An Analytical Approach for Mass Optimization of Flange Joint

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Abstract: This study has been undertaken to optimize the mass of flange joint by using finite element software tool with different iterative options keeping same functional capabilities of the joint. Flanges are usually used to assemble two components together where the flow of liquids or gas is required or just for extension of any component. Using optistruct as a solver, topology optimization of standardized ANSI Flanges B 16.5, Slip on Flange of Class 150 Lbs. has been done.

***Index Terms* – Geometry of flange, flange thickness, no. of fasteners, finite, element model, topology optimization.**

I. Introduction

Bolt flange connection is commonly used in various engineer applications. With the increasing of a safety and environmental concern, the tightness of gasket flanged connection becomes an important issue. In addition, Hwang [1] describes that the behavior of bolt joint is complicated and influenced by several factors such as preload, internal pressure, temperature etc., the clamp force in a joint is the key to maintaining joint integrity.

Optimization techniques are used widely in the design of a components to obtain predetermined performance goals subjected to constraints specified (mass reduction, etc.). Structural optimization can be categorized into three classes: size optimization, shape optimization, and topology optimization. Krishna [2] and Krishna and Anderson [3] use shape optimization in the design stage of an upper CA to reduce weight, bring down stresses, and raise the first frequency.

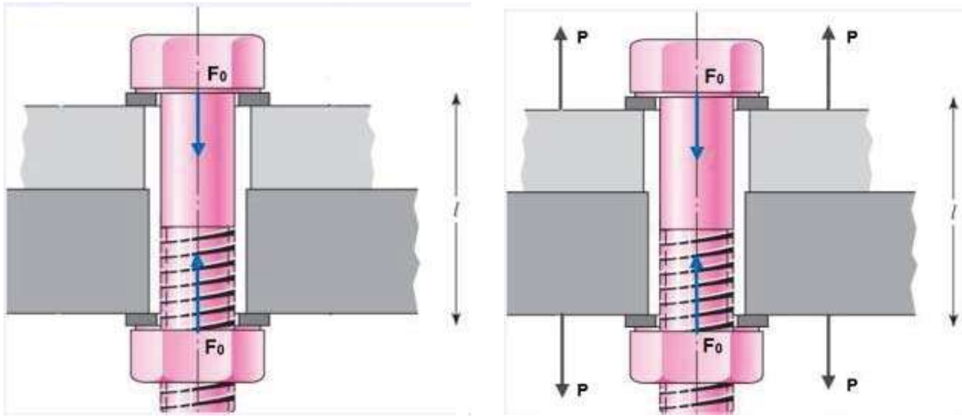
Two topology optimization approaches can be identified in the literature. The first approach (microstructure approach) introduced by Bendsoe and Kikuchi [4] is to find the size and orientation of holes in each element of the finite element analysis (FEA) model. The second approach (density approach) that has become very popular recently is based on the density formulation introduced by Rozvany and Zhou [5]. In the density approach, the material density in every finite element of the structure is selected as the design variable and the immediate density is penalized during the optimization iterations.

Nelson [6] describes a practical application of the die draw direction constraints in topology optimization and shows how they are effectively used to improve the design. Yang et al. [7] present and discuss new applications of topology optimization including weight reduction, manufacturing process selection, weld, and bead pattern designs for some three-dimensional automotive components.

II. Methodology of Flange Joint

From bolted flange connection theory, the total force of bolt is subjected not only to the initial preload and external working load, but also to the stiffness of bolt and stiffness of connected member. Figure 1 shows bolted joint subjected to initial preload and external load, respectively.

During bolt preload (see Figure 1(a)), the joint exists only the perforce of bolt, therefore, bolt stretched and connected member compressed in grip share the same preload.



(a) Initial Preload (F_0) (b) External load (P)

Figure 1: Bolt Joint Connection

Assume k_b denotes the stiffness of bolt, E_b denotes the elasticity modulus, A_b denotes the cross section area of the bolt, and the effective clamp length is l. k_m denotes the stiffness of member, T_m denotes the thickness, and E_m denotes the elasticity modulus. F_0 denotes the initial preload, and P denotes the external working load. According to the Shigley's formula[8], the deformation of the bolt flange is followed by Hooke's law. The stiffness of the bolt k_b follows equation

$$k_b = \frac{E_b A_b}{l} \quad (1)$$

The stiffness of the connected member k_m follows equation

$$k_m = \frac{E_m A_m}{l} \quad (2)$$

When external load F is applied to the joint, the bolt stretches an additional amount δ and the tensile force of the bolt will increase F_b. The connected parts in grip uncompress same amount δ due to the bolt elongation. As a result, the amount of the compression force will decrease P_m

$$\delta = \frac{P_b}{k_b} \quad and \quad \delta = \frac{P_m}{k_m} \quad (3)$$

$$P_m = P_b \frac{k_m}{k_b} \quad (4)$$

Since $P = P_b + P_m$

$$P_m = P_b \frac{k_m}{k_b} \quad (5)$$

$$P_m = P - P_b = (1 - C)P \quad (6)$$

Where C is defined as the stiffness constant of the bolt, which indicates the proportion of external load P that the bolt will carry.

$$C = \frac{k_b}{k_b + k_m} \quad (7)$$

The resultant bolt load F_b is following equation

$$F_b = P_b + F_0 = CP + F_0 \quad (8)$$

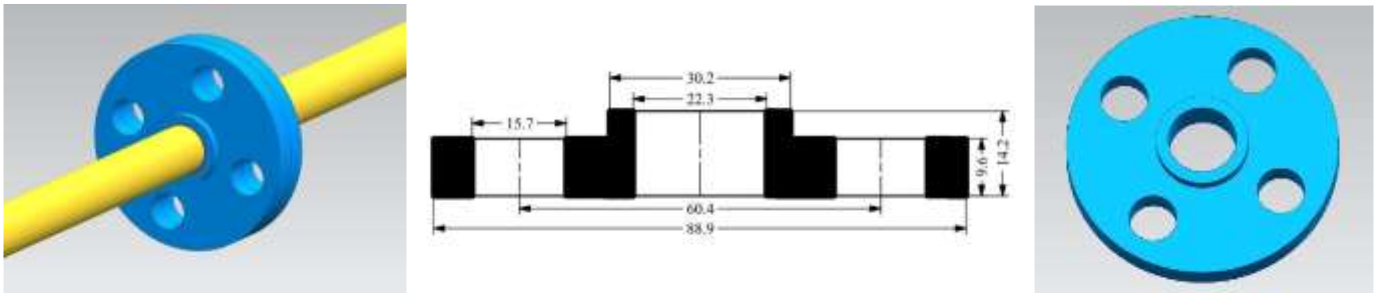
The resultant load F_m on the members is

$$F_m = P_m - F_0 = (1 - C)P - F_0 \quad (9)$$

These results are only valid if the load on the members remains negative, indicating the members stay in compression. However, the above equations assumes that the bending or shear stress has been ignored.

III. PROCEDURES OF TOPOLOGY OPTIMIZATION FOR SLIP ON FLANGE

Figures 2(a) and 2(b) shows Pipe Connection and Class 150 Lbs. flange with dimensions respectively. Pipes are inserted into the flanges and then welded externally. The flanges are connected to one another with the help of fasteners at the time of assembly.



(a) Pipe Connection (b) Class 150 Lbs. Flange with Dimensions

Figure 2: Pipe Connection and Flange

Figure 3 shows the flowchart for topology optimization of flange

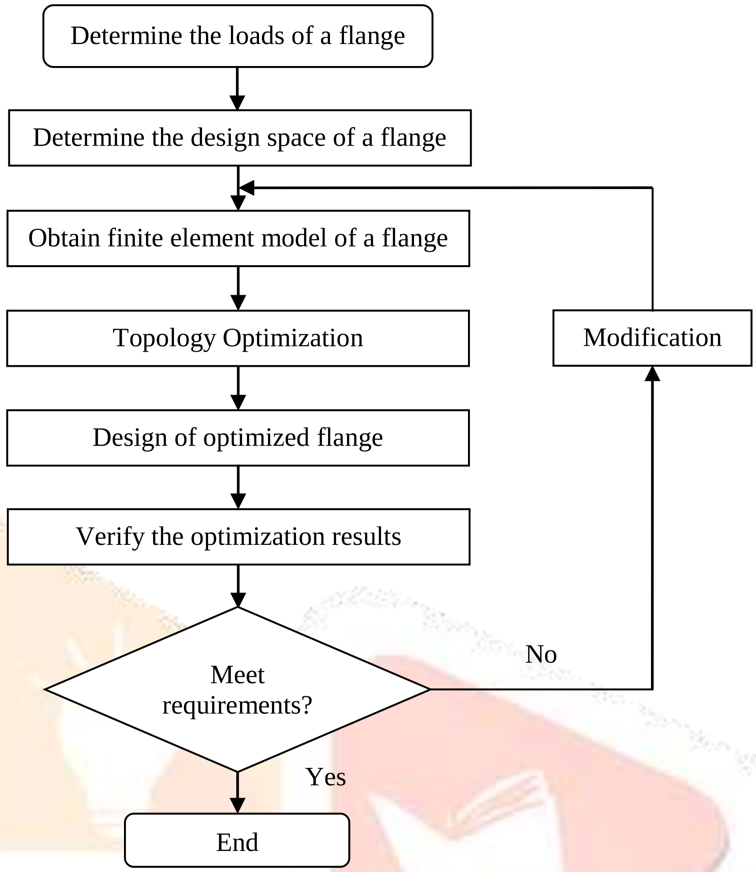


Figure 3: Topology Optimization Flowchart of the Flange

IV. FEA & TOPOLOGY OPTIMIZATION OF SLIP ON FLANGE

These section outlines the linear static analysis of flange under given conditions such as preload, displacement constraints, etc. and also topology optimization carried out using specific design variable, constraints & objective function.

3.1 Finite Element Analysis

Using finite element analysis tool, the solid geometry is meshed using mixed elements (quads & trias) with element size of 0.5 mm. Material of flange used is SS304, Figure 4 depicts the geometry model and finite element mesh of a flange.

Properties of material SS304: -
1) Modulus of Elasticity, E = 200 GPa
2) Yield Tensile Strength, S_{yt} = 215 MPa
2) Density, $\rho = 8 \times 10^{-6}$ kg/ mm^3
3) Poisson's Ratio, $\mu = 0.29$

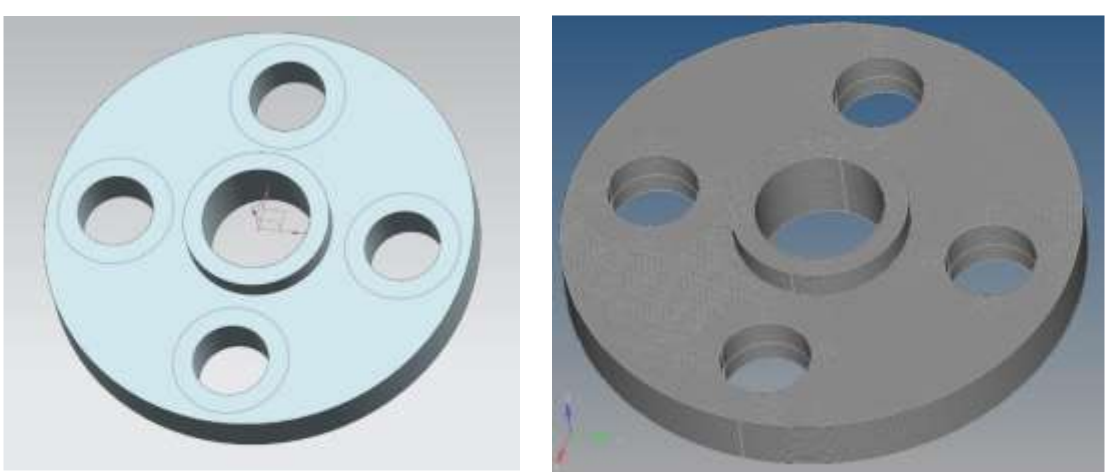


Figure 4: Geometry Model and Finite Element Mesh of a Flange

3.1.1 Preload Calculation and Displacement Constraints

As per standarized, torque value of 65.0 Nm is given for M12 fastener with metal to metal contact surfaces. Hence, using Eq.10 preload can be calculated as

$$T = K\,F_i\,d \qquad (10)$$

Where, T = Torque in Nm
K = Constant (0.20)
F_i = Preload in N or kN
d = Diameter of Fastener in mm

using Eq.10, $65 = 0.20 \times F_i \times 12 \times 10^{-3}$

Preload, F_i = 27083.33 N or 27.08 kN (single fastener)

Preload of 27.08 kN applied to each washer area respectively. All dof's fixed at the inner flat surface where the other flange mating is done. Figure 5 shows forces applied to the washer area and constraint at the mating surface.

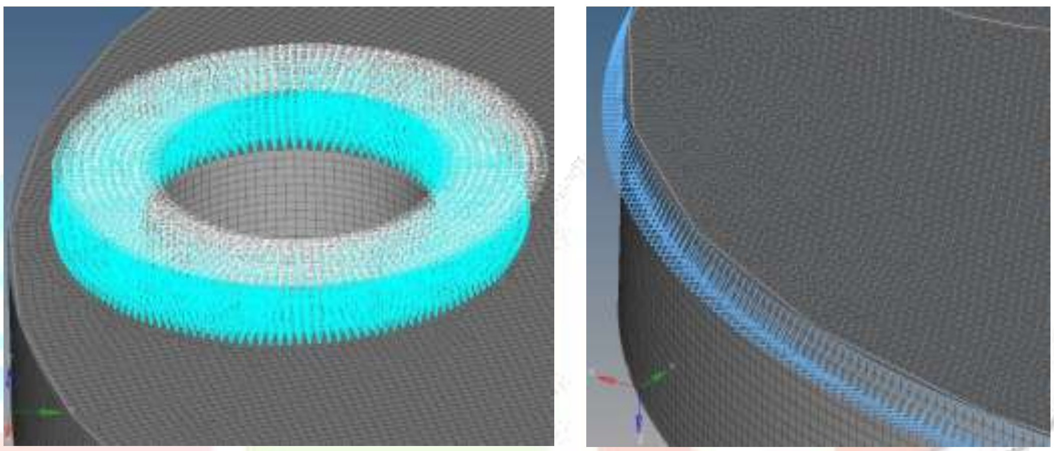


Figure 5: Forces and Constraints

3.1.2 Max. Displacement and Von-Mises Stress

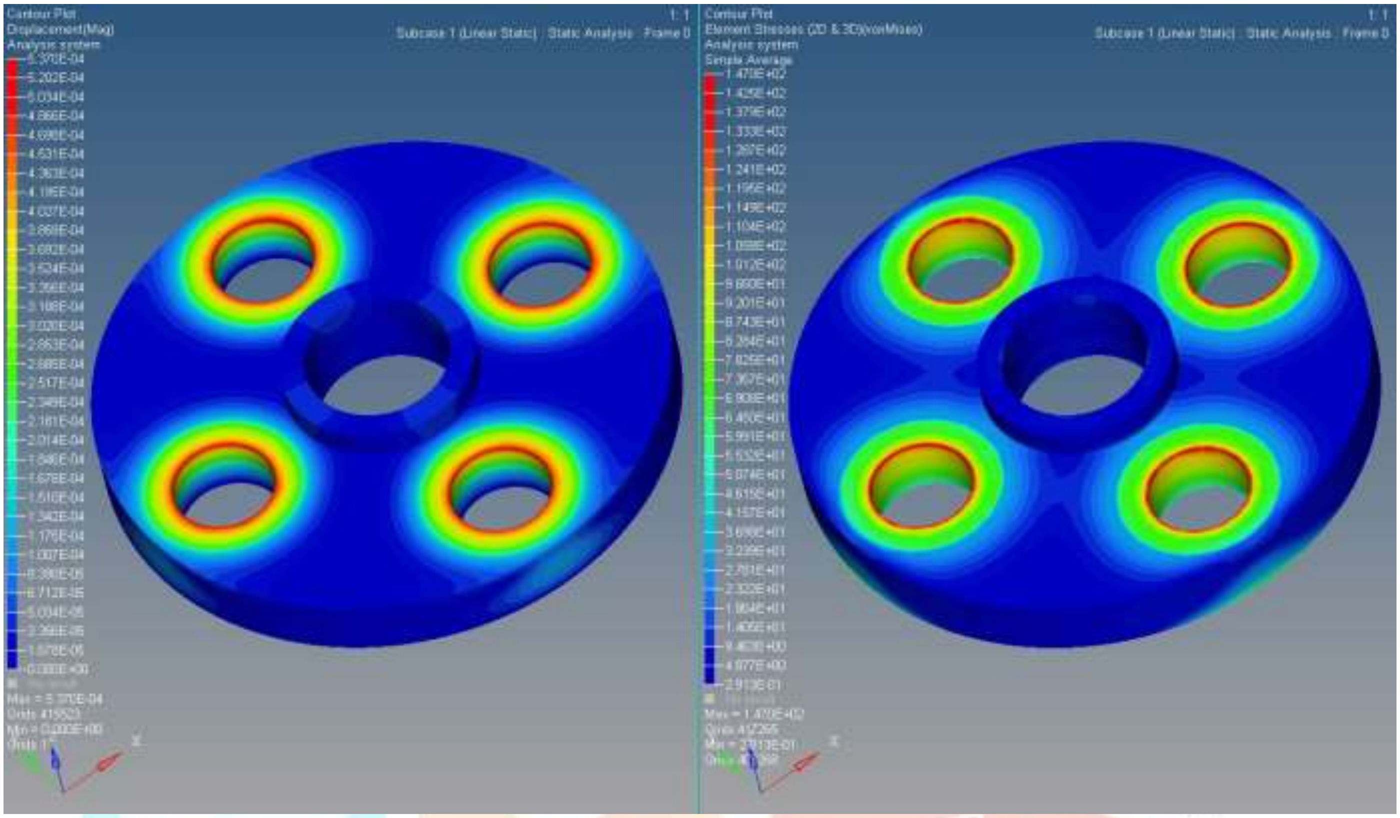


Figure 6: Max. Displacement and Von-Mises Stress Plot

3.2 Topology Optimization

It is a mathematical technique that optimized the material distribution for a structure within a given package space. Table 1 depicts various topology optimization parameters used.

Table 1: Topology Optimization Parameters

Objective Function	Minimize Weighted Compliance (increases stiffness of flange)
Constraints	Stress ≤ 10 MPa Mass Fraction: 0.50
Design Variables	The Density of each element of the flange

Also, manufacturing constraints used for topology optimization are:

i. Minimum member size control specifies the smallest dimension to be retained in topology design. Controls checker board effect and dicreteness.
min. member size = 3 x min. element size
= 3 x 0.5 = 1.5 mm

ii. Maximum member size control specifies the largest dimension allowed in the topology design. It prevents large formation of large members and large material concentrations are forced to more discrete forms.
max. member size = 2 x min. member size
= 2 x 1.5 = 3.0 mm

iii. Pattern grouping / repetition can be applied to enforce a repeating pattern or symmetrical design even if the loads applied on the structure are unsymmetrical or non-repeating. (1-Plane symmetry)

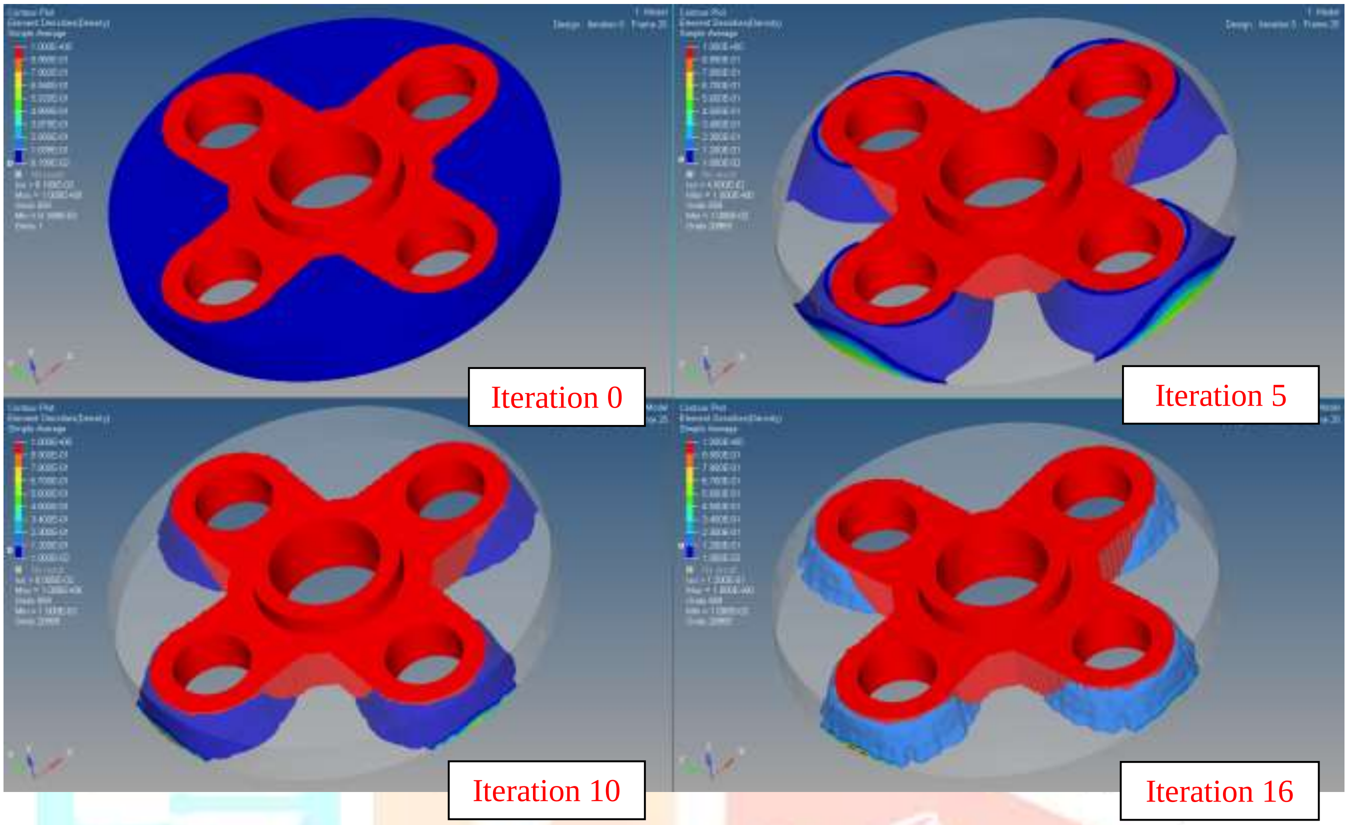


Figure 7: Topology Optimization for Flange

V. Results And Discussion

From this analysis and optimization study it is found that there is mass reduction of approximately 40% for a single flange. Analysis of optimized design was also studied and the results were stated almost to be same. Table 2 & 3 shows comparison for Mass of single flange and Results of Displacement & Von-Mises Stress respectively for standard and modified one.

Table 2: Comparison for Mass of Single Flange

Flange	Mass of Single Flange	Mass Reduction
Standard	394.240 grams	39.43 %
Modified	238.781 grams	

Table 3: Results of Displacement and Von-Mises Stress

Flange	Max. Displacement (z-axis)	Von-Mises Stress (Localized)
Standard	0.5 micron	147 MPa
Modified	5 micron	146.1 MPa

So, using this approach new flange can be designed which can replace standard flange where the requirement of mass of component is of major importance other than its cost of manufacturing. Also, the functional capabilities of joint doesn't change because we get the same amount of pressure generated at the interface of the joint.

VI. Acknowledgment

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