subjected lower stress in case of stepped flange bolted joints compare to conventional bolt joints.

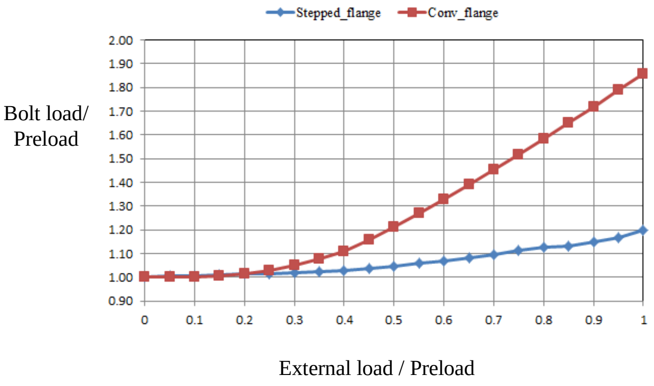

Fig.14. Load sharing of the bolt

VI. CONCLUSION

Significant insight has been gathered regarding the behavior of conventional back to back and stepped flange bolted joints for pretension and external axial loading conditions that aid the designer in achieving the necessary capability within the space and weight constraints of the aircraft engine application.

The flange separation increase as external load increase in case of conventional flange bolted joint. The leakage occurs when external load equal to 40% of preload. The flange separation is not significant as the external load increases in case of stepped flange bolted joint but always heel and toe portion of the flange is in contact, hence no leakage issue.

The induced maximum stress in the flanges is higher in stepped flange bolted joint compare to conventional bolted joint. This is due to bending of the flange about flange shell junction.

The load shared by the bolt is higher in conventional bolted joint compare to stepped flange bolted joint.

REFERENCES

[1] Schneider, R. W., 1968, "Flat Faces Flanges With Metal-to-Metal Contact Beyond the Bolt Circle," ASME J. Eng. Power, 90_1_, pp. 82–88.

[2] Hichem Galai and Abdel-Hakim Bouzid Analytical Modeling of Flat Face Flanges With Metal-to-Metal Contact Beyond the Bolt Circle

[3] Czachor RP. Unique Challenges for Bolted Joint Design in High-Bypass Turbofan Engines. Journal of Engineering for Gas Turbines and Power 2005;127:240-8.

[4] Montgomery, J. (2002). Methods for modeling bolts in the bolted joint. In ANSYS User's Conference, Pittsburgh, Pennsylvania U.S.A

[5] Hyde, T. H., Lewis, L. V. and Fessler, H. (1988). Bolting and loss of contact between cylindrical flat flanged joints without gaskets. The Journal of Strain Analysis for Engineering Design, 23(1), 1-8.

[6] Fessler H, Hyde TH, Lewis LV. Leakage through Loaded Flat-Flanged Joints without Gaskets. Proc. Inst. Mech. Eng. 1988 Part A, 202:1–13.

[7] Prasanna Kumar HS, Mayuram MM, Raghavan KS. Improved Analytical Model for Bolted Joint Evaluation in Gas Turbines. Proceedings of ASME 2012 Gas Turbine India Conference, GTIndia 2012.

[8] Grant M. Henson and Bryes A. Hornish "An Evaluation of common analysis methods for bolted joints in Launch Vehicles".

[9] Shigley JE, Mischke CR, Budynas RG. Mechanical Engineering Design. 8th ed. New York: McGraw-Hill; 2008.

[10] ANSYS User's Manual, Version 14.5