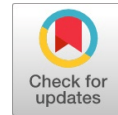


Failure Analysis of Strap Joint

Minakshee R. Shinde, Umesh S. Chavan, Kishor P. Deshmukh



Abstract: In Exhaust after treatment system strap joint is used for mounting sensor table on which DP, NOx, EGTS, PIN sensors are mounted. While, assembling the sensor table on exhaust system using strap joint multiple issues raised. In which, Strap Bolt Loosening Issue during Vibration Test, Plastic Deformation of Heat shield (outer body) and Bottoming Out of the strap. Under Strap contact area plastic deformation of heat shield is due to increasing contact pressure so that needs to check the recommended value of torque to avoid failures. The basic design assembly of straps consists of T bolt, nut, and trunnion with the strap. In this paper analysis and calculations for torque and parameters affecting the system function have been done to minimize the issues. To reduce plastic deformation internal stand support provided which increase the stiffness of heat shield and observed results showing Bridge strap design concept can be helpful to avoid localized plastic deformation near T-bolt. Calculations at assembly load showing maximum stress and contact pressure near the T bolt. Also effect of inertia load described to check slippage of the strap and after treatment system.

Keywords— Strap joint; Sensor table, after treatment system, FEA, Distortion, Heat shield

I. INTRODUCTION

Automotive, truck and other exhaust systems consist of the conduit for passing exhaust gas from the engine to remote location and the exhaust system includes a DOC, DPF, SCR and to build the design criteria exhaust system include hoses, pipes, tubes. [1] There are various applications of flat band clamp for connecting hoses, pipes, tubes mainly because it provides a pressure seal between the components by Applying the radial force. [2] for inserting T bolt into the band assembly loop arrangement is there and different configurations of the loop can use based on the application need. T bolt clamp has many advantages over other types because it is adjustable over a range of hose diameters and carries a higher load than other clamps. [4] For quick release application, there is band clamp mainly that does not damage the conduit on which it is connected. One widely used clamp is worm gear clamp used for tube applications basically for the resilient material conduit but one problem with them is they do not provide a seal along the circumference. [3] Clamps have been used in seismic application because of its easy installation and it avoids the weld so that it is reliable. [6]

Clamp band joints also have been used in launching a system in the aerospace industry. Because of contact and frictional slippage between the parts stiffness varies and it affects the dynamic characteristics of the system. For this, a three-dimensional (3D) finite element model for the clamp band joint developed by considering the frictional contact between the components and nonlinear static analysis had been done also bending capacity of the band joint found out based on the analytical model and the parametric study done for bending behavior of the clamp band joint. Along with the increment of the friction coefficient, the bending stiffness of the joint interface increases. [7] In exhaust system clamp for sealing a lap joint formed by a first pipe inserted within a Second pipe. [1] Working of the flat band clamp shows after applying the torque, induced bolt pretension creates radial force on the conduit due to increased tension in the band and resulting friction force causes the clamping action. Initially when band clamp is in open condition bending stress induces which represents the over opening of the clamp during installation and bending stress is maximum away from the T bolt. [2] After tightening the band clamp resulting frictional force causes hoop stress (circumferential stress) and that hoop stress is maximum near the T bolt [1] when the stress in band clamp goes beyond the yield limit plastic deformation starts, and angle around clamp at which plastic deformation starts which was calculated by shogi [5]. Also, due to largest contact pressure near the T bolt heat shield deformation takes place. The Coefficient of friction is the important factor for band clamp stress calculations. [1][7]

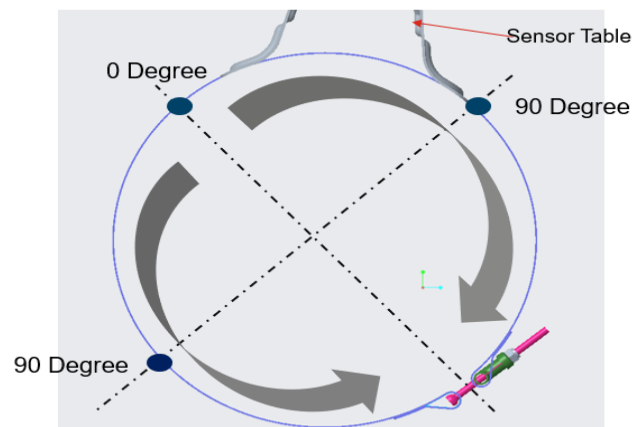


Fig. 1: Strap joint with angular orientation

This paper presents work on a sensor table strap which has been used in the exhaust after treatment system of heavy-duty vehicles for holding the sensor table. There are various failures are observed in the strap joint in which yielding of the strap and assembly due to preload, plastic deformation of heat shield, bolt loosening, thread stripping, strap bottoming out are major failures.

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Failure Analysis of Strap Joint

Different parameters like the coefficient of friction, strap width and thickness, angle around strap are considered for calculating the hoop stress and contact pressure in the strap and assembly. In FEA contact nonlinearity considered as the geometry is complex and there is an abrupt change in stiffness when two surfaces come in contact. Geometrical nonlinearity considered because there is a large deflection in strap by applying small amount of force. The results extracted from the FEA are compared with analytical calculations. And to avoid some issues of distortion of heat shield modified design with bridge strap introduced

II. SENSOR TABLE HOLDING STRAP JOINT MODEL AND CALCULATIONS

Model showing sensor table assembled on heat shield using strap joint with M6 bolt.

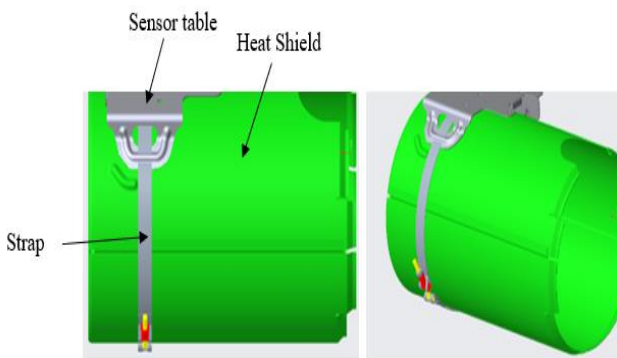


Fig. 2: Strap Joint Model

A. Strap Joint Material Properties

I. Material properties

Material : SS439		
Material property	Value	Unit
Material Density	7850	Kg/m ³
Young's Modulus	2E+11	Pa
Poisson Ratio	0.3	
Bulk Modulus	1.6667E+11	Pa
Shear Modulus	7.6923E+10	Pa
Tensile Yield Strength	2.9E+8	Pa
Tensile Ultimate Strength	4.6E+8	Pa

B. Assumptions

1. Strap Material is linear
2. Step provided on strap at sensor table location did not consider while calculation
3. Torque Factor: 0.18

Free Body Diagram for the sensor table holding strap shows that strap Tension T, reaction force due to strap tension is R and location of Centre of Gravity Shown in the fig.

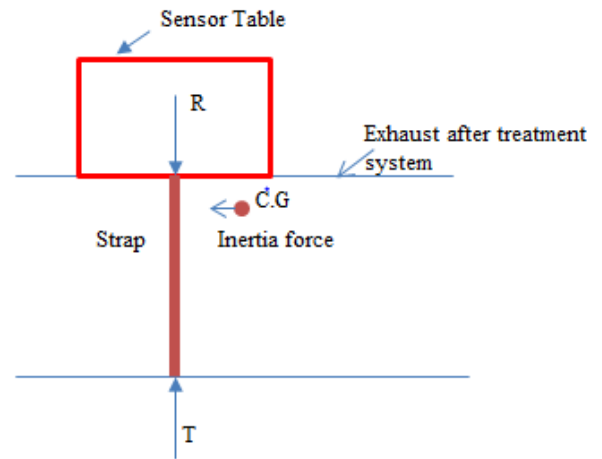


Fig. 3: Free Body Diagram of sensor table strap

C. Types of load

1. Assembly load (bolt preload)

Assembly load has been calculated from the torque and bolt size. Initially, to check how much torque required to apply so that there could not be over torquing or torque loss between the strap and SCR need to assume some slip margin and from that by trial and error need select bolt size and recommended torque. From diameter of the bolt and Torque bot preload calculated.

$$\text{Torque} = \text{Torque factor} * \text{Diameter (m)} * \text{Preload (N)}$$

... Torque factor=0.18

2. Applied load (Inertia load)

Inertia load calculated from the mass and G load.
Inertia load= Mass* G*g

Slip margin:

Frictional force / inertia force

Slip between heat shield and strap can occur if the frictional force due assembly load is less than the inertia force.

D. Types of Stress

After applying the torque on bolt induced preload causes the frictional force between the strap and heat shield Due to that frictional force hoop stress induced in strap along circumferential direction and it varies with respect to angle around strap.

To get simple approximate results These exponential relations between the forces in the strap and angle were proposed by Shoghi et al. (2003) for the flat band clamps.

Ratio of bolt pretension to force at an angle around clamp can be calculated from the formula

$$\frac{F_{\beta}}{F_{\alpha}} = e^{\mu(\beta-\alpha)}$$

Hoop Stress

$$\frac{F_{\beta}}{wte^{\mu(\beta-\alpha)}} = \sigma$$

Contact Pressure

$$p = \frac{\sigma \theta * t}{R2}$$

From these formulae hoop stress calculated for the sensor table strap

III. STRAP JOINT ANALYSIS

E. Assumptions

1. The Coefficient of friction is 0.15
2. All-important contacts are considered as Non-linear Contact. (i.e. related to the strap, sensor table and Heat shield)
3. Temperature effects are not considered.

F. Geometry import

The exhaust after treatment system assembly geometry (CAD Model) is imported in Ansys for numerical analysis. As the assembly requires a lot of time for a solution so to reduce the solution time, mid - surfaces are extracted from geometry and these surfaces are converted into the mathematical model as nodes and elements by doing meshing. Bolt, trunnion, nut assembly kept as a solid for analysis.

G. Meshing

Initially took strap element sizing 1mm and the heat shield mesh sizing 4 mm results showing patches in contact pressure between the strap and heat shield. By doing no. of iterations conclusion drawn is needs to keep the same element size for the strap and heat shield at least in contacting faces to get proper contact pressure. Quad elements are used for both straps and heat shield surfaces. Similarly, mesh for contacts of sensor table with the strap and with heat shield need mesh connectivity.

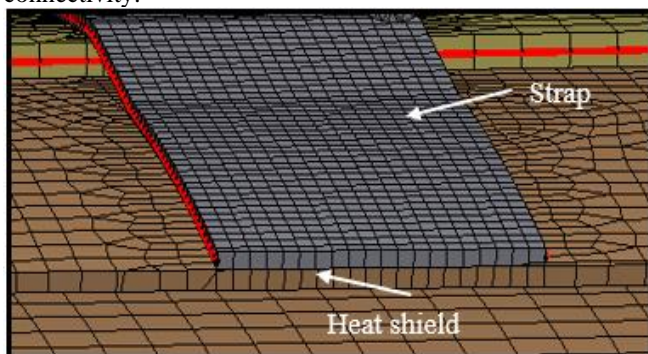


Fig. 4: Mesh model

H. Contacts

Contact status shows whether parts are touching or separated. Frictional contact applied between all the contacting faces of the strap, sensor table and heat shield. The assumed coefficient of friction is 0.15 for this analysis in further study effect of the coefficient of friction on stress has been considered. Various options of contact setting are explained below. Behavior is asymmetric means contact surface nodes cannot penetrate the target surface so asymmetric setting kept. In Workbench Mechanical, “Augmented Lagrange” is recommended for general frictionless or frictional contact in large-deformation problems. Augmented Lagrange formulation adds additional controls to automatically reduce penetration [9] Each Iteration Aggressive” sets the program to update stiffness at the end of each equilibrium iteration, but this option allows for a broader range in the adjusted value. [9] Any initial gaps are closed and any initial penetration is ignored creating an initial stress-free state. Contact pairs are “just touching” as shown.

I. Boundary Conditions

Bolt pretension applied such that the effect of loading and unloading can get from the results. Preload is divided into number of load steps to avoid the convergence issue, as if we apply a load in one step only then sudden change in stiffness creates the convergence error.

For M6 bolt calculated torque value is 8 N-m. Hence, bolt pretension showing maximum value 7593 N-m which is applied by dividing it into load steps.

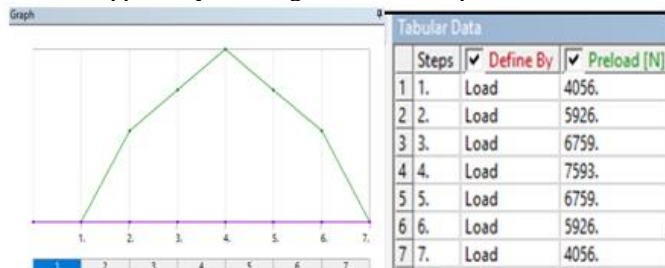


Figure 5: Preload steps

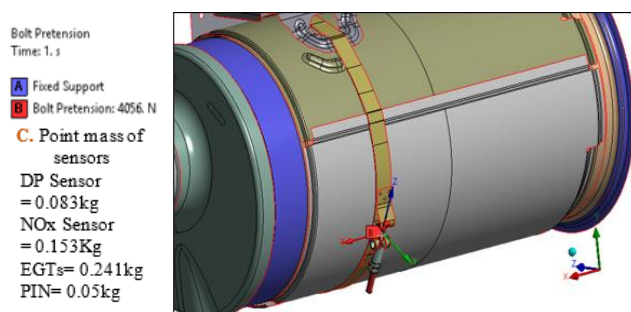
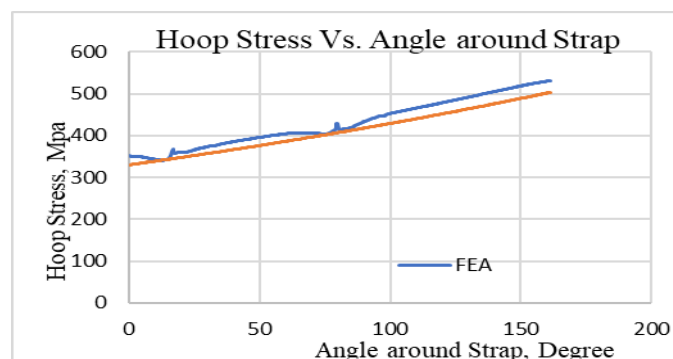


Fig. 6: Boundary conditions

IV. RESULTS AND DISCUSSION

Hoop Stress

At the region where the strap is modeled such that there should be no interference between the strap and sensor table, step has been made to strap over the sensor table. In analytical calculations strap assumed as a total circular, it has no steps so that analysis showing little variation in that area. Results for hoop stress have seen at maximum bolt pretension step.



Graph 1: Hoop Stress Vs Angle around Strap Variation

Failure Analysis of Strap Joint

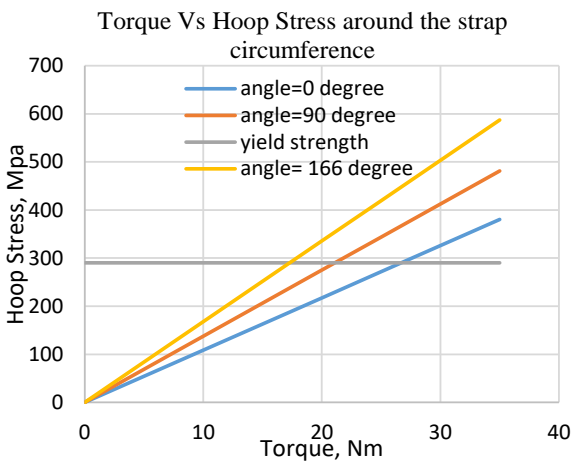
The largest stress has been occurred near the gap. Hence, yielding and plastic deformation will initiate at this point and gradually propagate towards the 0-degree angle. [5] as shown in the graph nature of hoop stress extracted from analysis is similar to the stress calculated by analytically.

J. Effect of Torque on Stress

Improper selection of torque value may cause the following failure reasons.

- T bolt Torque is not sufficient.
- T bolt not capable to handle required torque (yielding)
- Torque Loss because of Plastic Deformation of heat shield
- Thread Stripping during assembly

So to avoid the above conditions stress developed in the strap calculated with respect to torque and it is showing that stress increases with increasing in torque. As shown in the graph, three different angles are considered to check the relation of torque vs. stress.

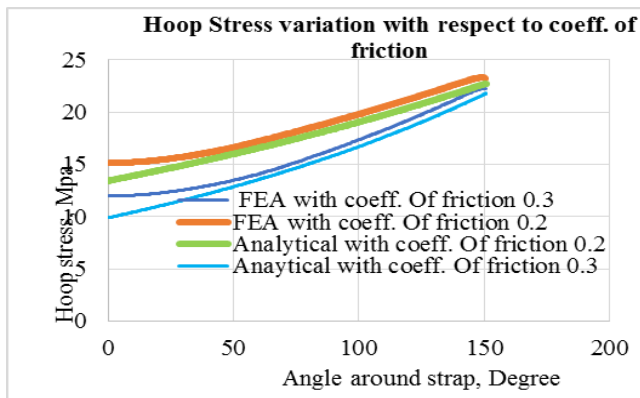


Graph 2 : Stress variation with respect to Torque

K. Effect of coefficient of friction on hoop stress

The coefficient of friction varies according to contacting materials. [11]

The magnitude of the friction coefficients depends on a number of factors Such as surface finish, material hardness and lubrication. To check the effect of the coefficient of friction on hoop stress two iterations have done with $\mu=0.2$ & 0.3 . As it took lot of time for nonlinear analysis so both iterations have done with the load of 1000N. Analytical calculations have done for same load condition.



Graph 3: Hoop Stress variation with coefficient of friction

Hoop stress increases with the coefficient of friction close to the gap in the band and decreases with an increasing coefficient of friction furthest from the gap. [2]

II. Hoop Stress Comparison by Analytical and FEA with respect to coefficient of friction

Angle around strap, degrees	Coefficient of Friction	FEA Stress, Mpa	Analytical Stress, Mpa	Difference (%)
150	0.3	22.20	21.78	2
	0.2	23.21	22.73	2.1
90	0.3	16.46	15.85	4
	0.2	16.46	18.39	5

The largest stress developed near the gap. Hence, yielding and plastic deformation will initiate at this point and gradually propagate towards the 0-degree angle. [5]

Deformation plot

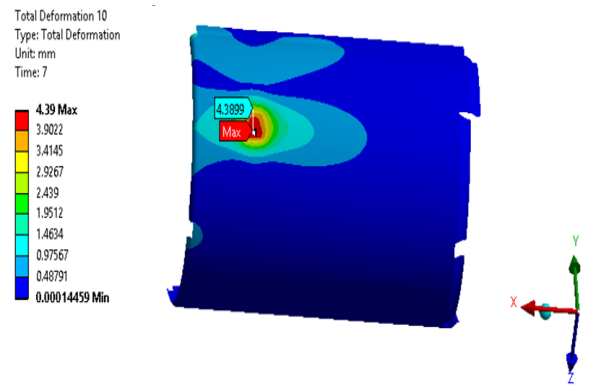


Fig. 7: Total Deformation

At load step 7 (unloading step) deformation plots extracted and it is showing maximum deformation of the heat shield below and near the bolt.

So that needs to check the equivalent plastic strain in the heat shield.

Equivalent Plastic Strain:

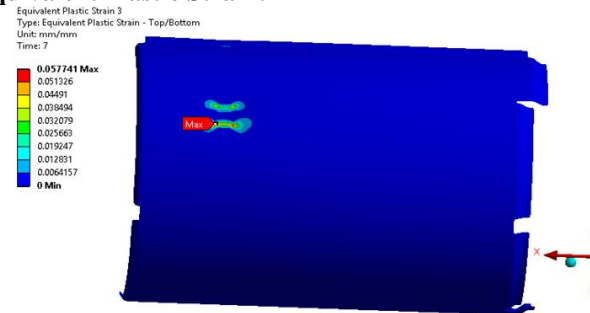


Fig. 8: Equivalent plastic strain

Equivalent Plastic strain of the heat shield at load step 7. Shows that after unloading it is not regaining its shape. It means heat shield Permanent deformation occurred.

V. ACTUAL TEST

Within Proto Build of we have observed Build Issue, Crushing of Heat Shield on SCR while Clamping Sensor Table, using Strap. During the unloading of strap heat shield bend remains same it is not recovering its initial position so to avoid the crushing of heat shield modified design approach discussed

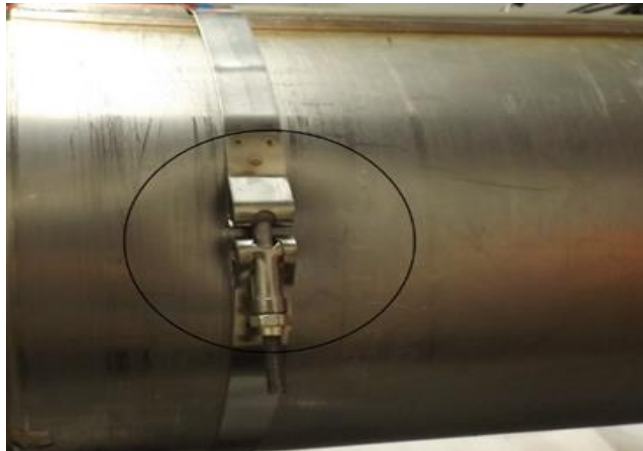


Fig. 9: Actual Test Image

VI. STRAP JOINT MODIFIED CONCEPT

The model with bridge has been developed to reduce the deformation of the heat shield. These bridge members have been employed in T-bolt clamp configuration for preventing or reducing the incidence of the formation of a bulge, or a portion of the hose Wall from moving radially away from the underlying fitting in the region between the band's looped ends because of the looped ends being drawn together during the clamp tightening process. [4]

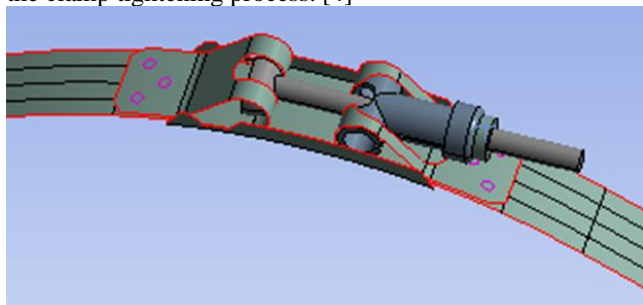


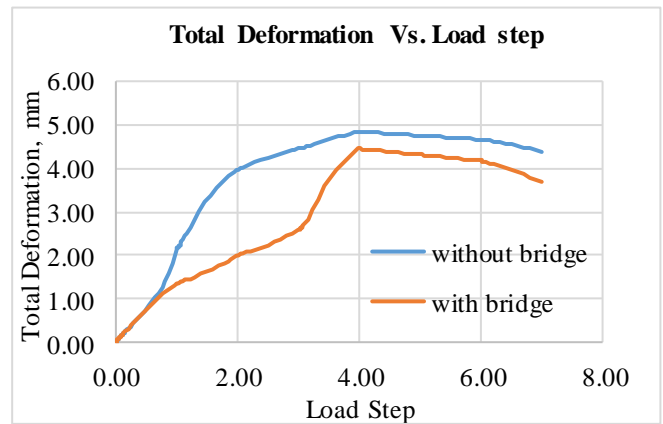
Fig. 10: Strap with bridge concept

As there was an issue of crushing of the heat shield so to avoid that one iteration with bridge strap design concept carried out. One end is welded and one end has hook to adjust in strap.

VII. RESULT AND DISCUSSION WITH MODIFIED DESIGN

Total Deformation

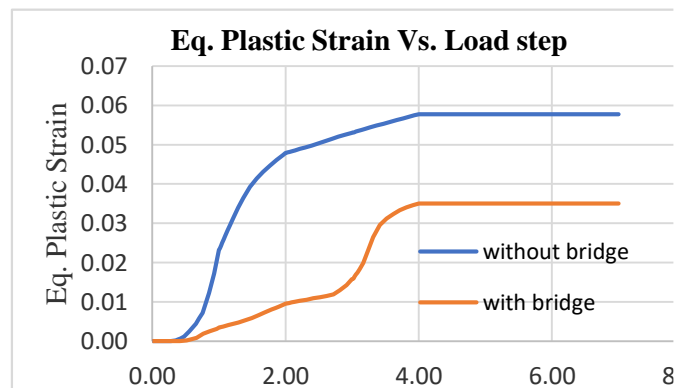
Initially when strap tightening started up to load case one (4056 N) deformation was same for both the cases. Once, strap gets tightened deformation with bridge strap reduced.



Graph 4: Total deformation with bridge strap and without bridge strap

Equivalent Plastic Strain

as per boundary conditions after load step 4 unloading started but as shown in the graph after load step 4 plastic strain does not decreases During the unloading of strap heat shield bend remains same it is not recovering its initial position.



Graph 5: Eq. plastic strain with bridge strap and without bridge strap

With bridge strap showing much decrease in the plastic strain compared to initial strap design.

III. With and without bridge strap deviation in results

Parameter	Load step	Without bridge	With bridge	% Difference
Total Deformation	1st	2.14 mm	1.36 mm	36.43
	4th	4.85	4.45	8
	7th	4.39 mm	3.69 mm	16
Eq. Plastic Strain	2nd	0.05	0.01	80
	4th	0.06	0.04	34

Tabulated results shown for different load steps and it is showing maximum 36% decrease in deformation and 80% decrease in plastic strain.

VIII. CONCLUSION

Hoop stress is maximum near the T bolt and minimum at an angle of 0 degrees.

Hoop Stress variation by analytically and by FEA are within 5%

Stress in radial and axial direction is very negligible as compared to hoop stress because force developed in strap due to bolt pretention is maximum along the circumference of strap joints

Hoop stress increases with increasing in torque

The Coefficient of friction is a sensitive parameter which affects the hoop stress and stress increases with increasing in the coefficient of friction near T bolt and decreases with increasing the coefficient of friction away from T bolt.

Hoop stress variation with respect to coefficient of friction by analytically and by FEA is within 5%

Contact pressure is not uniform around the circumference of the strap until the value of the coefficient of friction becomes zero.

For getting more realistic results or if stress is going beyond the yield limit of the material then need to consider nonlinear material properties.

The strap with bridge concept will be useful to avoid the crush of a part which is being held by the strap as it reduces the equivalent plastic strain.



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