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Shear Stress Distribution in a Fuselage of an Aircraft

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Abstract
The aircraft is assembled from basic components like fuselages, control surfaces, wings, and tail units. These components vary in different aircraft and have more than one specific function. The structure of an aircraft is designed to withstand two different types of loads namely the ground loads which includes landing loads, taxiing load, hoisting, and towing load. Air load is the second type which includes loads acting on the structure during flight by maneuvers and gusts. These two classes of load can be subdivided into surface forces which acts on the surface of the structure like hydrostatic pressure and aerodynamics, and body forces which is produced by inertia and gravitational effects and acts over the volume of the structure. The impact of these air loads results in bending stresses, shear stresses and torsional loads in all parts of the structure of the aircraft. The purpose of this paper is to calculate and plot the shear stress distribution as function of "a" $(3 \leq a \leq 15)$ on a cross section of an airplane fuselage made of 2014-T4 aluminum alloy. The plate thickness is 0.175a mm which is constant around the periphery and an applied torque of 200 kN.m. The radii of the fuselage are 50a mm and 32a mm respectively and it has a height of 69.5a mm. The fuselage is divided into sectors and triangles and their areas calculated. The shear flow which is a product of shear stress and thickness of the fuselage can be calculated. From the result it can be observed that as the magnitude of "a" increases the shear stress reduces. Verification and validation were carried out on solid works to test for convergence.
Keywords: Fuselage. Shear Flow. Aircraft. Aerodynamics. Hydrostatic pressure. Shear stress. Control Surfaces.

1. Introduction

The term fuselage as seen in Fig.1 comes from a French word "Fusele" [1, 2] which means spindle shaped. The Fuselage is the larger outer shell of an airplane's main body. Seats as well as other equipment are housed in the hollow interior. It is the outer shell of an airplane's main body, with the aircraft wings on the sides. The wings do not lie on the same plane but meet at an angle called the dihedral angle [3] which is the angle that the wings make with the local horizontal. The front of the fuselage contains the cockpit and the rear houses the tail.

The fuselage is essential for maintaining the structural integrity of the aircraft and provides aerodynamic stability. About 30% of the aircraft zero-lift drag source is known to be due to the fuselage. The aircraft cruise performance, which includes the fuel consumption are flights maximum speed are dependent from the zero-lift drag coefficient [4]. Because it is the outer shell of an airplane's body it is exposed to a significant amount of stress, therefore durability, reliability, strength, and material are key factors to be considered in the design. If the fuselage is breached the airplane's cabin may lose air pressure and cause the oxygen levels to drop and the airplane loses control.

The design of the fuselage is important particularly for commuter aircraft and general aviation categories. There are different types of fuselages namely: Truss fuselages which are characterized using welded metal tubes, they are light weight and high strength and durability with low cost of manufacture. Geodesic Fuselages use strip stringers to achieve a basket-like construction. They are designed to withstand localized structural damage without jeopardizing the integrity of the rest of the fuselage. Other types include monocoque shell and semi monocoque shell fuselages. Most airplanes use aluminum and its composites or carbon-epoxy composites to make its components because of their fatigue resistance, stiffness, strength, and fracture toughness (a limiting design consideration in aluminum fuselages).

There are three design approaches for a fuselage which are skin- stringer approach, frame- longeron approach and the sandwich skin fuselage approach. The primary load on the fuselage is concentrated around the wings-box, wing connections landing gears and payloads The skin carries the cabin pressure, which is tensile and the shear loads while the longitudinal stringers carry the longitudinal tension and compressive loads. The circumferential frames maintain the shape of the fuselage and redistribute the loads. During flight, the wings coupled with the tailplane loads usually generate bending stress along the fuselage. The upper part of the fuselage is subjected to tensile stress while the lower part of it is subjected to compressive stresses. The aircraft fuselage shear stress is the force that acts parallel to the cross-sectional area of the fuselage, it usually causes failure or deformation of the fuselage structure.

The aircraft fuselage is subjected to several loads during flight, shear stress is one of the key stresses that affect the fuselage, it is caused mostly by aerodynamic forces during flight. These aerodynamic forces could be wind, maneuvering or turbulence [5] shear loads are generated along the sides of the fuselage and when the aircraft turns and rolls the fuselage is subjected to torsional loads. Pressurization of the cabin at high altitude subjects the fuselage to internal tensile hoop stress. This project focuses on the shear stress distribution on a fuselage for an applied torque of 200 kN.m with a constant thickness of 0.17a mm for values of a ranging from 3 and 15.

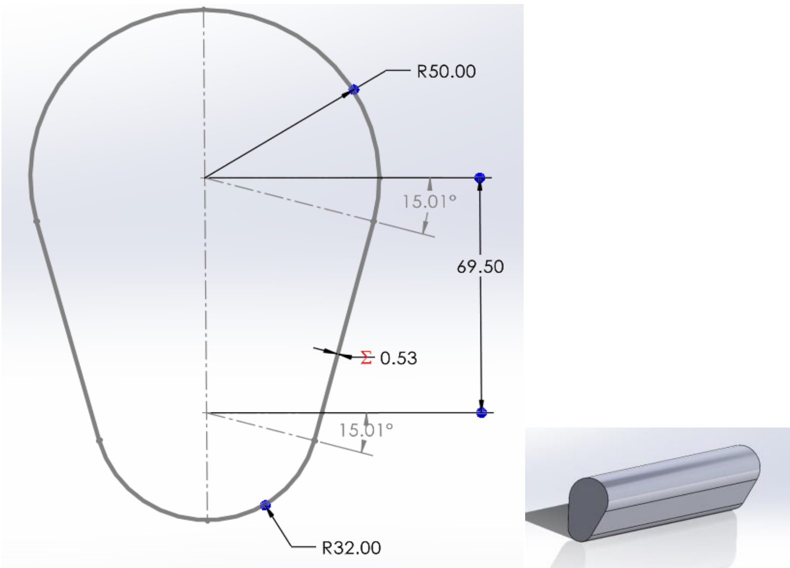

Figure 1: Fuselage

Table 1 Mechanical Properties of 2014-T4 Aluminum Alloy

Elastic Modulus	72 GPa
Brinell Hardness	110
Elongation at break	14%
Fatigue Strength	140 MPa
Poisson’s Ratio	0.33
Rockwell B Hardness	69
Shear Modulus	27 GPa
Shear Strength	260 MPa
Tensile Strength (Ultimate) UTS	430 MPa
Tensile Strength Yield (Proof)	270 MPa

Method of Analysis:

Since the plate thickness is constant for the entire periphery, the shear flow is constant [6].

- Arc $B\hat{E}C$ subtends an angle of 210°, that is (180° + 15°+ 15°)
- Arc $A\hat{F}D$ subtends and angle of 150°, that is (180°- 15°- 15°) = 150° (sum of angle on a straight line)

While ABCD can be divided into four triangles. We first find the area of the two sectors and four triangles and then add up to get the total area of the fuselage. For consistency of units the torque was converted to N.mm and a minimum thickness of 0.53mm (at a = 3) was used for the 3D drawing.

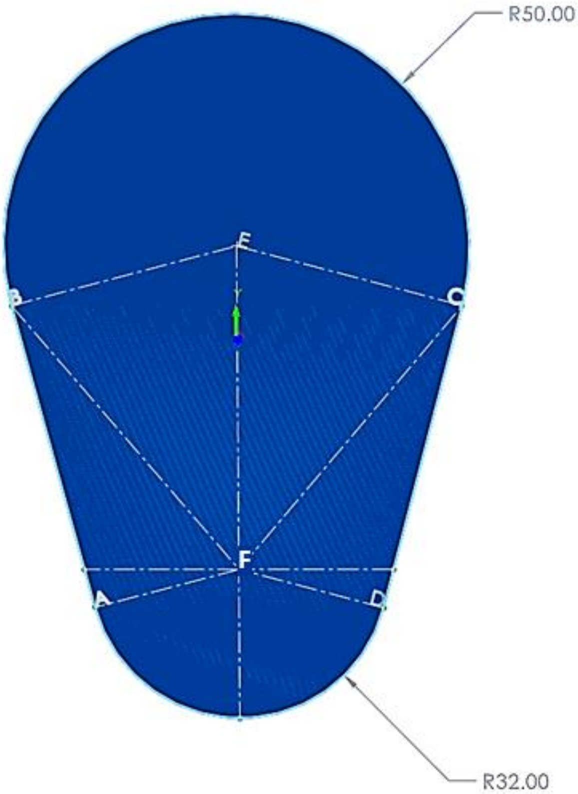

Figure 2: Fuselage divided into sectors and triangles.

$Area\ of\ Sector\ \ B\hat{E}C = \frac{\theta}{360}\pi r^2 = \frac{210\times 3.142\times(50a)^2}{360} \quad = \quad 4582.08a^2mm^2$ *(i)*

$$Area\ of\ Sector\ A\hat{F}D\ = \frac{\theta}{360}\pi r^2 \ = \frac{150\ \times 3.142\times(32a)^2}{360} = 1340.41a^2mm^2$$

$Area\ of\ a\ Triangle\ = \frac{bh}{2}$ *(ii)*

b=50amm and h=69.5amm and then substituting we have

$$Area\ of\ Tiangle\ BEF = CEF\ = \frac{1}{2}\times 50a\times 69.5a = 1737.5a^2mm^2$$

$Area\ of\ a\ Triangle\ AFB = DFC\ \ = \frac{bh}{2}$ *where b=32amm and h= 69.5amm*

$$AFB = DFC = \frac{1}{2}\times 32a\times 69.5a = 1112a^2mm^2$$

$Total\ Area = \left(B\hat{E}C + A\hat{F}D + BEF + CEF + AFB + \ DFC\right)a^2mm^2$ *(iii)*

$$= (4582.08 + \ 1340.41 + 1737.5 + 1737.5 + 1112 + 1112)$$
$$= 11621.49a^2mm^2$$

Torque is proportional to volume under a membrane[6].

$T\ = 2Aq$ *(iv)*

Where A=Area of the fuselage

T=Torque = 200kN.m

q= τt *with dimensions [F/L], is called shear flow* *(v)*

$\tau = shear\ stress\ \ t = thickness$

Solving equation (iii) in terms of q and substituting equation (v), T=200 $\times 10^6$*N.mm and Area=11621.49*a^2mm^2 *we have*

$$q = \frac{200\times 10^6\ N.mm}{2\times 11621.49a^2mm^2} = \left(\frac{8604.75}{a^2}\right)N/mm$$

$q = \tau t = \rightarrow \tau = \frac{q}{t} = \frac{8604.75}{a^2\times 0.175a} = \left(\frac{49170}{a^3}\right)N/mm^2$ *(vi)*

Table 2: Result after substituting the values of ‘a’ in Equation (vi)

a (mm)	Shear Stress, τ (N/mm^2)
3	1821.111
4	768.281
5	393.360
6	227.639
7	143.353
8	96.035
9	67.449
10	49.170
11	36.942
12	28.455
13	22.381
14	17.919
15	14.569

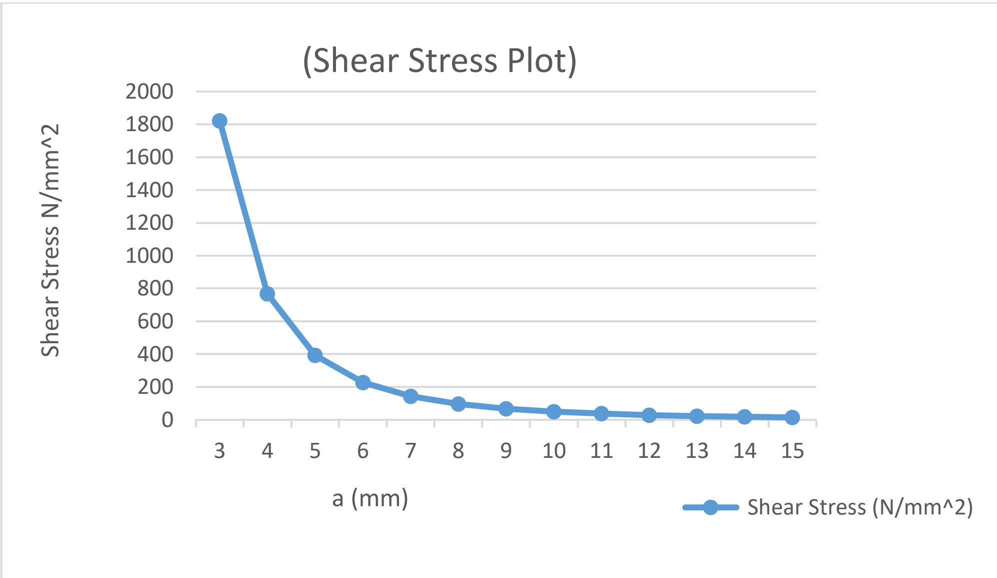

Figure 3: Shear Stress Distribution in the Fuselage

Verification and Validation:

To test for convergence of the analytical solution and numerical solution, Anyanwu *et al.* (2022) [7] the surface area of the 3D solid in Figure (1) is calculated, using *Solid Works* and the result is shown at Figure 4

```
Mass properties of inside volume
    Configuration: Default
    Coordinate system: -- default --

Density = 0.00 grams per cubic millimeter

Mass = 0.00 grams

Volume = 1.14 cubic millimeters

Surface area = 22853.41  square millimeters

Center of mass: ( millimeters )
     X = 156.95
     Y = -21.07
     Z = 0.00

Principal axes of inertia and principal moments of inertia: ( grams *  square millimeters )
Taken at the center of mass.
      Ix = ( 0.00,  1.00,  0.00)      Px = 0.65
      Iy = (-1.00,  0.00,  0.00)      Py = 1.71
      Iz = ( 0.00,  0.00,  1.00)      Pz = 2.36

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 1.71                        Lxy = 0.00                        Lxz = 0.00
     Lyx = 0.00                        Lyy = 0.65                        Lyz = 0.00
     Lzx = 0.00                        Lzy = 0.00                        Lzz = 2.36

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 2.22                        Ixy = -3.78                       Ixz = 0.00
     Iyx = -3.78                       Iyy = 28.80                       Iyz = 0.00
     Izx = 0.00                        Izy = 0.00                        Izz = 31.02
```

Figure 4: Surface area of the Fuselage

From the result, the surface area of the solid is $\frac{22853.41\, mm^2}{2} = 11426.70\, mm^2$. This is approximately equal to $11621.49a^2 mm^2$ which is the area of the fuselage calculated from equation (iii). There is an error of about 1.67 % when you compare the two values.

Conclusion and Future Scope:

From the results it can be observed that the shear stress reduces as the value of “a” increases. Shear stress is maximum at a=3mm and minimum at a=15 mm. The shape of the graph is parabolic. The material will have the maximum shear stress at minimum thickness. The graph approaches/approximates a steady state value with a step size of 3, the value of shear stress is reduced by half as seen from table (2). At a= 11, τ = 36.943, at a= 14, τ = 17.919, and at a=12 τ =28.455 and a= 15 τ = 14.569. The future scope of this project will be to calculate the shear stress distribution of other components of the aircraft like the wings and landing gear at specific torques.

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