FINITE ELEMENT ANALYSIS AND DESIGN IMPROVEMENT OF AEROSPACE COMPOSITE HINGES

by

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The completion of my research was achieved with the humble contribution from the MAE faculty, my parents and my friends.

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Lastly, I would like to thank my friends who supported me throughout this research.

May 4, 2018

Abstract

FINITE ELEMENT ANALYSIS AND DESIGN IMPROVEMENT OF AEROSPACE COMPOSITE HINGES

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The University of Texas at Arlington, 2018

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Hinges are the most commonly used mechanical bearings to connect 2 objects for relative rotational motion. Modern day aerospace hinges are generally made using either Aluminum, Steel or bronze. The study analyzes the use of composite material as an alternative to traditional materials for manufacturing these hinges. The research is focused on the Finite element Analysis of a composite hinge as well as an aluminum hinge. The load capacity of both the types of hinges are compared. To improve the design of the composite hinge, a combination of composite material and aluminum is used to model a hybrid hinge design. The load capacity of this hybrid hinge is compared to that of an aluminum hinge. The research also talks about the use of solid lubricants as an alternative to traditional wet lubricants. This includes the different varieties of solid lubricants, their properties and their usage in different operating conditions.

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Chapter 1

Hinges

A hinge is a type of bearing mechanism that allows relative rotational motion between two objects with a fixed axis of rotation. A hinge mechanism has only 1 degree of freedom. Hinges come in many shapes and form. Some of the commonly used hinge types include Continuous hinges, Butt hinges and Spring-loaded hinges. The materials most commonly used to manufacture these hinges include Aluminum alloy, Stainless steel, Bronze, Inconel and plastics.

1.1. Hinge materials

The most commonly used material for making a hinge is Aluminum. This is due to its good strength and light weight. It is also easy to process when compared to stainless steel. Stainless steel is preferred when the hinge is required to carry a heavy load. Plastics, especially thermosets are used to make hinges as well. These hinges are very lightweight but their load carrying capacity is low. Another limitation of plastic hinges is that they cannot be operated on high speed due high temperature created by friction due to which the plastic hinges deteriorate. The choice of the material depends upon the usage scenario. Factors like applied load, operating temperature, operating speed and cost determine the material choice for a hinge.

1.2. Hinge nomenclature [1]

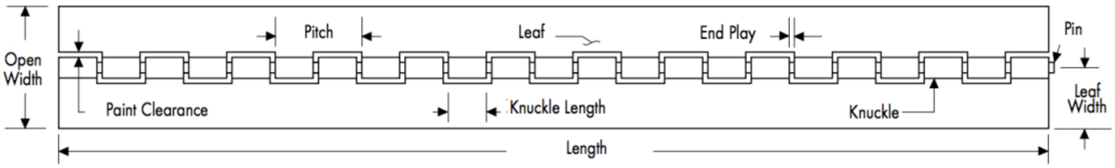

Figure 1. Hinge nomenclature [1]

Length-The length of the hinge is measured parallel to the pin.

Leaf -The part of the hinge which extends laterally from the knuckle, which usually revolves.

Open width -The dimension of the leaves which is measured perpendicular to the pin. around the pin.

Knuckle-The hollow circular part through which the pin is passed.

Pitch-The dimension from a point on a knuckle to the same point on the adjacent knuckle on the same leaf.

Pin-Rod running through the length of the pin. It holds the two leaves together.

End Play-The clearance for axial movement of the hinge.

1.3. Manufacturing methods for hinges [2]

Hinges are manufactured using different techniques that include Extrusion, Casting and cold working.

Extrusion

In this method the metal component is compressed against a die. This method gives us very strong hinges, but the manufacturing cost is much higher.

Casting

In this process the metal used has to be melted first. After this the liquid metal is poured into a mold which is of the shape of a hinge leaf. The metal then solidifies after which the part is removed from the mold. The strength of these hinges is less than that of the hinges produced by extrusion.

Cold working

In this technique the metal is subjected to external force which produces mechanical stresses which in turn changes the crystalline structure of the metal. This makes the hinges stronger.

Thus, in conclusion the strength of a hinge is highly dependent on its manufacturing process.

1.4. Aerospace hinges

Aerospace hinges are specialty hinge designed specifically for commercial and military aerospace applications. These hinges have to endure harsh environmental conditions in which ordinary hinges cannot function optimally. Some of these environmental factors include zero gravity, very high and low temperatures and radiation. The dimensional tolerance for aerospace hinges is very high. Aerospace hinges are designed according to strict military standards for compatibility and easy replacement. These hinges can be found on the exterior as well the interior of an aircraft. These include cargo doors, wings and tail assemblies. These hinges are also used in space satellites and other devices that are deployed in the outer space. [2]

1.5. Continuous Aerospace hinges

Continuous hinges are the most widely used type of hinges. This is due their ease of manufacturing and their ability to support loads over a long length. These hinges evenly distribute the load over an entire length thus providing stability and reducing the stresses developed. Mounting methods for continuous hinges include welding, screwing or bolting and using adhesives. The natural factor of safety for these continuous hinges is taken as 1.5, and for this factor of safety we consider yield load as criteria and not the ultimate tensile load. For this research we will be focusing on the Military standard continuous hinges. The hinges specifically taken into consideration is the MS20001 hinge.

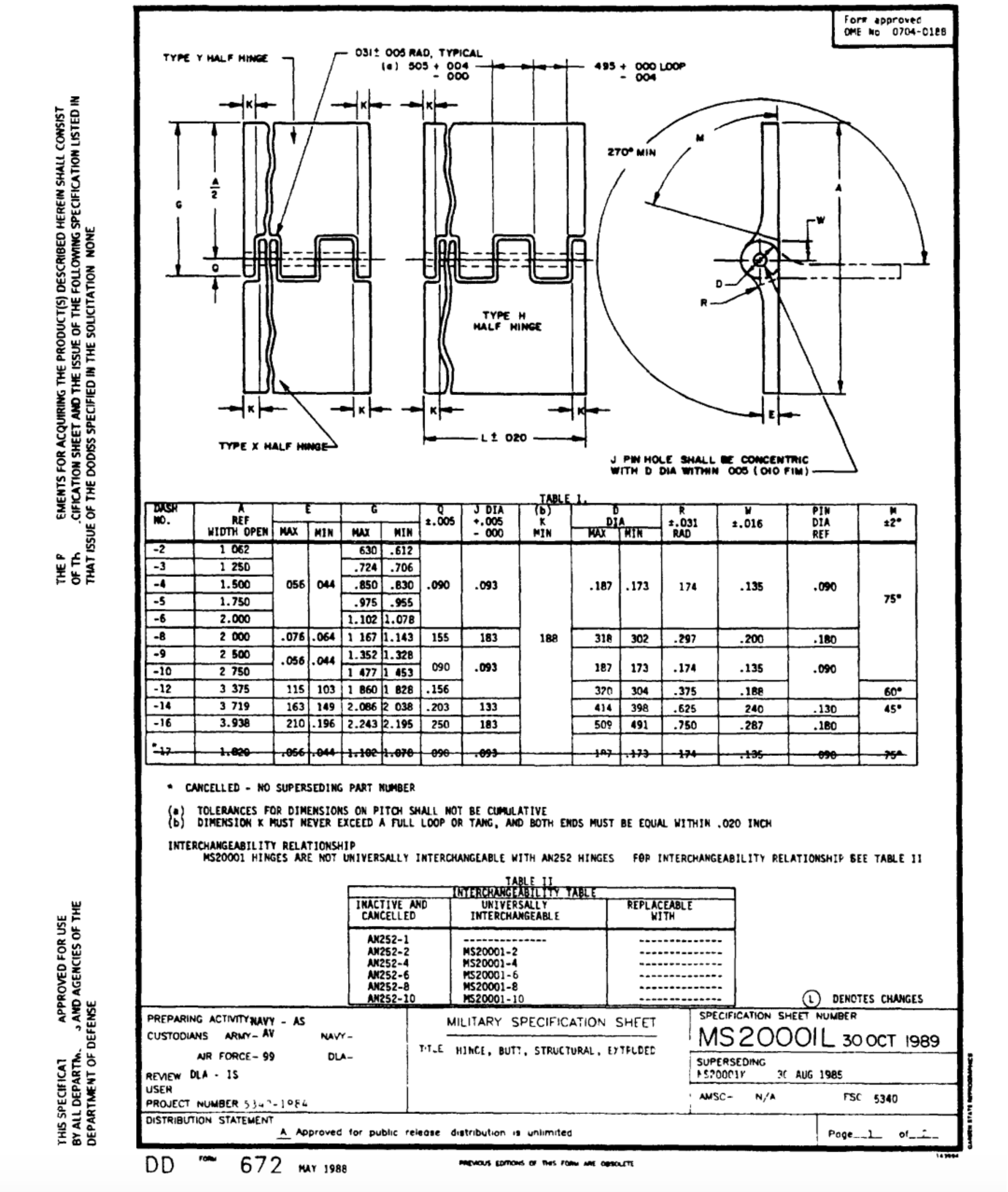

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TABLE I.

DASH NO.	A REF WIDTH OPEN	E		G		Q ±.005	J DIA +.005 - 000	(b) K MIN	D DIA		R ±.031 RAD	W ±.016	PIN DIA REF	M ±2°
		MAX	MIN	MAX	MIN				MAX	MIN				
-2	1 062	056	044	630	.612	.090	.093	188	.187	.173	174	.135	.090	75°
-3	1 250			.724	.706									
-4	1.500			.850	.830									
-5	1.750			.975	.955									
-6	2.000			1.102	1.078									
-8	2 000	.076	.064	1 167	1.143	155	183		318	302	.297	.200	.180	
-9	2 500	.056	.044	1.352	1.328	090	.093		187	173	.174	.135	.090	
-10	2 750			1 477	1 453									
-12	3 375	115	103	1 860	1 828	.156			320	304	.375	.188		60°
-14	3 719	163	149	2.086	2 038	.203	133		414	398	.625	240	.130	45°
-16	3.938	210	.196	2.243	2.195	250	183		509	491	.750	.287	.180	
~~*-17~~	~~1.820~~	~~.056~~	~~.044~~	~~1.102~~	~~1.078~~	~~090~~	~~.093~~		~~187~~	~~.173~~	~~174~~	~~.135~~	~~090~~	~~75°~~

* CANCELLED - NO SUPERSEDING PART NUMBER

(a) TOLERANCES FOR DIMENSIONS ON PITCH SHALL NOT BE CUMULATIVE
(b) DIMENSION K MUST NEVER EXCEED A FULL LOOP OR TANG, AND BOTH ENDS MUST BE EQUAL WITHIN .020 INCH

INTERCHANGEABILITY RELATIONSHIP
MS20001 HINGES ARE NOT UNIVERSALLY INTERCHANGEABLE WITH AN252 HINGES FOR INTERCHANGEABILITY RELATIONSHIP SEE TABLE II

TABLE II
INTERCHANGEABILITY TABLE

INACTIVE AND CANCELLED	UNIVERSALLY INTERCHANGEABLE	REPLACEABLE WITH
AN252-1	--------------	--------------
AN252-2	MS20001-2	--------------
AN252-4	MS20001-4	--------------
AN252-6	MS20001-6	--------------
AN252-8	MS20001-8	--------------
AN252-10	MS20001-10	--------------

Ⓛ DENOTES CHANGES

PREPARING ACTIVITY NAVY - AS
CUSTODIANS ARMY- AV NAVY-
AIR FORCE- 99 DLA-
REVIEW DLA - IS
USER
PROJECT NUMBER 534?-1984

MILITARY SPECIFICATION SHEET
TITLE HINGE, BUTT, STRUCTURAL, EXTRUDED

SPECIFICATION SHEET NUMBER
MS20001L 30 OCT 1989
SUPERSEDING
MS20001K 30 AUG 1985
AMSC- N/A FSC 5340

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Page 1 of 2

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Figure 2. The guide used to model a MS20001 hinge. [4]

Following this design criteria, a CAD model was created in Solidworks.

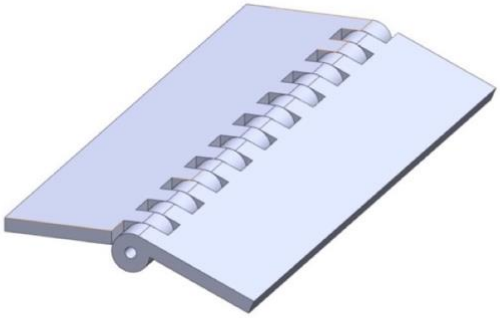


Figure 3. Isometric view of the model

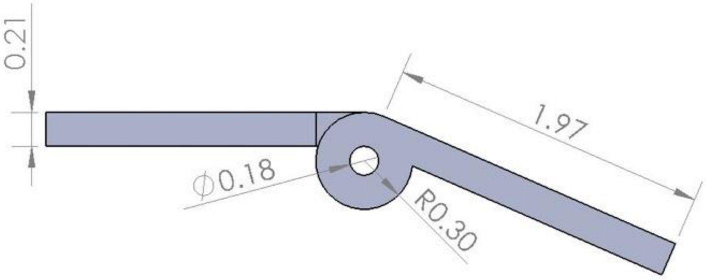


Figure 4. Side view

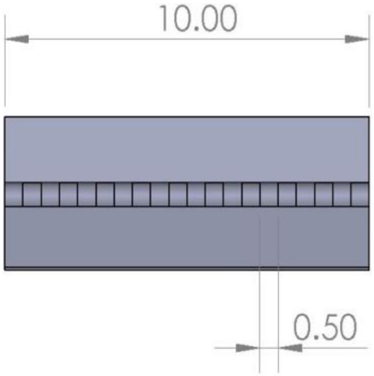


Figure 5. Top view

CHAPTER 2

Composite Hinge

2.1. Composites

Composites are special materials which are produced using two to more constituent material which have different physical and chemical properties. When these are constituents are combined they produce a material with different properties than their parent material. This research considers the use of fiber reinforced composites. A fiber reinforced composite has 2 elements, first one being the fiber and second one being the matrix. Fibers are the load carrying component of the composite. They provide rigidity and prevent the propagation of cracks and the matrix surrounds these fibers and maintains the relative position of these fibers.

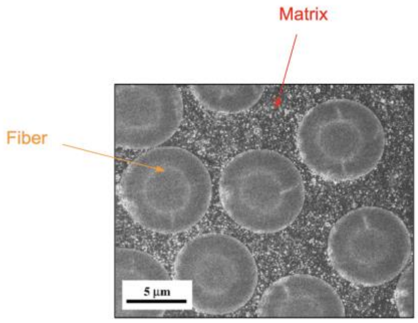


Figure 6. Fiber reinforced composite [5]

Some primary advantages of composite material over traditional materials include High Strength, Low weight, Corrosion resistant, Vibration damping, Reduced part count and Fabrication flexibility.

For our study we will be focusing on Carbon fiber reinforced polymer composites (CFRP). The composite material chosen for our research is Carbon Epoxy Fabric (Woven Plain weave). This carbon epoxy composite is stacked on top of one another in different orientations to form a stack up. The stacking sequence is quasi-isotropic, meaning that the in-plane properties of the stack up are same. By choosing a quasi-isotropic stack up the problem of fabric draping is avoided. Draping occurs when a composite fabric is laid on a curve surface. This leads to change in the fiber direction, due to which the polar properties of the fiber change and this change has to be accounted for. But by using a quasi-isotropic setup the draping is accounted automatically. The stacking sequence we choose is: $[(0, \pm 45, 90)_2/0,45]_s$. A total of 20 plies are used for this stack up. The total thickness of this stack up is 0.197 inches.

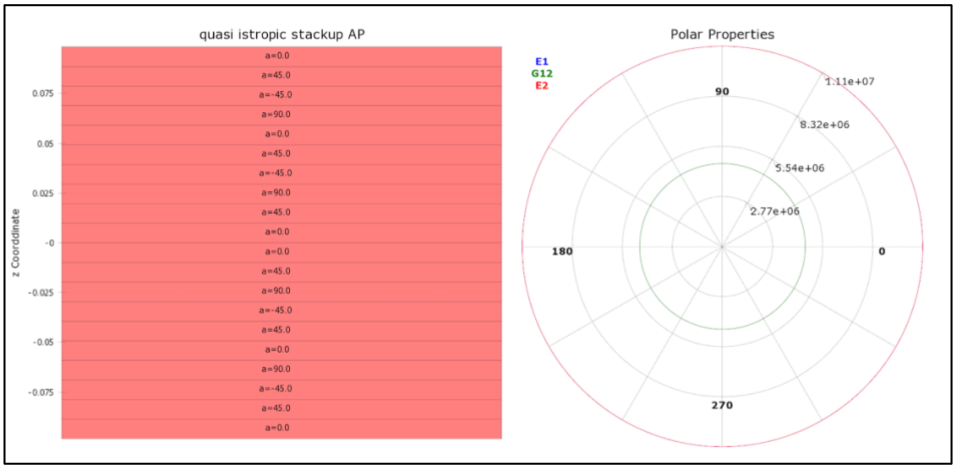


Figure 7. Stack up sequence and Polar properties of the 20 plies stack up

2.2. Composite hinge model

This stack up was used to model a composite hinge model in ANSYS Composite Pre-post. The 3D CAD model is shown below.

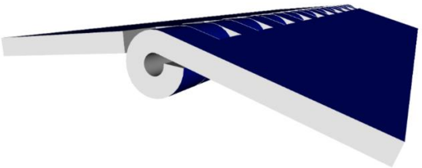


Figure 8. Composite hinge CAD model

The geometry of the hinge in the Ansys Composite Pre-post model is slightly different from the geometry in the Solidworks model. This gap is in intentional to prevent the excessive bending of fibers in the composite structure.

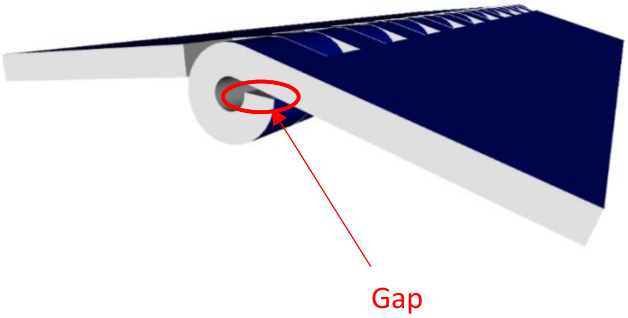


Figure 9. Gap in the Composite CAD model

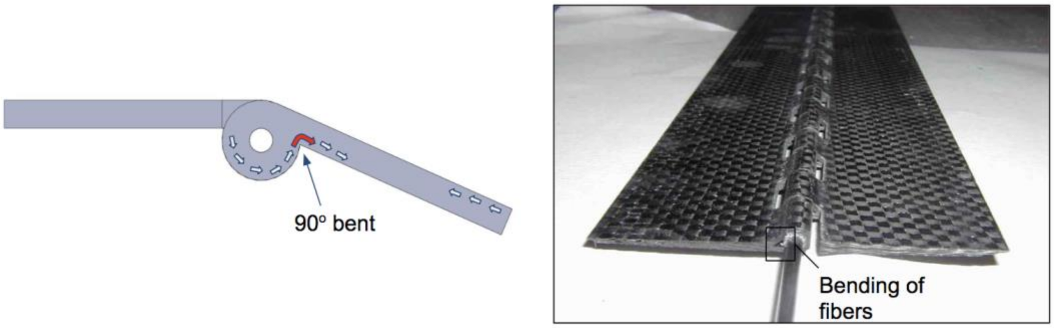


Figure 9. Bending of fibers [6]

2.3. Manufacturing methodology of the composite hinge

Manufacturing of a composite part requires the use of mold and supports to give it the correct shape and form. Individual plies are stacked on top of this mold corresponding to the provided stacking sequence. After the stack up is completed, it is transferred to an autoclave for the whole assembly to cure. Next step is to remove the part from the autoclave and then machine it to give its final dimensions.

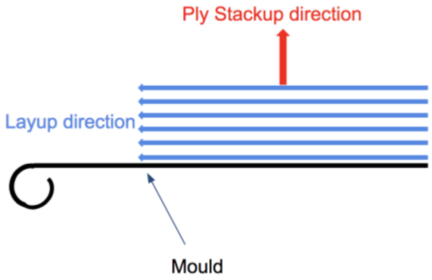


Figure 10. Mold shape with layup and stacking directions

The drawback of this layup method is the creation of free edges which are the points of stress concentration. To overcome this issue the outermost ply is used to wrap around these free edges thus sealing them, providing better dimensional control and elimination of edge stresses.

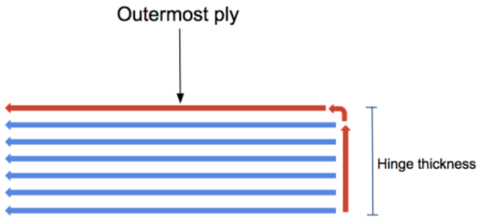


Figure 11. Sealing of edges

2.4 Aluminum hinge

An aluminum alloy hinge is modeled in Solidworks using the same dimensions as the Composite hinge. This model is then imported into Ansys Static Structural to carry out the Finite Element Analysis. The aluminum alloy chosen is of the 6061 series. Materials like Stainless steel, Bronze and Titanium can also be used as an alternative to Aluminum. The reason for choosing Aluminum for the comparison is that, aluminum is the most common and widely used material for aerospace hinges.

CHAPTER 3

Finite Element Analysis

Both the models, the composite hinge 3D model and the aluminum hinge model are completed. After this these models are loaded into Ansys static structural to carry out the Finite element analysis.

3.1. Meshing

The CAD model generated is meshed using solid elements (brick elements). The designation of these elements is SOL185. This element type has 8 nodes. Each of these nodes has 3 degrees of freedom which is translation in X, Y and Z directions. Other features of this element include Plasticity, Stress stiffening, Large deflection and Large strain. This element type has orthotropic properties. The final meshed model has 13282 elements in total.

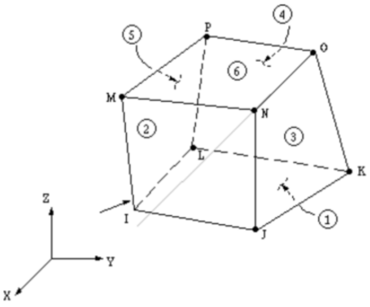


Figure 12. Sol185 element [7]

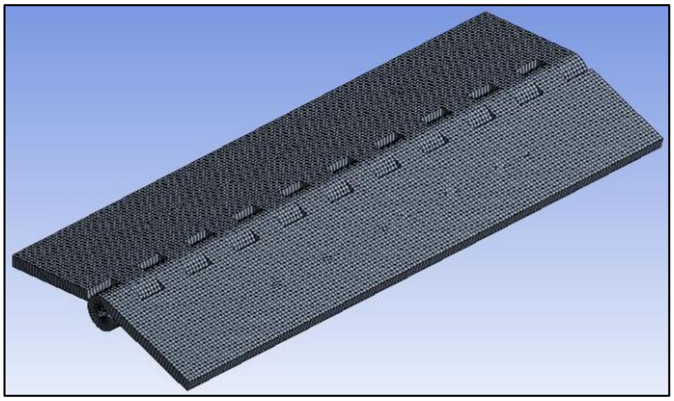


Figure 13. Meshed model

3.2. Loads and Failure criteria

Understanding of the loads acting on a hinge is crucial to determine its strength. When a hinge is attached vertically to a door, the weight of the door has two types of loading effects on a hinge. First one is the vertical load which acts parallel to the length of the hinge (this load is compressive in nature) and the second one is the radial bearing load which is a result of the moment generated but the weight of the door. This radial bearing load causes a reactionary force in the opposite direction by the hinge pin on the hinge pin hole.

The moment generated by the door is,

$$M = W\ x\ d$$

where,

W = Mass of door

d = perpendicular distance of door’s C.G from the hinge pin

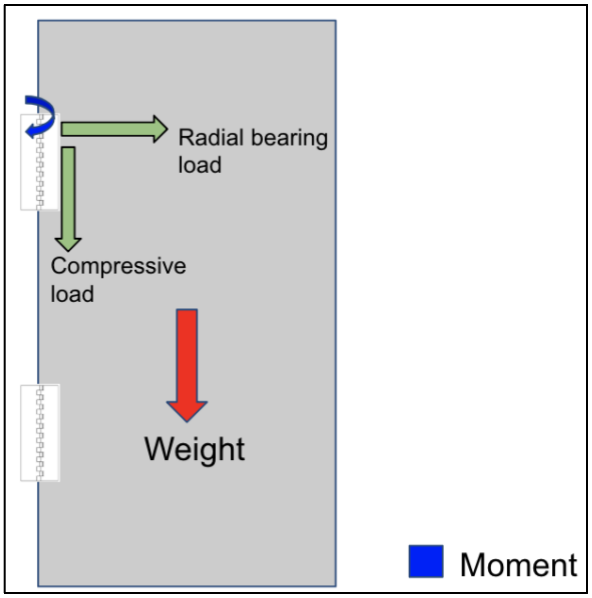


Figure 14. Loads acting on vertically installed hinge

To know the strength of the composite hinge it is necessary to understand the failure criteria that will be used to determine the strength of the hinge. The most commonly used failure criteria for composite parts in the industry are:

- Max Strain criterion
- Max Stress criterion
- Tsai Hill criterion

When a load is applied and the safety factor for each criterion are calculated, the criterion that gives the lowest value is taken as the critical failure criteria and that criterion will be considered for the comparison with the aluminum hinge results.

3.3. Connections/Constraints

Before going forward with the analysis, it is necessary to define connections in our model. These help us in constraining the model since our analysis is going to be of a static type. These connections also aid in simulating a rigid pin. This is because the analysis is focused on the hinge failure and not the pin failure. In most realistic scenarios the hinge pin likely bends and is therefore the first cause of failure for a hinge assembly. The connection type is MPC, which stands for Multipoint Constraints. It is a bonded connection. The MPC connection uses rigid constraint equations between the solid elements on the contact and target faces for a truly bonded connection. Some advantages of MPC connections are that degrees of freedom at the nodes on the contact and target faces are eliminated by the constraint equations, A contact stiffness calculation is not required because a rigid connection is defined by the constraint equations, both translational and rotational degrees of freedom are accounted for and since the constraint equations are MPC-based they will be updated in large deformation analyses.

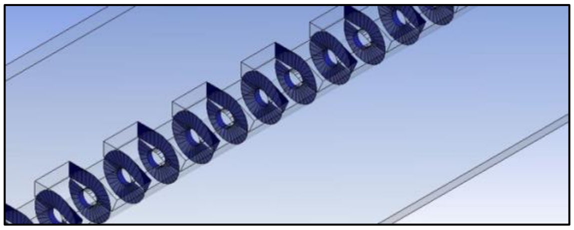


Figure 15. MPC face connections

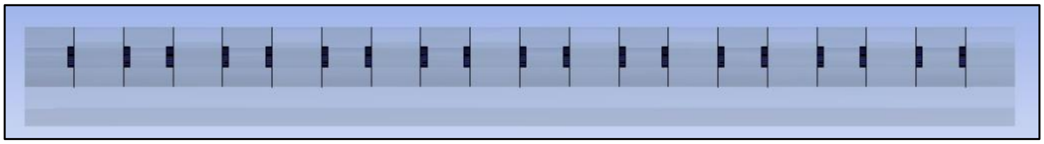


Figure 16. MPC connections to simulate rigid pin

3.4 Vertical load analysis

The compressive vertical acts on the leaf of hinge which is attached to the door. This leaf is free to rotate along the hinge axis. The other leaf is considered as a fixed support.

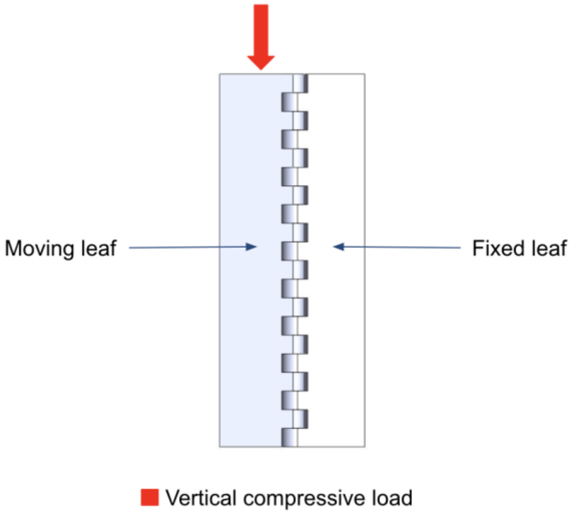


Figure 17. Vertical load illustration

The load on the hinge is slowly increased, it is observed that a force of 600 lb. gives the lowest safety factor. We will consider the Tsai Hill criteria since it’s the most critical out of the 3.

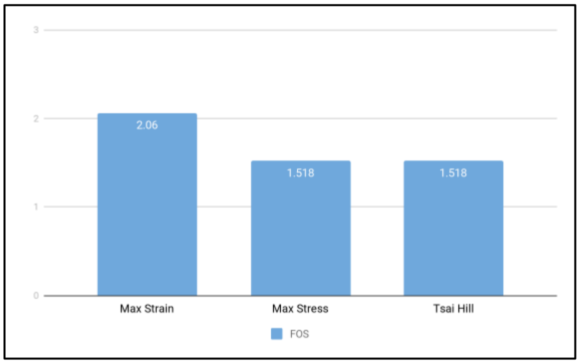


Figure 18. Safety factor comparison. for vertical load of 600 lb.

As the force on the hinges is increased the Tsai hill (3D) criterion becomes the critical criterion because it is the fastest to reach below the value of 1. The failure load is 900 lb. and the mode of failure is that of the matrix compression.

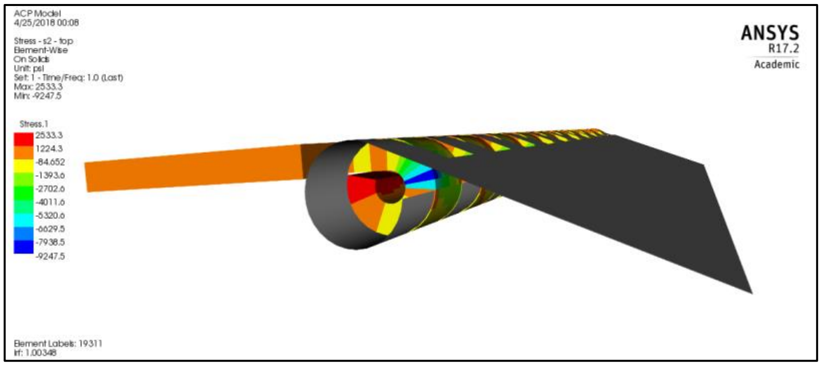


Figure 19. Stresses in matrix due to vertical load of 900 lb.

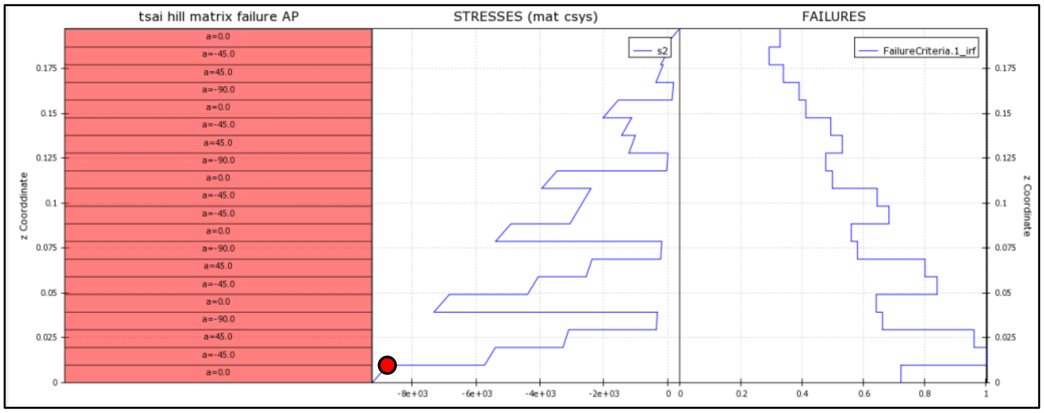


Figure 20. Increase in matrix stress at critical element

The red dot indicated the point at which the stresses in the matrix reach their critical compressive load capacity, which leads to failure. Here we use the inverse reverse factor as a criterion. When the inverse reverse factor reaches the value of 1 failure will occur.

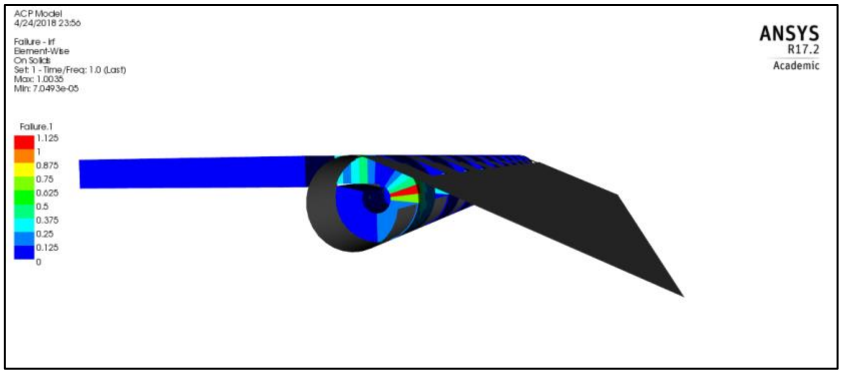
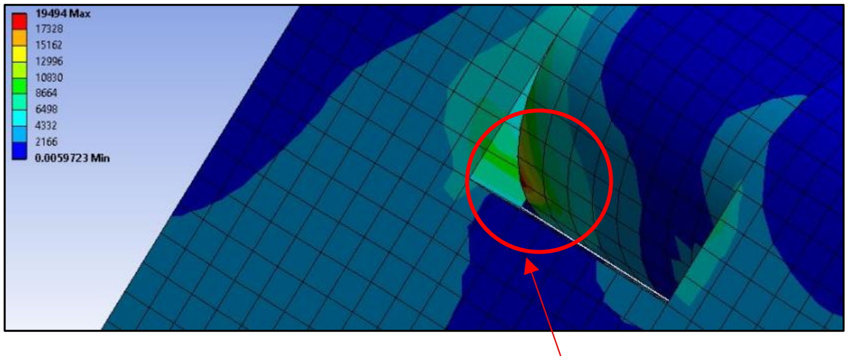


Figure 21. Failure distribution due to 900 lbf vertical load

The aluminum hinge model is subjected to gradually increasing load. It is seen that for a load of 1200 lb. the Maximum shear stress factor of safety reaches a value of 1.5. The Maximum Von Misses Factor of Safety is 1.78 for the same load. Therefore, we will take the Maximum shear stress safety criterion as the most critical one. This also indicates that the mode of failure for the aluminum hinge is Shear failure. A load of 1800 lb. causes the shear failure to occur on the aluminum hinge.



Failure region

Figure 22. Max shear stress distribution (Aluminum- Vertical load)

Comparing the vertical load capacity of both the hinges, it is observed that the vertical compressive load capacity for the composite hinge is 50% of that of an aluminum hinge.

3.5. Horizontal Radial bearing load capacity

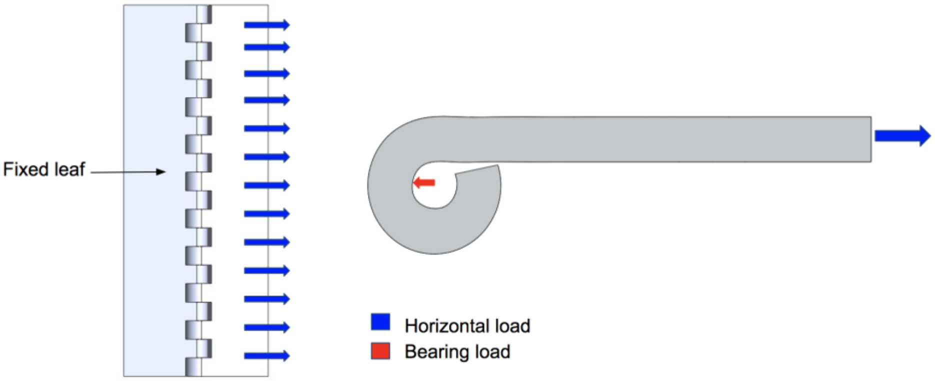


Figure 23. Horizontal radial bearing load depiction

To better understand the effect of radial bearing load on the hinge we make use of lug joints. Lugs are connector type elements used as structural supports for pin connections. A continuous hinge is a type of lug joint. Therefore, a lug joint was modeled in Solidworks with the same dimensions as that of the hinge.

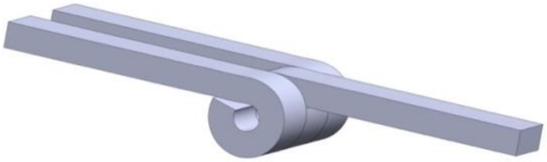


Figure 24. 3D model of lug joint

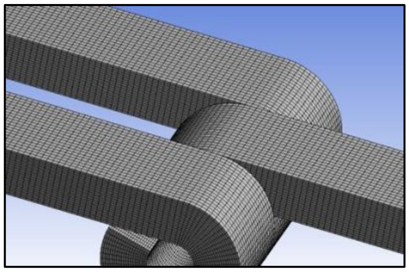


Figure 25. Meshed model of lug joint

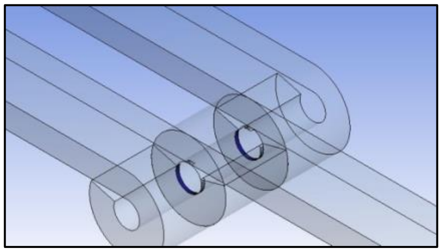


Figure 26. MPC connections for rigid pin (Lug joint)

It is important to keep in mind that the end lug joints of the hinge are in single shear while the inner joints are in double shear. We will be considering the double shear of the lug joint. For a single shear lug joint the load capacity is half of that of the double shear lug joint.

The load on the composite lug is gradually increased. It is observed that for a load of 28 lb. A safety factor of 1.5b is obtained based on the Tsai hill failure criteria. The load capacity for a single shear lug joint is 14 lb. In our hinge model we have 8 double shear lug joints and 2 single shear lug joints. Therefore, the total load capacity of our composite hinge for a radial bearing load in the horizontal direction would be = (8 x 28) + (14 x 2) = 252 lb. The load on the lug is increased beyond 28 lb. for which it is observed that a load of 45 lb. causes failure. It is due to the compressive failure perpendicular to ply layup direction.

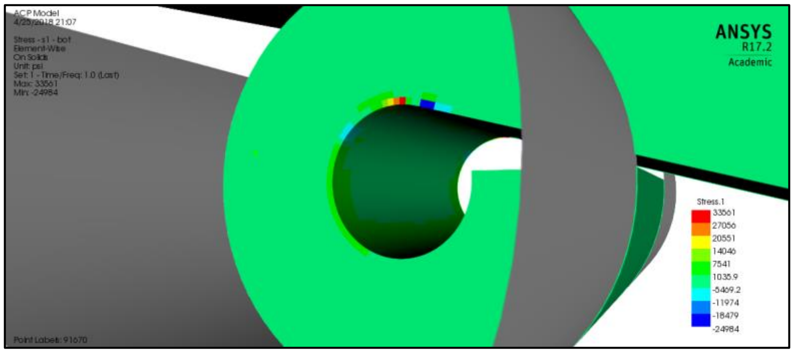


Fig 27. Stresses distribution in fibers (Horizontal bearing load)

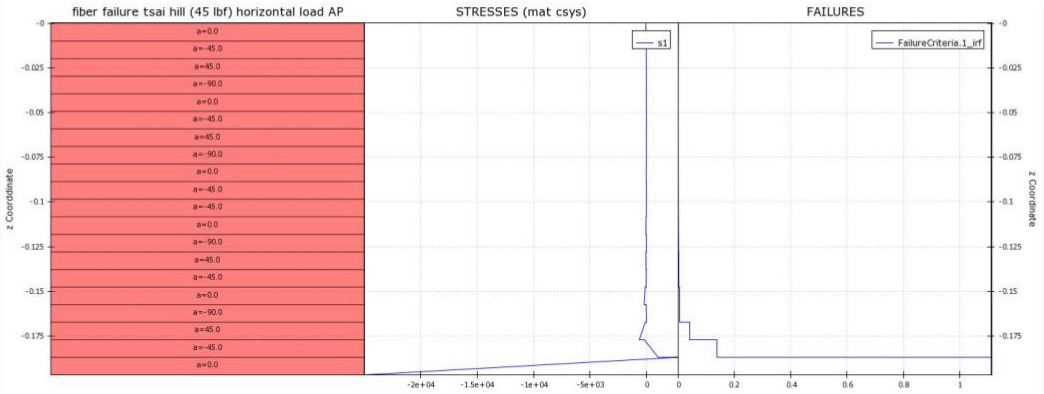


Figure 28. Fiber stresses at critical element (Horizontal bearing load)

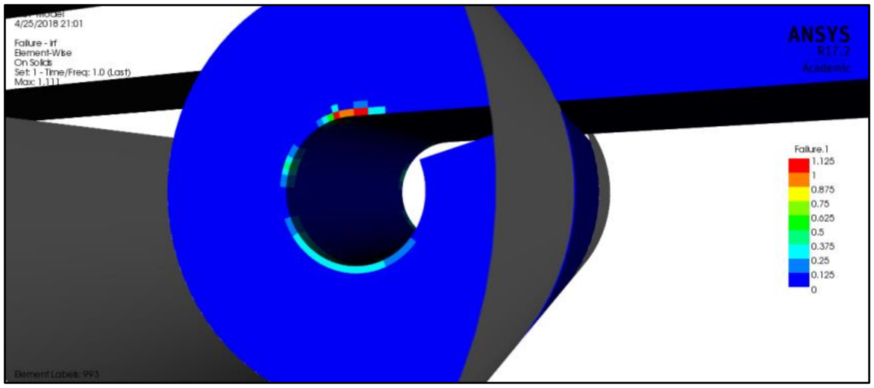


Figure 29. Failure distribution (Horizontal bearing load)

For an aluminum lug the force is gradually increased from zero. It is observed that a load of 49 lb. caused the factor of safety for maximum shear to be 1.5. The factor of safety for Von-misses factor of safety is more than that of the shear stress criterion. Increasing the load to a value of 78 lb. shows that the model suffers shear failure.

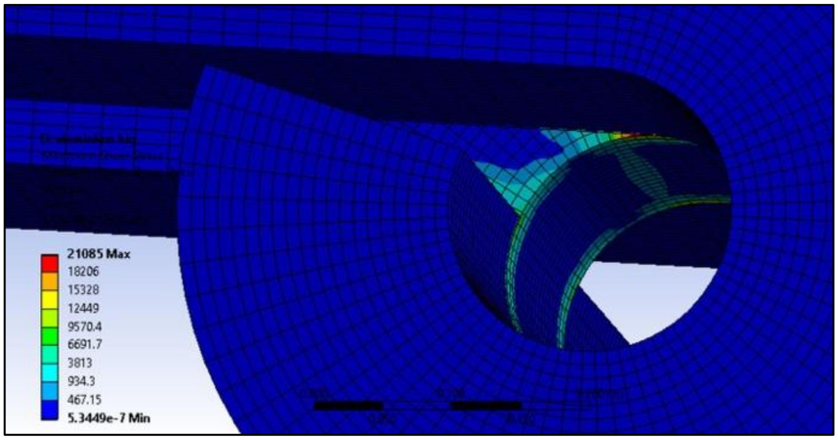


Figure 30. Max shear stress distribution (Aluminum- Horizontal bearing load) (i)

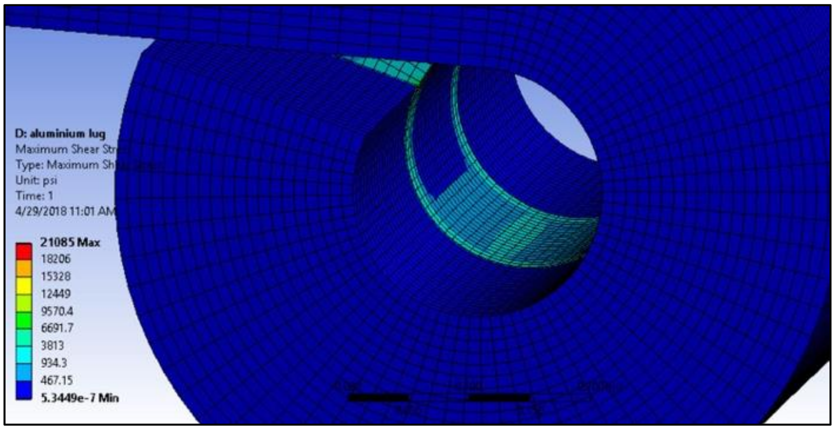


Figure 31. Max shear stress distribution (Aluminum- Horizontal bearing load) (ii)

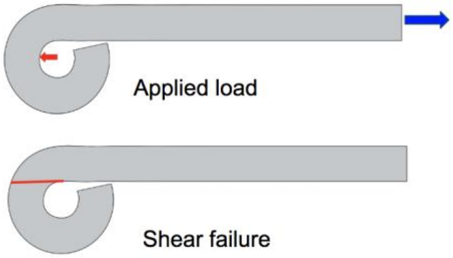


Figure 32. Shear failure depiction (Horizontal bearing load)

Comparing the overall horizontal radial bearing load capacity of the entire composite hinge with the aluminum hinge it is observed that there is 42.85 % decrease in the loading capacity of the composite hinge when compared to the aluminum hinge.

3.6. Vertical radial bearing load analysis

This type of load is induced on the hinge when the hinge is installed horizontally, there is radial bearing load that is induced on the hinge on the inner hole of the hinge. The direction of this bearing load is perpendicular to the length of the hinge.

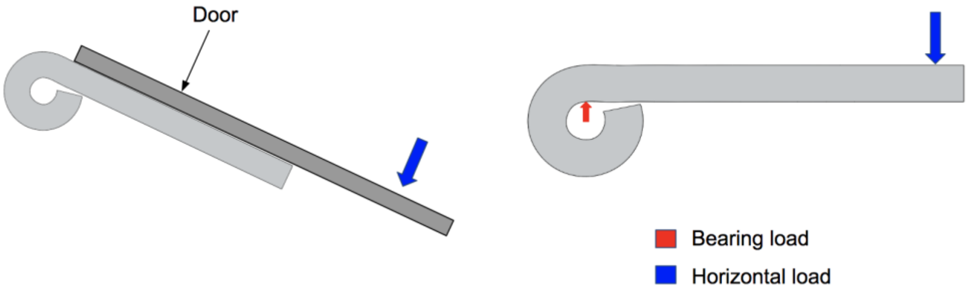


Figure 33. Vertical radial load illustration

For this analysis we make use of the same lug joint to better understand the safe loads and failure loads. The load is gradually increased to 26 lb. this is when the Tsai hill failure safety factor reaches 1.5. This is the safe vertical radial bearing load on the hinge. The load is increased further to 42 lb. after which failure occurs. The primary mode of failure is the tensile failure of fibers and the criteria is the Tsai hill failure criteria.

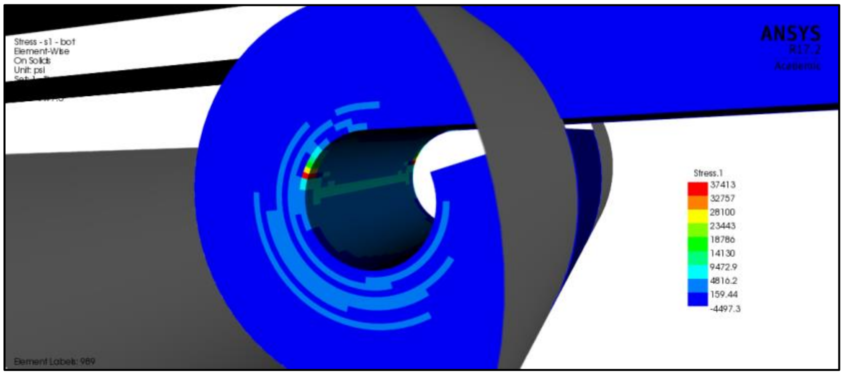


Figure 34. Stresses in fiber (Vertical bearing load)

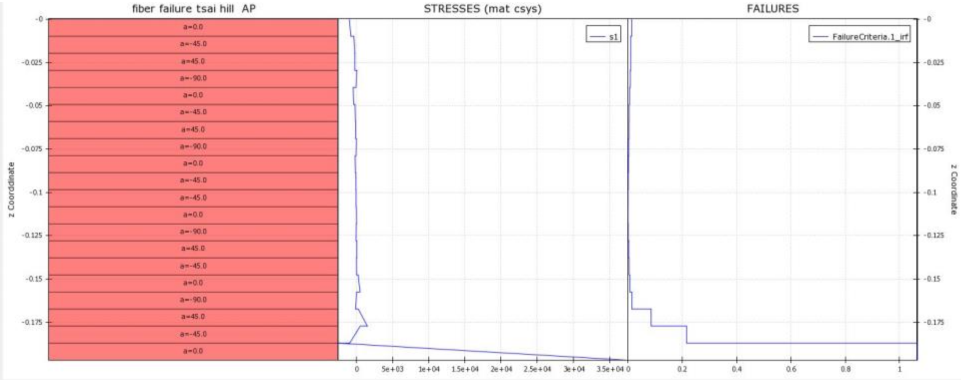


Figure 35. Fiber stresses at critical element (Vertical bearing load)

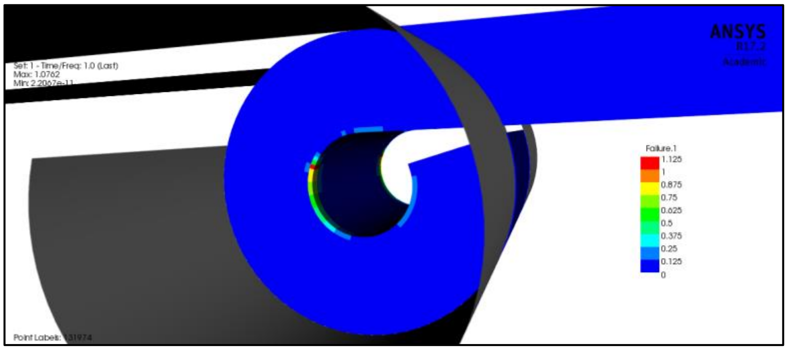


Figure 36. Failure distribution (Vertical bearing load)

For an aluminum lug under vertical radial bearing load the safe load is 49 lb. The safety factor considered is the maximum shear stress criterion. The load is gradually increased to 78 lb. It is observed that at this load the failure of the aluminum lug occurs. The mode of failure is the shear failure of the lug.

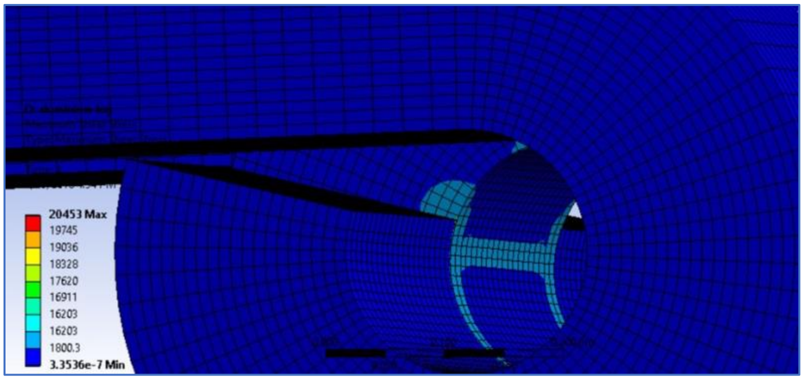


Figure 37. Max shear stress distribution (Vertical bearing load)

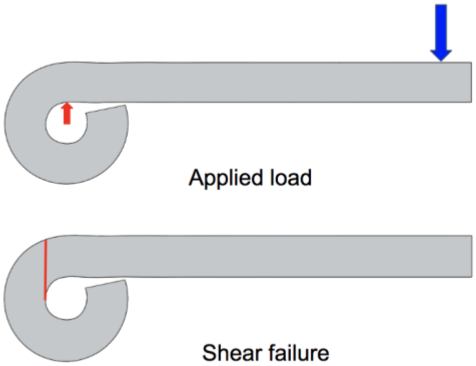


Figure 38. Shear failure depiction (Vertical bearing load)

3.7. Finite element Analysis summary

	Composite hinge	Aluminum hinge	Results
Compressive vertical load	600	1200	50%
Horizontal bearing load	252	441	42.85 %
Vertical bearing load	234	441	46.93 %
Mass	0.49	0.914	47 %

Table 1. Finite element analysis results

Load: lbf.

Mass: lbm.

3.8. Analytical calculations:

The accuracy of the Finite Element Analysis can be estimated by comparing the results with analytical calculations. Since there are no analytical formulae for a composite lug failure, we will focus on the analytical formulae for the failure of the aluminum lug.

Analysis of a lug is deceptively complex since there are several simultaneous, interacting failure modes. These failure modes are associated with different areas of the lug.

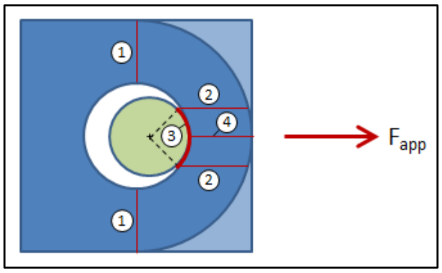


Figure 39. Lug failure modes [8]

The failure modes for the lug are listed below. The numbers correspond with the labeled sections from Figure 39.

1. Tension failure across the net section
2. Shear failure along two planes
3. Bearing failure
4. Hoop tension failure / fracture on single plane

The failure of a lug joint can be predicted using 3 methods.

- Simplified Analysis

This method is based on first principles and involves making simplifying assumptions about the nature of the failure and calculating factors of safety. [8]

- Air force method

This method follows closely with the methods presented in Melcon & Hoblit and Bruhn. It relies heavily on curves generated by empirical data. This method takes into account the interaction between the lug and the pin. Since our pin is rigid we do not adopt this method for analytical failure analysis. [8]

- ASME BTH

The ASME method of lug analysis is described in ASME BTH-1, "Design of Below-the-Hook Lifting Devices". This method also takes into account the interaction between the lug and the pin. Since our pin is rigid we do not adopt this method for analytical failure analysis. [8]

Therefore, we will be adopting the Simplified Analysis approach for calculating the failure of the aluminum lug. The mode of failure considered will be the shear tear out, for the aluminum lug.

$$As = total\ shear\ plane\ area = 0.21\ in^2$$

$$Ssy = Yield\ shear\ strength$$

$$Ssy = 0.55 \times tensile\ yield\ strength = 20305\ psi$$

$$Psy = yield\ shear\ load = Ssy \times As = \mathbf{4264.05\ lbf}$$

Therefore, according the analytical calculations a load of 4264.05 lb. caused the complete shear tear out of the aluminum lug joint. The load obtained from the simplified analysis is applied to the 3D aluminum lug model.

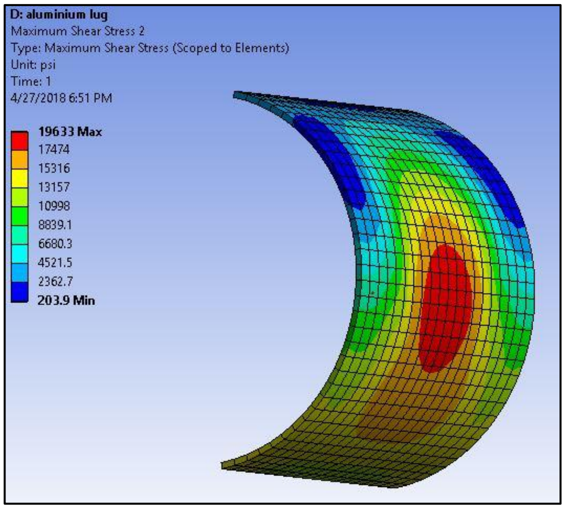


Figure 40. Shear stresses on the outer surface of the lug

The area chosen to compare is the outer surface of the lug. If the stresses on this surface go beyond the maximum shear stress capacity of aluminum, failure occurs. Observing the FEA results the maximum stress developed on the outer surface is 19633 psi. While for the analytical approach the shear stress calculated is 20305 psi. Comparing both the stress values we conclude that there is a 3.3 % variation in solutions for the analytical and FEA analysis.

CHAPTER 4

Hybrid hinge

To improve the strength of the composite hinge, a new kind of. hinge design was proposed. In this hinge design. A composite stack up is sandwiched between two aluminum sheets. The composite stack up has 10 plies in total.

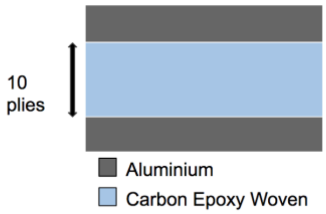


Figure 41. Hybrid hinge design

Thickness of the composite stack up = 0.0985 in

Thickness of each aluminum hinge = 0.04925 in

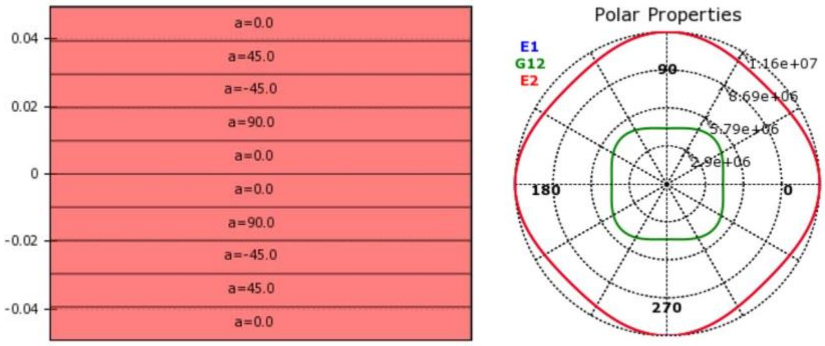


Figure 42. Stack up and polar properties of hybrid hinge composite core

When a vertical compressive load is applied on the hinge it is observed that for a load of 1100 lb. the safety factor is 1.5. When the load is increased to 1550 lb. failure is observed.

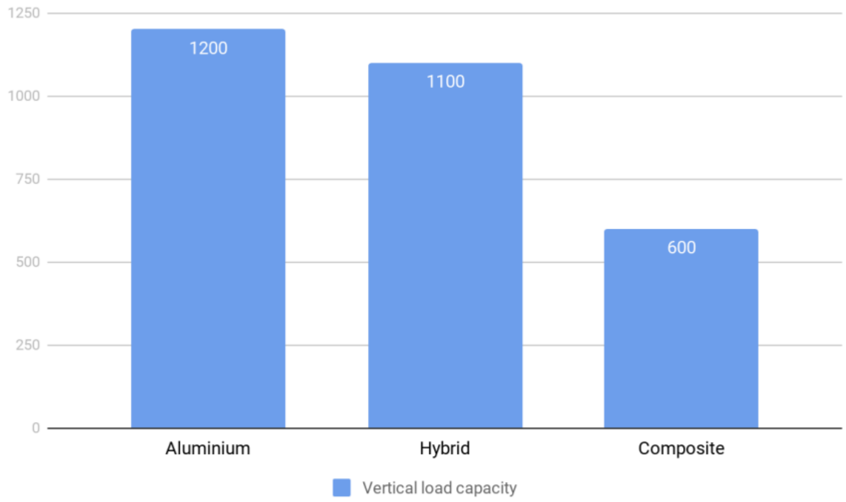


Figure 43. Vertical load capacity comparison of Hybrid hinge

We conclude that from a 50 % reduction of vertical compressive loading capacity of the composite hinge, the hybrid hinge has a loading capacity which is just 8.3 % lower than that of an aluminum hinge. There is no change in the bearing load capacity for the hybrid hinge when compared to the aluminum hinge.

Comparing of the mass of hinges made using different materials it is seen that the composite hinge is the lightest while a hinge made using steel is heaviest. The aluminum hinge is lighter than the steel hinge but heavier than the composite hinge. The hybrid hinge is lighter than aluminum but slightly heavier than the composite hinge. The hybrid hinge is 23.41 % lighter than aluminum.

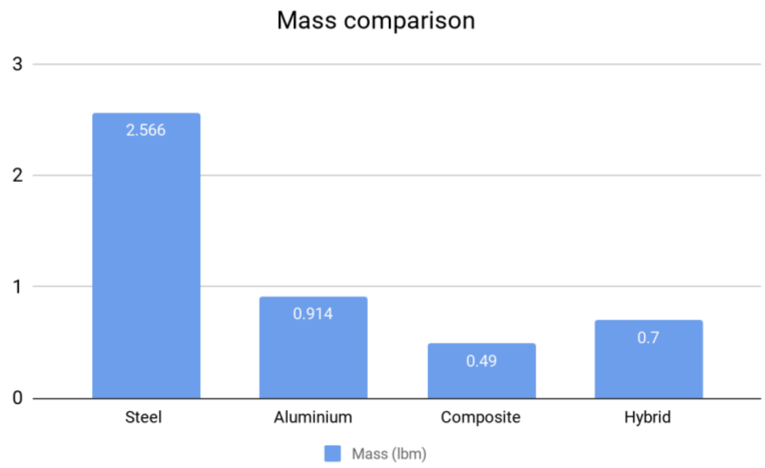


Figure 44. Overall mass comparison for different hinge materials

CHAPTER 5

Solid lubricants literature review

Dry lubricants or solid lubricants are materials that, despite being in the solid phase, are able to reduce friction between two surfaces sliding against each other without the need for a liquid oil medium. [10]

Solid lubricants	**Wet lubricants**
Negligible vapor pressure (no contamination)	Finite vapor pressure
Friction speed independent	Friction speed dependent
Low temperature sensitivity	Sensitive to temperature
No viscosity effects	Affected by viscosity
Electrically conductive	Electrically insulative

Table 2. Solid lubrication and wet lubrication comparison [10]

There are numerous types of solid lubricants available, some of them are:

Soft metal - Au, Ag, Pb.

Lamellar solids- MoS_2, WS_2.

Polymers - PTFE, Polyimide, UHWPE, Epoxy resins, Polyester.

Soft solids - Cd, Zn, Co.

For this study we will focusing on Lamellar solid and Polymer based solid lubricants.

5.1. Graphite

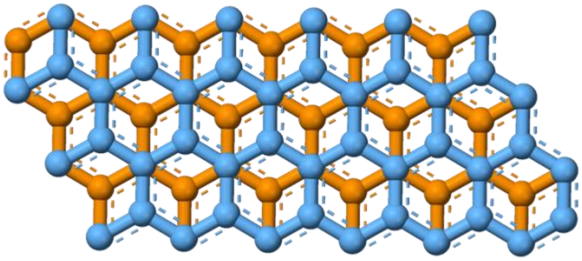


Figure 45. Plane view of graphite layer stacking

Graphite is lamellar solid which is extensively used as a solid lubricant. The crystal lattice of graphite consists of hexagonal rings forming thin parallel planes (graphene). Each carbon atom is covalently bonded to three other atoms in the plate (the angle between two bonds is 120°). The graphene are bonded to each other by weak Van der Waals forces. The layered structure allows sliding movement of the parallel planes. Weak bonding between the planes provides low shear strength in the direction of the sliding movement but high compression strength in the direction perpendicular to the sliding movement. Friction forces cause the graphite particles to orient in the direction, in which the graphene are parallel to the sliding movement. The anisotropy of the mechanical properties imparts the combination of low coefficient of friction and high carrying load capacity to graphite. Lubricating properties of graphite are highly dependent on the presence of vapor in the ambient atmosphere. [10]

5.2. PTFE

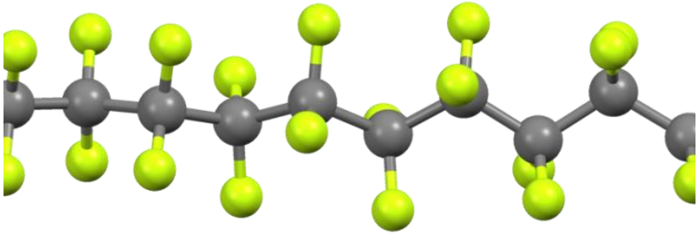


Figure 46. PTFE chain

PTFE is widely used as a solid lubricant. PTFE does not have a layered structure. The macro molecules of PTFE slip easily along each other, similar to lamellar structures. PTFE shows one of the smallest coefficients of static and dynamic friction, down to 0.04. Operating temperatures are limited from -73 ºC to 290ºC. PTFE is also hydrophobic. Sometimes additional additives are required to improve the load bearing capacity of PTFE lubricants. [10]

5.3. Polyimides

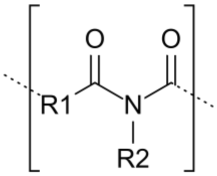


Figure 47. Chemical structure of polyimide

Polyimides have better load carrying capacity than PTFE with low friction. Additives are not required in case of Polyimides since their inherent load carrying capacity is higher than PTFE. These polymers are suited to operate in the temperature range of 25℃ to 300℃. It is important to keep in mind that these polymers are sensitive to the presence of water vapor hence cannot be effectively used in atmospheric conditions. Polyimides also have among the lowest wear rate. Also, polyimide composite can be used as bearing material for several applications. [10]

5.4. UHMWPE (Ultra high Molecular Weight Polyethylene)

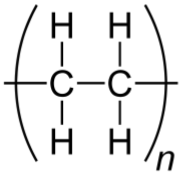


Figure 48. Chemical structure of UHMPE

UHMWPE have excellent load carrying capacity (Highest impact strength of any thermoplastic). These also excel at lower temperatures. The downside to UHMWPE is that it melts at 101 ℃, therefore it cannot be used in high temperature environments. [10]

5.5. MoS_2

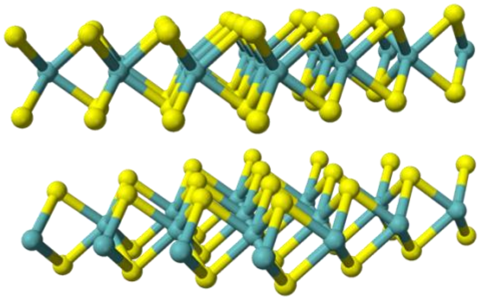


Figure 49. MoS_2 crystal structure

MoS_2 can be used by itself or as additive to PTFE. It can only be used in vacuum since its life is shortened if it slides in air too much or if its kept a long time in storage it starts to decompose. MoS_2 cannot be used in low earth orbit because lower earth environment has atomic oxygen with which MoS_2 oxidizes easily forming MoO_3 and Sulphur dioxide. The operating temperature range for MoS_2 is from -180 ℃ to 400℃. An advantage of MoS_2 is that its friction coefficient decreases with increase in load. [10]

5.6. Self-lubricating composites

Self-lubricating composites are composites which have low coefficient of friction due to which they exhibit lubricating characteristics. These composites consist of 3 components.

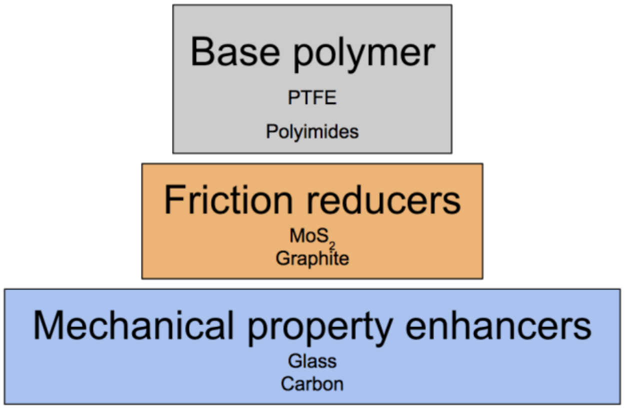


Figure 50. Components of solid lubricating composites

The base polymer is the matrix material for these types of composites. Polymers like PTFE, Polyimide and sometimes epoxy are used as base polymers. The base polymers is the bulk of a lubricating composite. Friction reducers are additives which help in lowering the coefficient for these composites. The most commonly used additives include MoS_2 and Graphite. and the mechanical property enhancers are additives used to increase to load bearing capacity of these lubricating composites. Chopped glass fibers or carbon fibers are a popular choice for these additives. Advantages of solid lubricating composites include Better vibration absorption than metals, easy machining and their electrical conductivity.

Some disadvantages of these solid lubricants include low thermal conductivity and sensitivity to radiation. [10]

For this study we consider Solid lubricating composite which as PTFE as the base polymer and MoS_2 as the additive. MoS_2 reduces the friction and also increases the load capacity of the composite.2 variants of this composite are considered.

1. 15M (which has 15 % MoS_2 by weight)
2. 30M ((which has 30 % MoS_2 by weight)

Both of these have similar friction characteristics. From room temperature to 200 ℃ we prefer 30M and for temperature up to 300 ℃ 15M is preferred. [11]

5.7. Mechanism for lubrication

In order to provide best lubrication some sort of shear layer must develop between sliding surfaces. This shear layer is generated due to weak Van-der-Waals forces between hexagonal planes. What is desired is a very thin plastically flowing transfer film (less than 2μm). This shear layer thickness depends on the contact area. If the contact area is more, it will form ridges and cause high localized stress leading to higher friction. [10]

5.8. Application methods for Solid lubricants

Solid lubricants may be present in the friction area in forms of either dispersed particles or surface films. Some of the application techniques are.

Coating (film) - In this technique solid lubricating mixture is ionized or sometimes painted over the area that is to be lubricated.

Dispersion -Dispersion in the case of composite lubricant is done by adding particles of a solid lubricant throughout the matrix. Dispersion is also done by introducing solid lubricating additives in oils or greases.

Powder -Powdered solid lubricant are delivered to the contact area by rubbing these powders (dry lubrication). This technique produces an uneven layer of lubrication. [12]

The solid lubricating composites can be used on the inner surface of the hinge to provide lubrication to the hinge. The solid lubricating layer can be around 1 to 2 plies thick. The lubricating composites can be cured together with the hinge composite material to give a 1-part hinge design.

Figure 51. Solid lubrication application on the hinge

5.9. Uses of Hybrid Composite hinge

The new hinge design can be used in deployable solar array in outer space. They can also be used inside a space rocket to reduce its overall weight, thereby saving cost and energy. These hinges can also be used on airplanes as hinges for cargo door and other equipment that rely on a hinge mechanism. For cryogenic application such a hinge can be used in electron microscopes and various other components that require precision in their motion.

CHAPTER 6

Conclusion

It is seen that the only composite hinge has 50 % vertical load carrying capacity of that of the aluminum hinge. The radial bearing load capacity is also drastically low (≈ 43 % to 47 %) for the composite hinge over the aluminum hinge. The weight of the composite hinge is 47 % percent lower than the aluminum hinge.

Sandwiching a layer of composite between 2 layers of aluminum drastically improves the load bearing capacity over the composite only hinge while keeping the weight low. This hybrid hinge design is a viable alternative to the current generation of aerospace hinges.

Solid lubricants are required for such a hinge design to function optimally. The ideal solid lubricant would be PTFE + MoS_2, Polyimide and MoS_2.

CHAPTER 7

Future work

The fatigue life of such hinge design has to be determined for better understanding of the hinge life. Dynamic FEA need to be done to see the stress distribution of the new hinge design. Progressive damage of the hinge needs to be analyzed. Titanium can be used as an alternative to aluminum in the hybrid hinge design. An actual physical hinge has to be manufactured to compare the FEA results and real-world test data. Analyzing its performance when factors related to temperature are involved. (thermal stresses).

Appendix A

Material properties

Property	**Value**	**Units**
Density	0.10007	lbs./in^3
E	1.0298×10^7	psi
ν	0.33	
G	1.0094×10^7	psi
σ_y (Tensile Yield)	40611	psi
σ_u (Tensile Ultimate)	44962	psi
σ_y (Compressive Yield)	40611	psi
σ_u (Compressive Ultimate)	0	psi
τ	3.871×10^7	psi

Table 3. Aluminum alloy properties [13]

Property	Value	Units
Density	0.053468	lbs./in^3
E_1	1.331×10^7	psi
E_2	1.331×10^7	psi
E_3	1.305×10^6	psi
ν_{12}	0.05	
ν_{23}	0.3	
ν_{13}	0.3	
G_{12}	2.828×10^6	psi
$G_{23} = G_{13}$	4.351×10^5	psi
σ_1 (Tensile)= σ_2 (Tensile)	1.2×10^5	psi
σ_3 (Tensile)	7251.9	psi
σ_1(Compressive)=σ_2(Compressive)	-63672	psi
σ_3 (Compressive)	-20305	psi
τ_{12}	17405	psi
$\tau_{23} = \tau_{13}$	7251.9	psi
thickness	0.25	mm

Table 4. Carbon Epoxy composite properties. [9]

(HMCF - 120° Cure) [9]

Appendix B

Load capacity comparisons

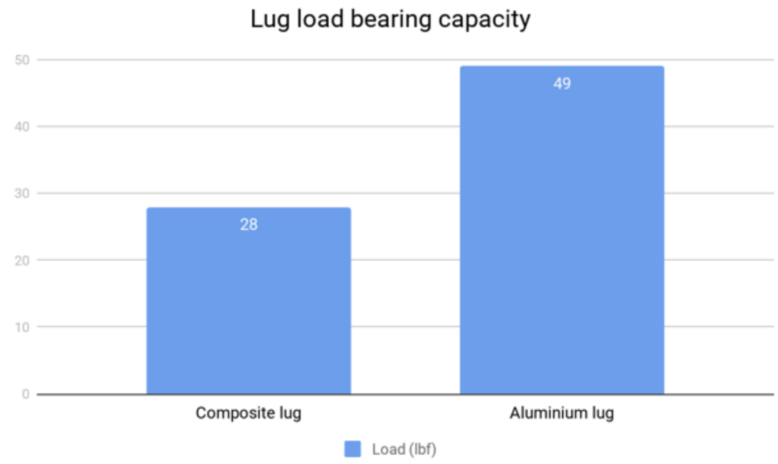


Figure 52. Horizontal radial bearing load comparison [LUG]

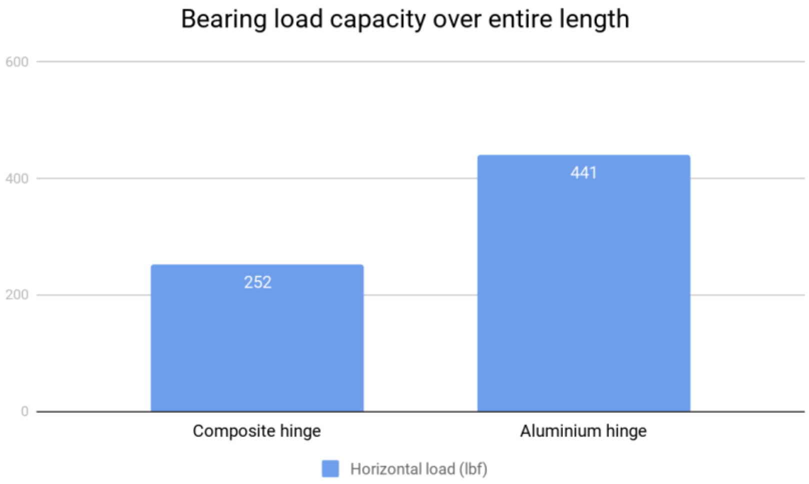


Figure 53. Horizontal radial bearing load comparison [HINGE]

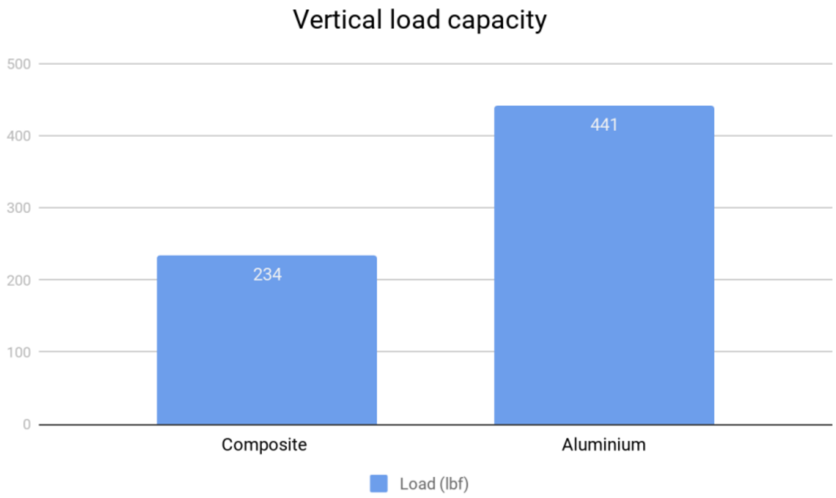


Figure 54. Vertical radial load bearing capacity [HINGE]

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Biographical Information

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