NASA/CR—2019-220145

Composites for Advanced Drive Systems

Cody Anderson and Gilbert Morales
Bell Helicopter Textron, Fort Worth, Texas

July 2019

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Glenn Research Center
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Table of Contents

List of Figures

List of Tables

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I. Introduction

With the desire for increased power/weight for advanced drive system configurations, the investigation of materials, like composites is being explored to determine the feasibility of integration into advanced drive systems. This area of research directly aligns with the vision of the NASA (National Aeronautics and Space Administration) Revolutionary Vertical Lift Technology (RVLT) Project, which is to enable a generation of vertical lift vehicles that can achieve aggressive goals in the areas of high speed, high efficiency, high performance, low noise, and low emissions.

Composite materials are lightweight, especially when comparing to the metallic materials commonly utilized in rotorcraft drive systems. By integrating composite materials into the drive system, the potential for improvements to power/weight exists as well as other potential benefits such as reductions in vibration and/or noise. Each of these areas of potential benefit will largely influence the overall performance and reliability of future vertical lift vehicles. Prior NASA research has been performed that developed a prototype hybrid double helical bull gear which was successfully demonstrated (LaBerge, Kelsen E.; Handschuh, Robert F.; Roberts, Gary; Thorp, Scott;, 2016) and current NASA research is being performed to optimize the hybrid gear design.

While the potential benefits of composite materials in vertical lift drive systems mentioned above are highly desirable, many challenges exist that need to be addressed. To address the benefits and challenges with the integration of composite materials in advanced vertical lift drive systems, the identification of advanced drive system configurations and technical challenges is required. For this project, Bell Helicopter Textron identified an advanced drive system configuration and provided conceptual designs for this advanced drive system configuration, identified technical challenges, and provided recommendations as to how those challenges can be overcome.

II. Drive System Configuration Assessment

To identify the optimum platform for weight reduction with the integration of composite materials an assessment of current drive system configurations was performed. Drive System Configurations A, B, and C were considered. To determine which of these three drive system configurations offer the most potential for increased power/weight, a consistent assessment was performed for each configuration and compared against one another. From this side by side comparison, the desired configuration for further development with the integration of composite materials was recommended. The assessment consisted of calculating a baseline power/weight using actual power and estimated weight for each drive system configuration. Then, an increased power/weight ratio was calculated for each configuration assuming a reduction in weight of one pound. A power/weight percentage increase due to a reduction in weight of one pound was calculated usingthe baseline power/weight and increased power/weight due to a reduction in one pound. This percentage provides a basis for understanding the potential performance improvements when considering power/weight. With the percentage of improvement, additional considerations with the configurations components shall be investigated, specifically characteristics, like types and sizes. These characteristics can be leveraged to identify the components with the greatest potential for implementation of composite material.

Table 1 summarizes the data from the assessment performed for Drive System Configurations A, B, and C. The data shows that baseline power/weight for Configuration B is the greatest at 8.234, while for Configuration A it is the lowest at 2.292. However, when a reduction in weight of one pound is considered and the percentage of improvement in power/weight is calculated, Configuration A has the greatest potential for improvement (+0.30%), while Configuration C has the least potential for improvement (0.10%). Even though the absolute power/weight value is the largest for Configuration B, a reduction in weight of one pound results in an improvement of +0.13%, which is 0.17% less than that observed for Configuration A.

Table 1: Estimated performance improvements with a one-pound weight reduction for Drive System Configurations A, B, and C.

	Configuration A	Configuration B	Configuration C
Baseline Power/Weight	2.292	8.234	2.865
Power/Weight for 1 lb Reduction	2.299	8.245	2.868
Power/Weight Improvement (%)	+0.30	+0.13	+0.10

With the primary consideration being the performance improvement due to increased power/weight, Drive System Configuration A provides the greatest potential. A secondary benefit associated with Configuration A is that, amongst the other two drive system configurations assessed, it contains the gear (helical bull gear) with the largest major diameter. The size of this gear provides good opportunity for weight reduction from a single part. Based on these considerations, the bull gear from Configuration A was selected as the baseline design that would guide the conceptual designs of an advanced drive system configuration. While the bull gear was the primary component of interest, additional gearing and shafting would be worth considering for hybridization in each of the drive system configurations assessed. Each drive system configuration would require an extensive study to identify which components are suitable for hybridization. This would then allow for an even greater understanding of potential power/weight improvements.

III. Design and Analysis

Following the identification of the baseline design, the conceptual design for advanced drive system configurations began. The approach utilized to identify potential designs involved both design and analysis efforts that informed and guided one another, resulting in multiple concepts that are feasible for integration in a drive system configuration. In utilizing the baseline design,the conceptual designs of a hybrid composite gear were configured such that the possibility to procure and test an actual gear was achieved.

The initial step involved taking the baseline design, which a cross section of the baseline design is shown in Figure 1, and envisioning and modeling preliminary concepts that could be integrated into Drive System Configuration A without any modifications to additional components and systems. So, hard restrictions existed such as space, interfacing, and required load transfer. With the preliminary concepts modeled and identified, an analysis was performed to determine if the metallic and composite structures could be joined with just adhesive, or if other retention features would be required. In addition to the calculated shear stress at the joints, the percentage of weight savings was determined as well. Based on this analysis, the desired concepts for further consideration were identified and designed.

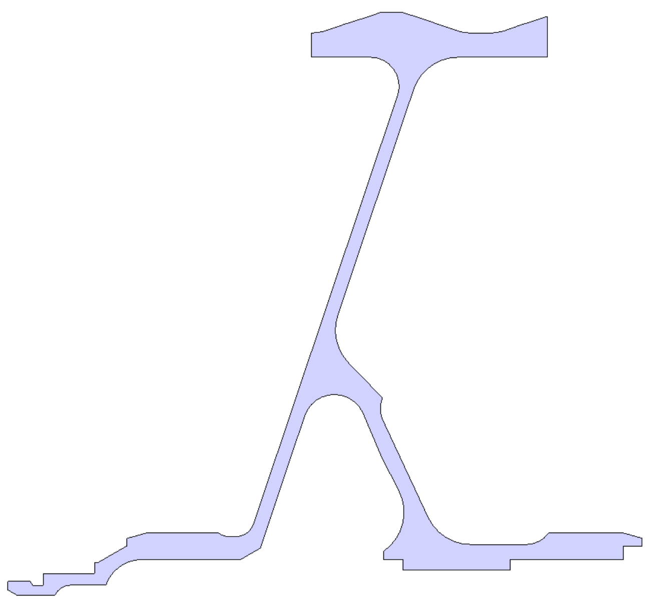


Figure 1: Cross sectional view of baseline configuration, Drive System Configuration A.

While the primary consideration for this project was reduced weight to improve performance based on power/weight, additional primary considerations were redundancy and manufacturability. Redundancy is a key consideration, especially with the primary desired means of utilizing adhesive at the interfaces between the composite and metallic structures. Redundant features provide greater confidence in the survivability of the gear in the event that the adhesive bond is compromised. This is likely to occur during a high temperature situation, where the maximum operating temperature exceeds that of the maximum serviceable temperature of the adhesive (e.g. loss of lubrication event). Redundancy is also something that will be critical to the certification of such technology in a drive system configuration. Manufacturability is a key consideration as the desired outcome is to be able to feasibly and reliably procure components that can be transitioned into a drive system configuration for testing and integration into future drive systems. By incorporating manufacturability into the conceptual designs, composite technology can have a more immediate impact on drive system configurations.

i. Preliminary Concepts

The preliminary concepts were developed to understand the possible weight savings, as well as the maximum shear stresses to determine if the interfaces between the composite and metallic structures could be joined by adhesive only. Each preliminary concept incorporates a combination of composite and metallic structures with consistency across all of them regarding which components are made of metallic material and which are made of composite material. For this project, the components that contain the gear teeth, spline, and bearing raceways and journals are all made from metallic material, specifically gear steel. These components are the outer ring gear and inner ring shaft(s). The components between the outer ring gear and inner ring shaft(s), the web, are made from composite material.

A cross section of all the preliminary concepts analyzed are shown in Figure 2 through Figure 16.

Each preliminary concept incorporates a two-piece composite web. By utilizing a two-piece composite web, advantages to manufacturing and assembly are achieved due to the nature of the geometry required for the gearing.

For each interface between the composite and metallic material, adhesive is utilized as well at the interface between the two composite webs. In addition to the adhesive at the interfaces for preliminary concepts 1, 2, and 5, mechanical fasteners were incorporated at the outer and inner primary interfaces between the composite and metallic components for preliminary concepts 1 and 2 (see Figure 3 and Figure 4) and only at the inner primary interfaces between the composite and metallic components for preliminary concept 5 (see Figure 7). The axis of the mechanical fasteners is always parallel to the axis of the entire gear assembly. For the analysis of the preliminary concepts with mechanical fasteners, the mechanical fasteners were removed in order to understand the capability of the adhesive as the primary mode of joining the assembly. A cross section of preliminary concept 1 with the mechanical fasteners included for illustrative purposes is shown in Figure 2.

For the composite web of each preliminary concept, a contour was included that generally represents the shape of the web for the baseline configuration. This ensured no interference between adjacent components within Drive System Configuration A.

Preliminary concepts 2, 3, 4, 5, 6, 8, 11, and 12 incorporate a two-piece composite web that extends beyond the inner diameter of the inner metallic shafts with a flange that enables additional surface area for bonding. In comparing preliminary concepts 1 and 2, the increased surface area for bonding can easily be visualized.

For preliminary concept 7, a single inner shaft was analyzed as compared to a two-piece inner shaft for the other analyzed preliminary concepts.

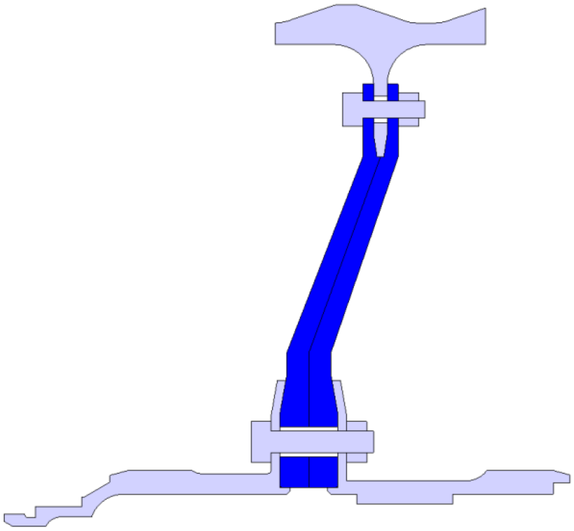


Figure 2: Cross sectional view of preliminary concept 1. Mechanical fasteners shown for illustrative purposes only.

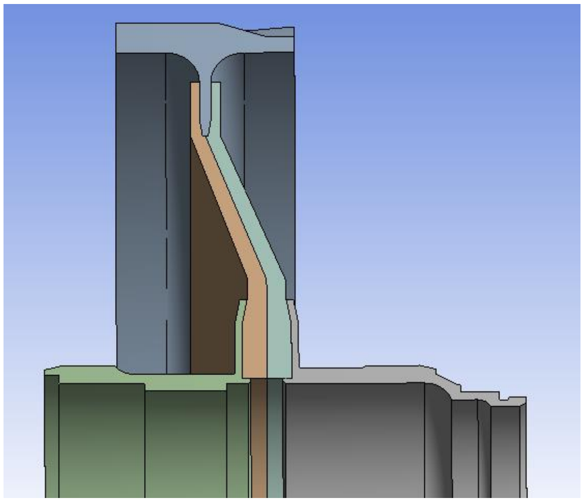


Figure 3: Cross sectional view of preliminary concept 1. Mechanical fasteners not included for analysis purposes only.

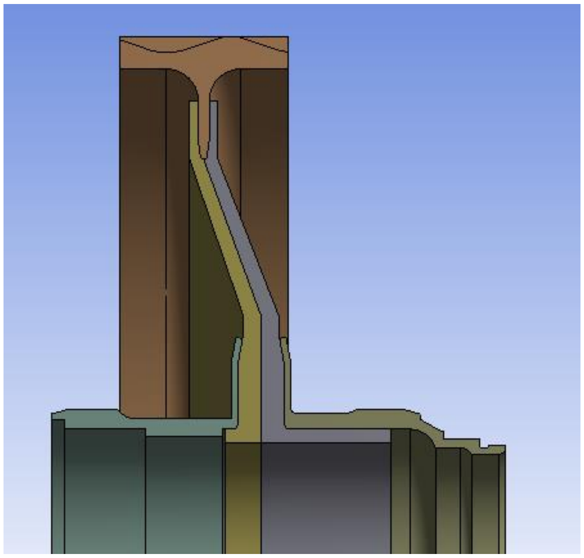


Figure 4: Cross sectional view of preliminary concept 2. Mechanical fasteners not included for analysis purposes only.

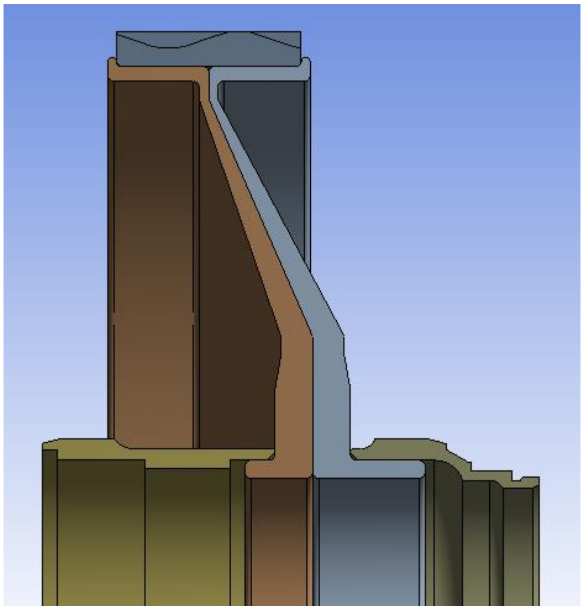


Figure 5: Cross sectional view of preliminary concept 3.

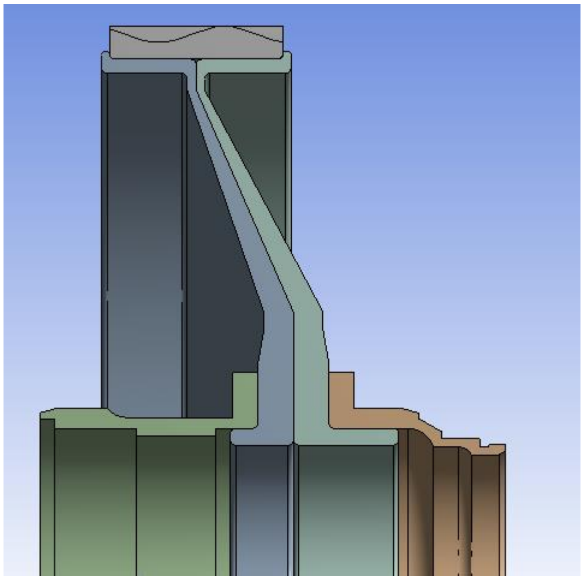


Figure 6: Cross sectional view of preliminary concept 4.

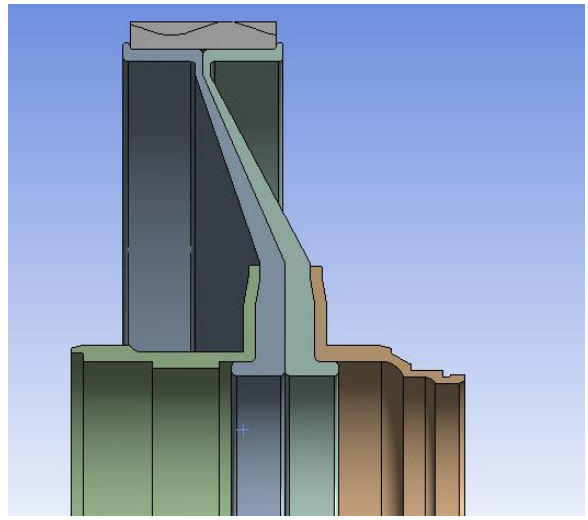


Figure 7: Cross sectional view of preliminary concept 5. Mechanical fasteners not included for analysis purposes only.

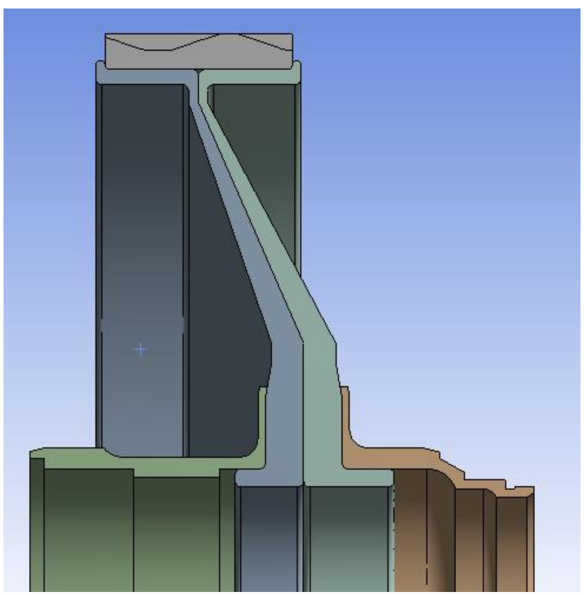


Figure 8: Cross sectional view of preliminary concept 6.

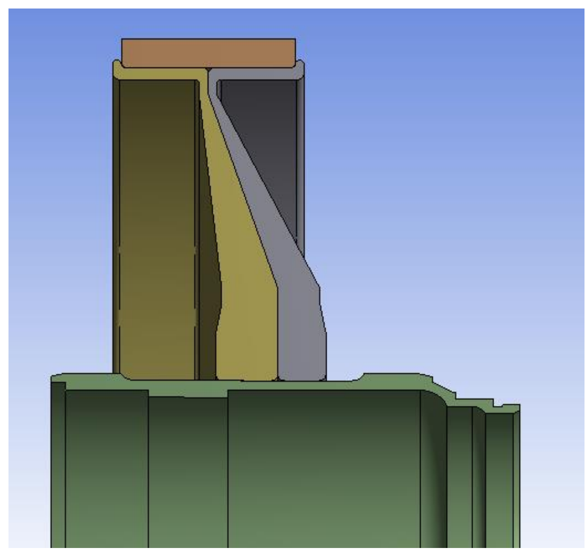


Figure 9: Cross sectional view of preliminary concept 7.

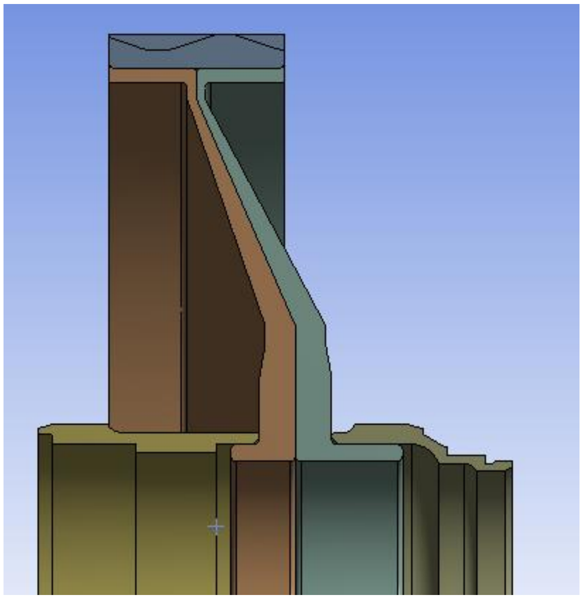


Figure 10: Cross sectional view of preliminary concept 8.

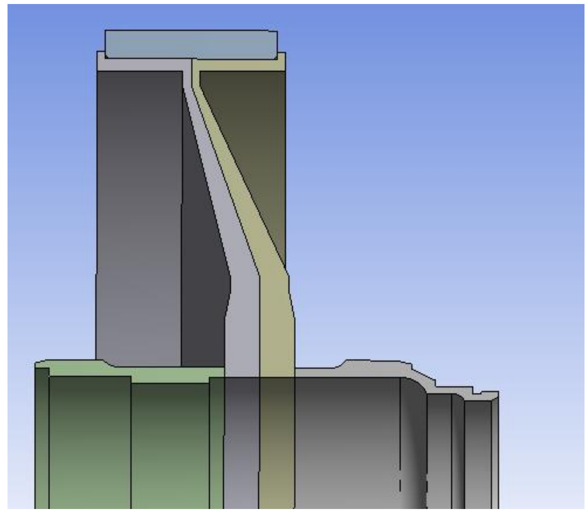


Figure 11: Cross sectional view of preliminary concept 9.

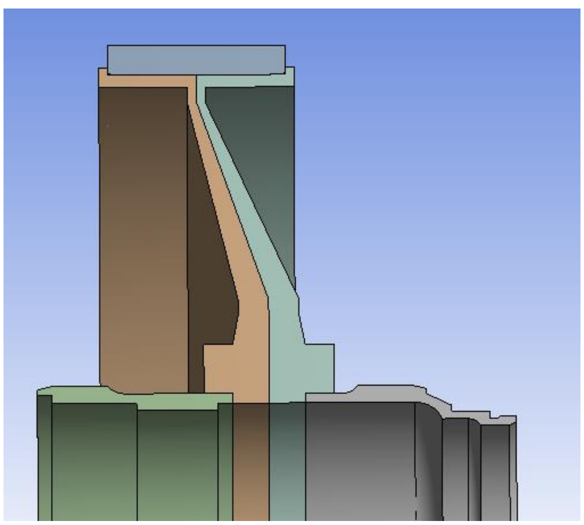


Figure 12: Cross sectional view of preliminary concept 10.

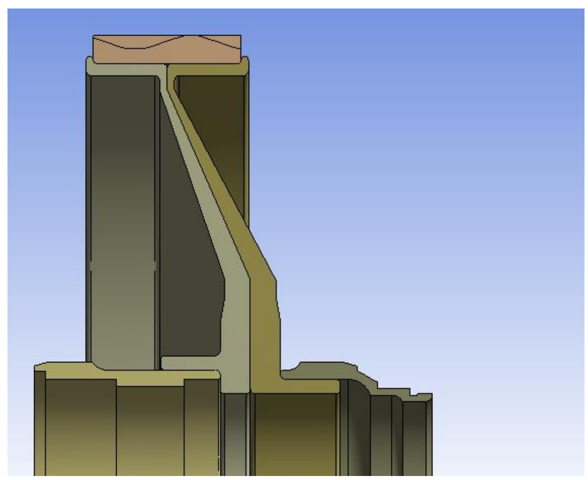


Figure 13: Cross sectional view of preliminary concept 11.

Similar to the interface between composite and metallic components utilized by NASA during prior work, a lobed feature at the inner ring interface between the metallic inner shafts and the composite webs was incorporated in preliminary concept 12. The lobed interface serves as a mechanical lock in the circumferential direction, ultimately restraining the rotation of the inner shafts and composite webs. An exploded view of the preliminary concept is shown in Figure 14. For this preliminary concept, two iterations were analyzed where a difference in the thickness of the lobed flange was investigated (compare Figure 15 and Figure 16).

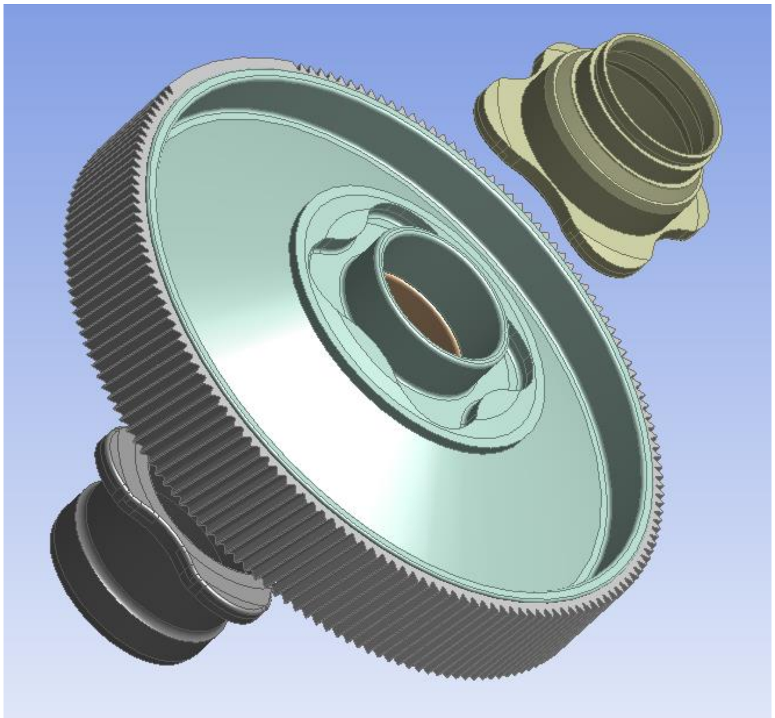


Figure 14: Exploded view of preliminary concept 12 highlighting inner lobed interface feature.

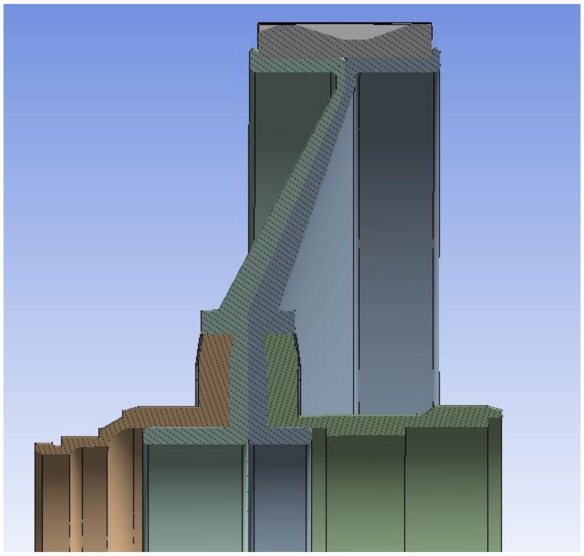


Figure 15: Cross sectional view of preliminary concept 12a.

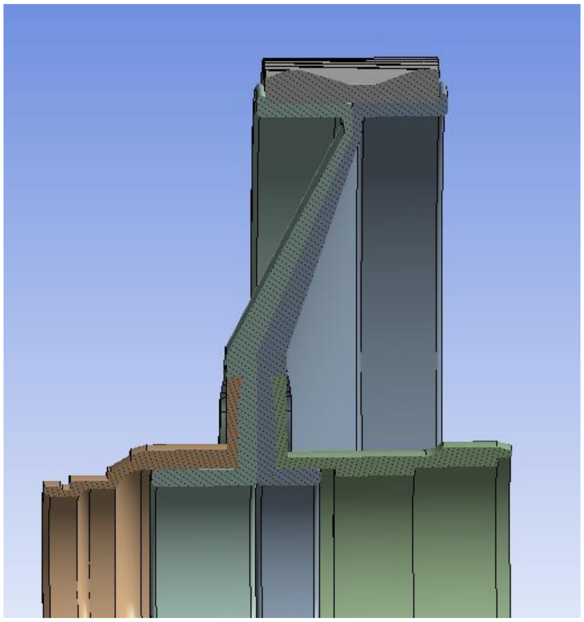


Figure 16: Cross sectional view of preliminary concept 12b.

With the preliminary concepts defined, each was analyzed to understand weight savings and capability of the adhesive at the defined interfaces for transferring the load. From this analysis, the preliminary concept for integration into a conceptual design was determined.

ii. Preliminary Analysis

A preliminary analysis was performed to understand the shear stresses between the composite and the metallic components in the hybrid gear. This analysis was performed using the ANSYS finite element analysis software. A simplified model was created to quickly calculate shear stresses for different configurations. The model was created to understand the magnitude of the shear stresses on the adhesive between the metal and the composite. In the model the torque was applied by a tangential load of 10,884 lbs on the outer diameter of the bull gear. This load was applied as a line load on the outer diameter of the bull gear. To prevent rotation, the flanged part of the assembly was restrained to simulated the torque transmitted from the teeth to the flange geometry in Figure 17. Bolts were removed from this initial analysis and all the loads were transferred between the composite and the steel through the adhesive layer attaching these components. This assumption was simulated by using bonded contacts between the composite and steel geometries.

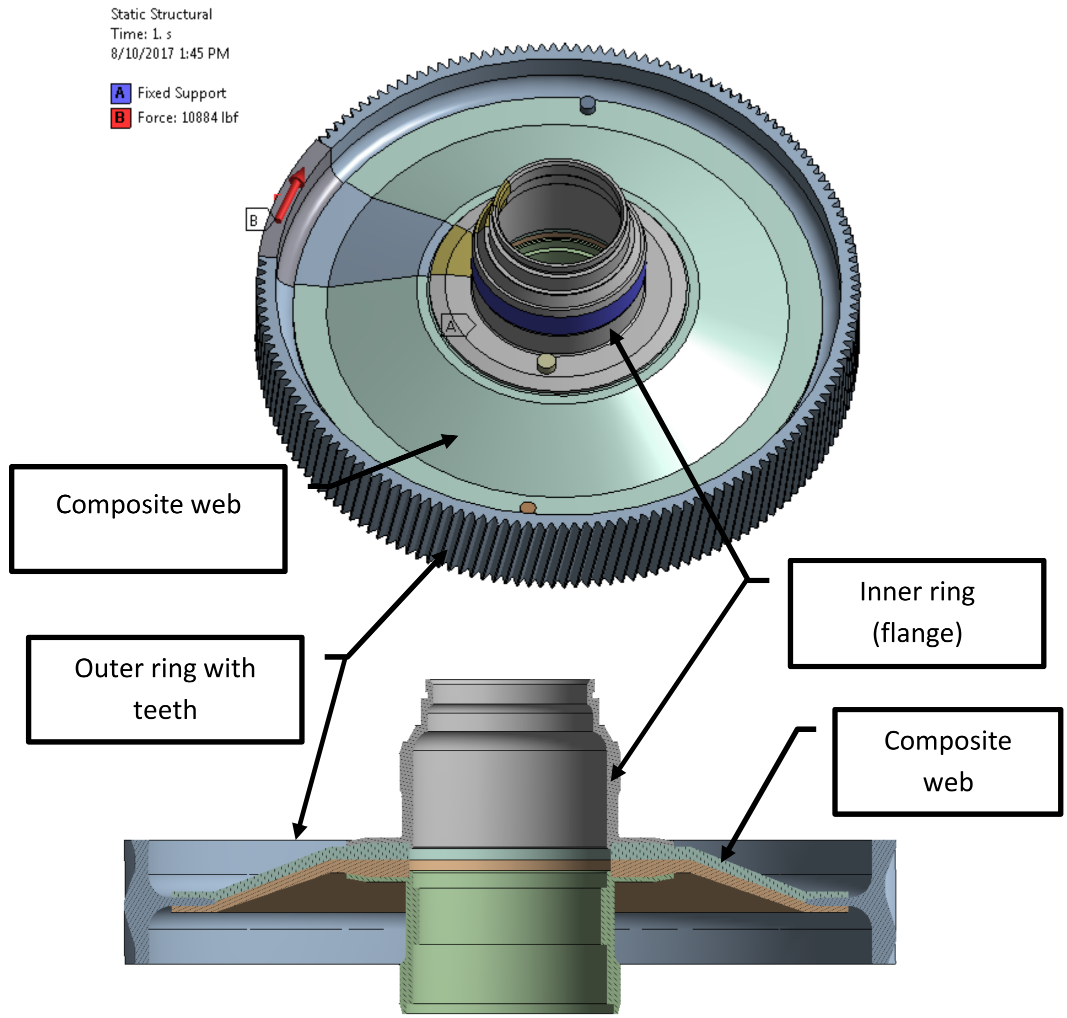


Figure 17: Top figure shows the loads applied to the simplified FEA model. Figure on the bottom shows a cross section of the modeled geometry.

Figure 18 shows the shear stresses for preliminary concept 1 due to the applied torque. As can be observed in Figure 18, the maximum sheer stress the composite sees is at the interface between the inner ring/composite and the outer ring/composite which happens to be the shear stress on the adhesive between the composite and the steel. To ensure a strong and permanent adhesive bond, the maximum shear stress on the inner diameter (ID) and outer diameter (OD) of the composite should be kept below the shear strength of the adhesive.

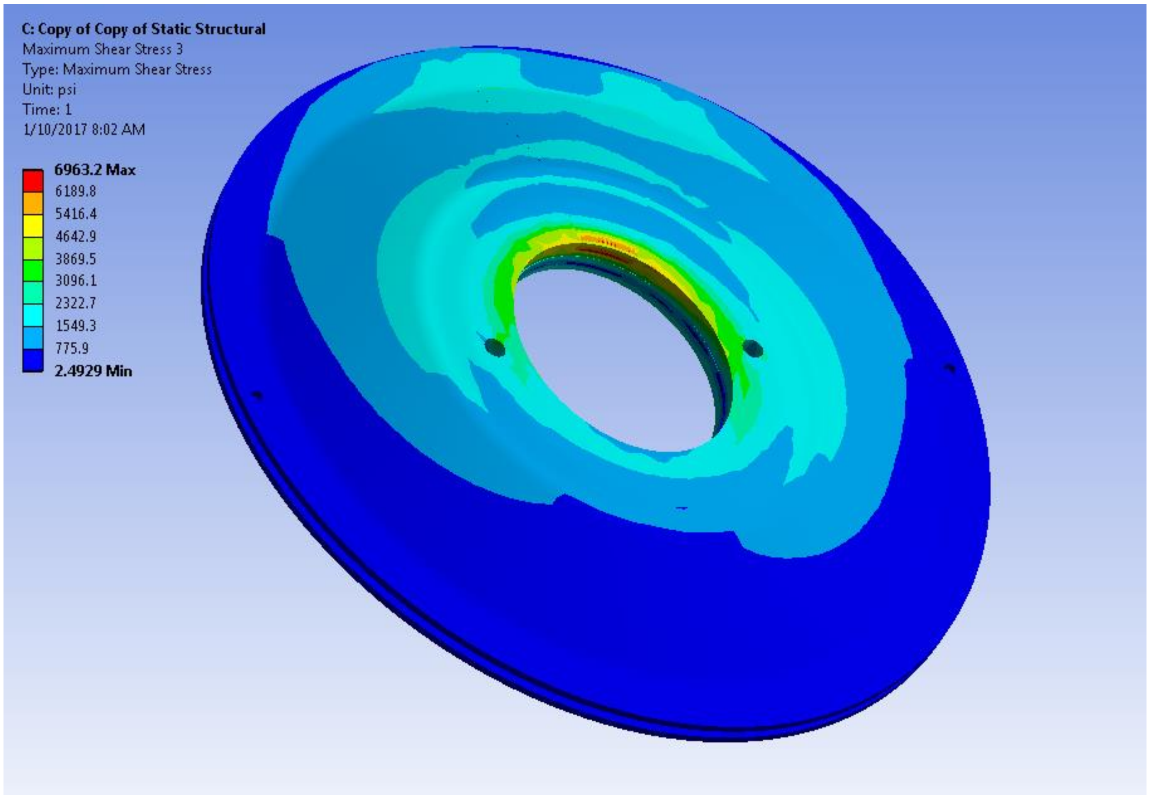
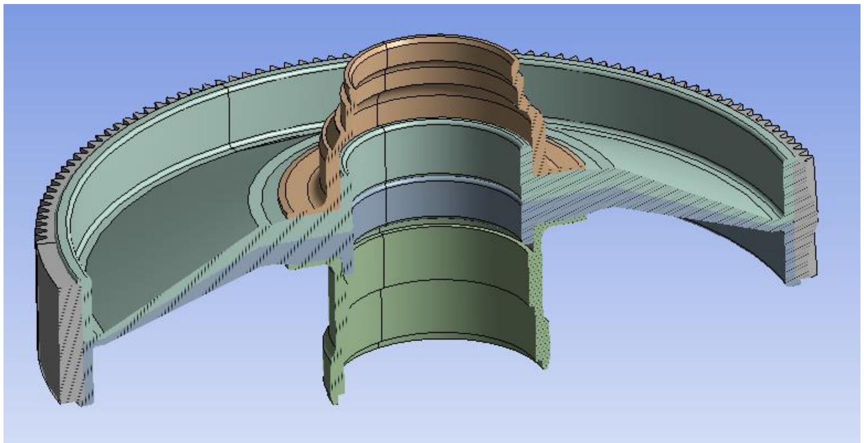


Figure 18: Shear stresses on composite web for preliminary concept 1 due to the applied torque.

The DOT/FAA/AR-02/97 report lists the shear strength for various adhesives (Tomblin, John; Seneviratne, Waruna; Escobar, Paulo; Yon-Khian, Yap;, 2002). One of the adhesives described in the report is FM 300. This adhesive has been used in the aerospace industry for more than 30 years to bond composites and it has a cure temperature of 350°F. The measured shear strength for the FM 300 adhesive is 5.0 ksi at the elevated temperatures of 180°F and wet conditions. For this analysis, this value of 5.0 ksi was used as the maximum allowable shear value between the composite and steel components.

The preliminary concepts shown in Figure 2 Figure 16 were analyzed using the technique just described to determine the shear stress at the composite/steel interface. Figure 19 shows the maximum shear stresses for preliminary concept 6. As in preliminary concept 1, the maximum shear stress between the composite and the steel is at the ID of the composite web.



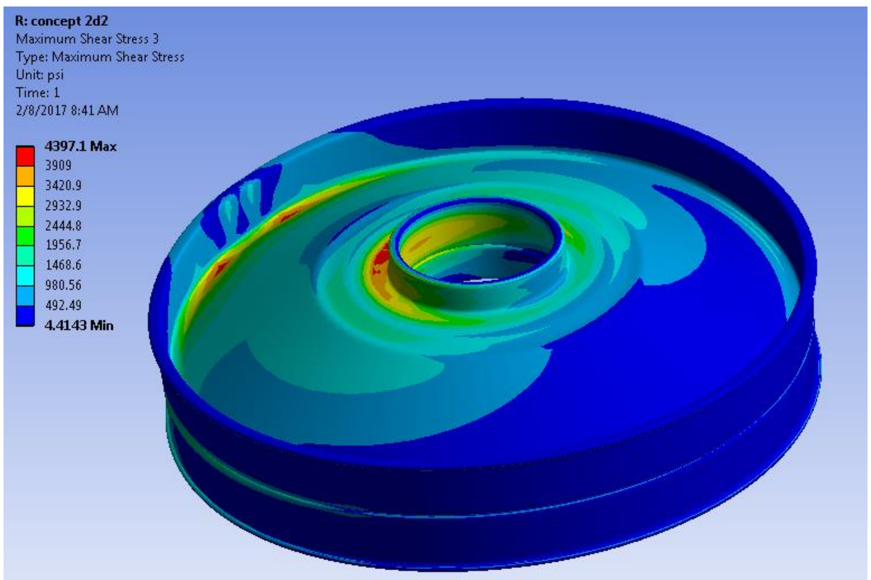


Figure 19: Top figure shows the cross section of preliminary concept 6. Bottom figure shows the maximum shear stress on the composite due to the applied torque.

Figure 20 shows the calculated maximum shear stresses for the various preliminary concepts. Figure 20 also shows the weight savings as compared to the baseline bull gear. The preliminary concepts with high shear stresses described in Figure 20 were due to small contact areas between the composite and the steel. The preliminary concept with the lower shear stresses had a large contact area. A larger contact area requires adding more metal which decreases the weight savings. That is why the preliminary concepts with the largest weight savings also had the largest shear stresses. As stated before, this analysis was performed assuming the adhesive transferred all the load and therefore no bolts were included in this part of the analysis.

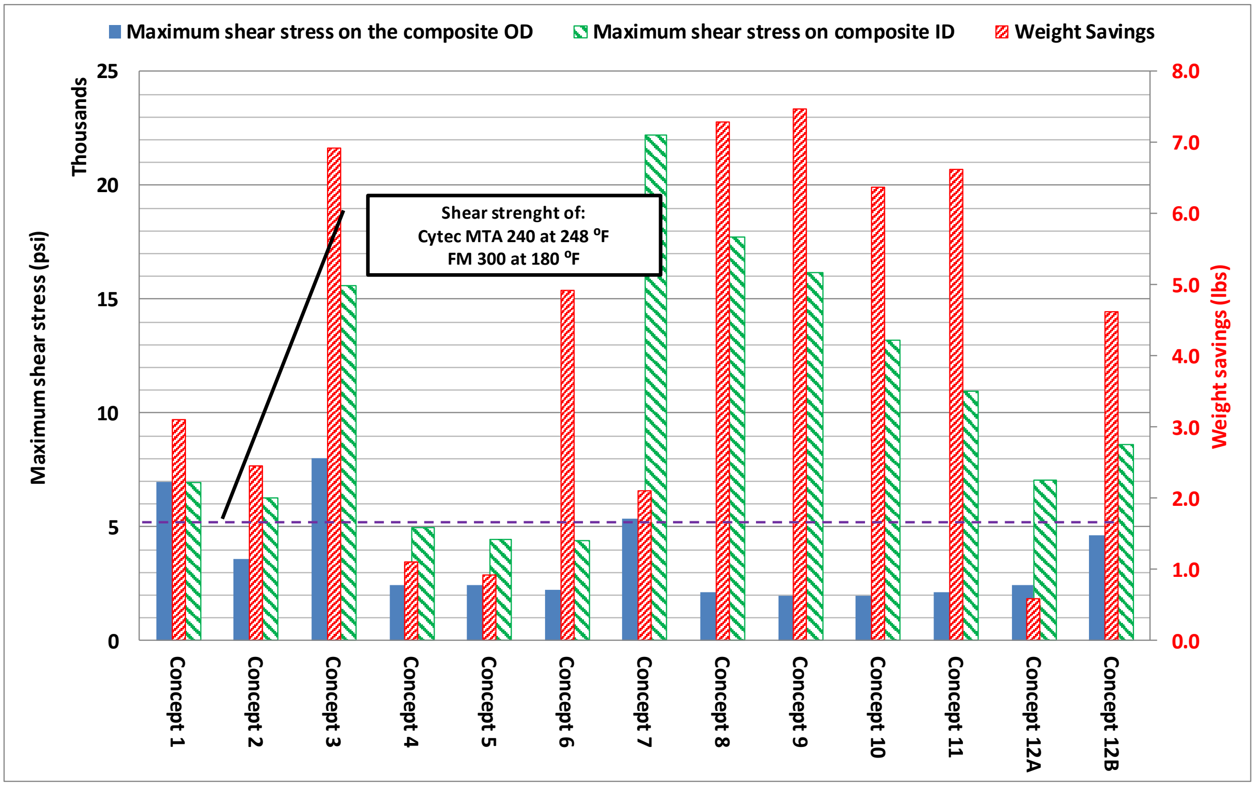


Figure 20: Shear stresses on the composite/steel interface and the weight savings for the analyzed preliminary concepts.

Preliminary concepts 1 and 6 were the most intriguing from all the preliminary concepts shown in Figure 20. Preliminary concept 6 has the most weight savings of 9% while keeping the shear stresses below the shear strength of the adhesive. This preliminary concept also has enough material on the flange to allow for fasteners as a backup system in case the adhesive fails during operation. Weight savings are due to the removal of the material in the outer metal ring where fasteners could be used to attach the composite and outer ring. Due to this, there is not enough metal for fasteners between the outer metal ring and the composite.

Preliminary concept 1 has low shear stresses on the ID and OD of the composite and the weight savings are only 6%. The shear stresses are above the 5 ksi strength of the adhesive but this configuration allows for bolts on the OD of the composite. It was decided to use this configuration because it provides a backup system in case the adhesive fails and the shear stresses are close enough to the 5 ksi strength of the adhesive and they could be reduced in later iterations by adjusting the bonded surface between the composite and the metal. Further analysis was performed on this configuration with bolts on the ID and OD of the composite ring for backup in case the adhesive fails.

Preliminary concept 6 was not analyzed further because it did not provide for a backup system in case the adhesive failed. Due to time constrains it was decided to concentrate on preliminary concept 1 to perform the detail analysis on the composite web.

iii. Design of Conceptual Design 1

Conceptual design 1 includes a metallic outer ring gear, two-piece composite web, two-piece metallic inner ring shaft, and mechanical fasteners both at the outer and inner diameter interfaces. An isometric view is shown in Figure 21 and a cross sectional view is shown in Figure 22. The design includes features required for integration in Drive System Configuration A.

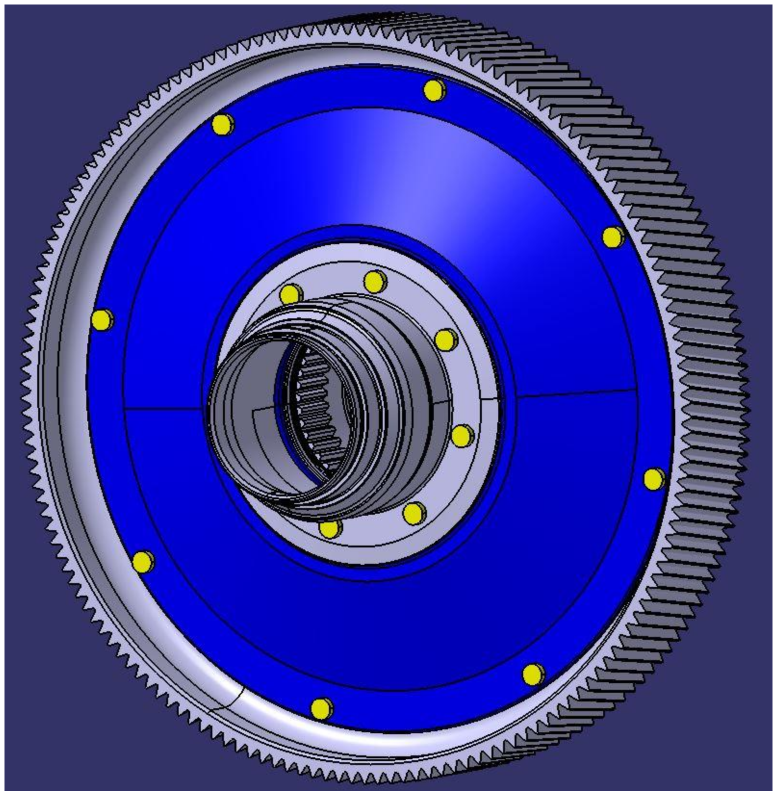


Figure 21: Isometric view of conceptual design 1.

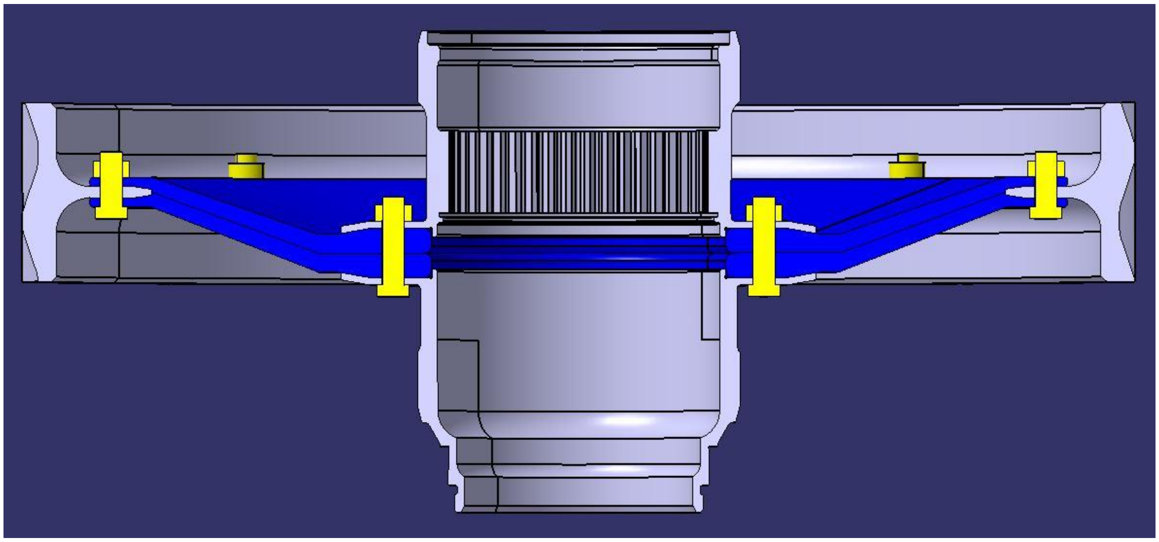


Figure 22: Cross sectional view of conceptual design 1.

The metallic outer ring gear contains helical gear teeth along the outer diameter with an inner flange. The inner flange allows for the composite web to be joined at the interface with both adhesive and mechanical fasteners. The metallic inner ring shaft is split creating two separate components. By having two inner shaft components, the gear is able to be assembled. One of the inner shafts contains a bearing raceway on the outer diameter as well as a spline on the inner diameter that interfaces with the main rotor mast assembly of the transmission. The other inner shaft contains both a bearing raceway and bearing journal on its outer diameter. For both of these inner shafts, a contoured flange was designed on the outer diameter at the interface between the composite web. This flange was designed to provide adequate surface area for fastening by both adhesive and mechanical fasteners. The composite web is split into two separate components which enables a simpler procurement process. The contoured design of the web embodies a similar contour and placement of the web compared to the baseline design. This contour ensures no inference with adjacent components in the transmission.

A gear steel, such as Pyrowear® Alloy 53 (X53) is desired for the outer ring gear and inner ring shafts. As mentioned before, special considerations are required with the outer ring gear due to the likelihood of distortion occurring. A BMI resin-impregnated carbon fiber, such as IM7 is desired for the composite web. As mentioned before, special consideration with the layup is required to determine the best orientation of the fibers for the given design.

The interfaces between the composite and metallic components required both adhesive and mechanical fasteners to ensure reliability and safety of the assembly. While the use of adhesive is the primary means of joining the components, the potential issue exists where the integrity of the bond is compromised due to various reasons, with a primary one being high operating temperatures. Rotorcraft transmissions are designed to overcome extreme operating conditions, such as those due to loss-of-lubrication. These conditions result is extremely elevated temperatures that exceed the operational temperature thresholds of current adhesives. With this in mind, the need for redundant features to maintain the integrity of the assembly for a sufficient amount of time to safely ground the rotorcraft are required. This resulted in the design of mechanical fasteners at the interfaces between the composite web and outer ring gear and inner ring shafts. For the inner interface, the minimum required bolts are three. For the outer interface, the minimum required bolts are two. For conceptual design 1, eight bolts were included at both the inner and outer interfaces to allow for a greater margin of safety and load distribution. For the inner and outer interfaces, the preliminary minimum spacing was calculated to be 1.5 inches and the preliminary minimum edge distance was calculated to be 0.75 inches for the metallic structure and 0.9375 inches for the composite structure. The preliminary minimum spacing is four times the nominal diameter of the fasteners and the preliminary minimum edge distance is two times the nominal dimeter of the fasteners for the metallic structure and two and half times the nominal diameter of the fasteners for the composite structure. Further analysis is required to finalize the number of fasteners as wells minimum spacing and edge distance. Ultimately the mechanical fasteners are designed to transfer load only when the adhesive bond has been compromised to the extent where it is no longer able to transfer the entire load.

Considering manufacturability, conceptual design 1 is capable of being produced with current materials, technology, and processes. With the metallic components, special considerations need to be taken with the outer ring gear, especially when utilizing a carburizing steel. With the current geometry, distortion during the heat treatment process is anticipated based on prior experience. This would favor the consideration of a nitride steel as it has proven from past experience to be more stable and predictable with distortion for similar geometry. With the composite components, special considerations need to be taken with the orientation of the carbon fibers. Overall, conceptual design 1 is a feasible design for integration of composite materials in a drive system configuration with current state of the art materials and processing.

iv. Analysis of Conceptual Design 1

After deciding on conceptual design 1, the finite element analysis was expanded to include the actual loads seen by the baseline bull gear. Drive System Configuration A has two input pinions as see in Figure 23. These input pinions engage the gear shafts which in turn engage the bull bear. Each gear shaft applies a load of 10,286 lbs. on the bull gear as shown on Figure 23, which is broken into a radial load of 9208 lbs, a tangential load of 4347 lbs and an axial load of 1458 lbs.

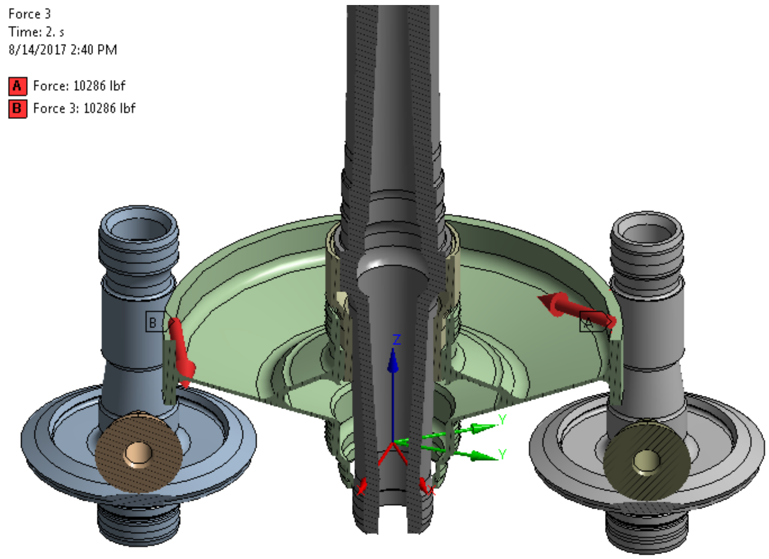


Figure 23: Loads on the bull gear for Drive System Configuration A.

Loads were applied to conceptual design 1 as shown in Figure 24. The splines shown in Figure 22 were removed in the model and the splined surface was restrained from spinning and moving in the z direction to replicate the loads from the spline as seen in Figure 24. Bearing on the bull gear were simulated by restraining the radial displacement on the bearing surfaces as seen in Figure 25. Figure 26 shows the mesh and loads applied to conceptual design 1. The composite was modeled as an IM7 laminate and the smear properties on Table 2 were used in this preliminary analysis.

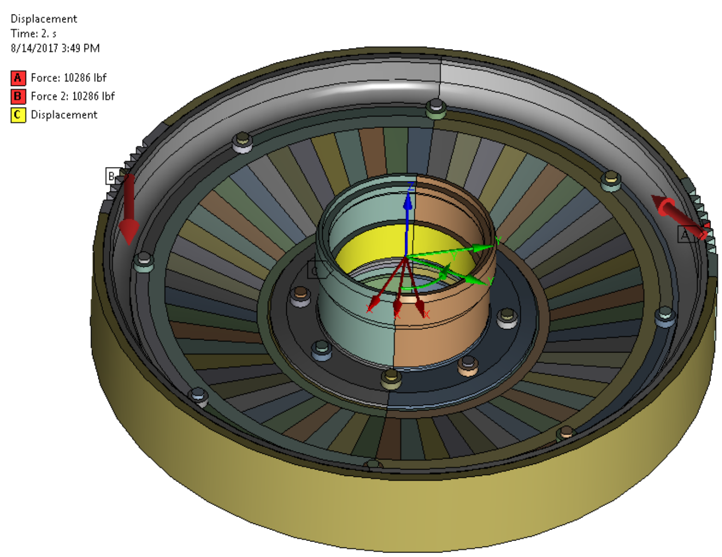


Figure 24: Loads from the gear shafts and restraint from the spline.

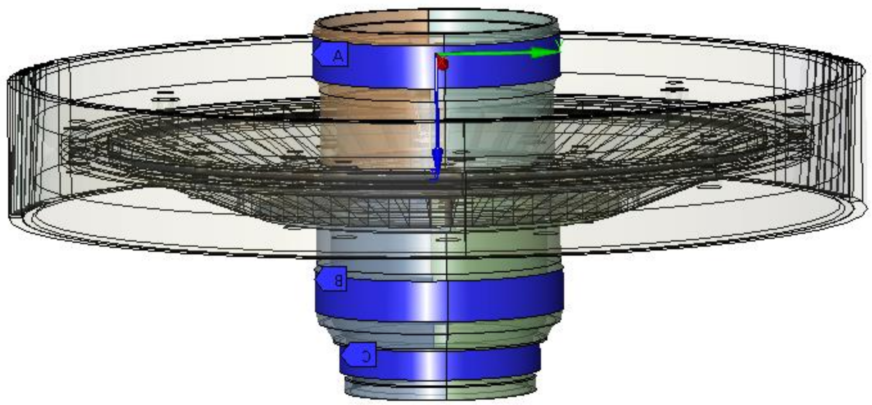


Figure 25: Surfaces radially restrained to represent the bearings.

Table 2: Composite properties used in the initial analysis.

Smear Material Properties for IM7/8552	
E_{11}	23.4 Msi
E_{22}	1.65 Msi
E_{33}	1.65 Msi
ν_{12}	0.32
ν_{13}	0.32
ν_{23}	0.451
G_{11}	0.75 Msi
G_{22}	0.75 Msi
G_{33}	0.534 Msi

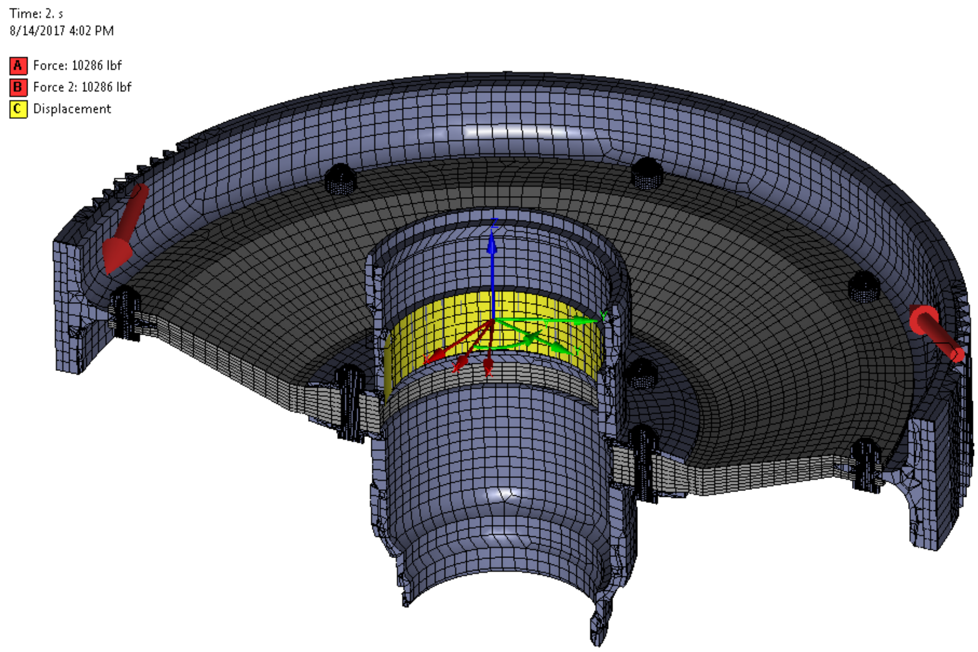


Figure 26: Mesh and loads on conceptual design 1.

Teeth loads on the bull gear produce a twisting on the gear mesh as seen in Figure 27. To understand if the composite fibers would be placed in tension or compression, the radial deformation was plotted and the compression was plotted with the color gray. As seen in Figure 28 a large part of the web is placed in compression due to the teeth loads. Further analysis was conducted to understand why the web is in compression since composite fibers prefer to be in tension instead of compression.

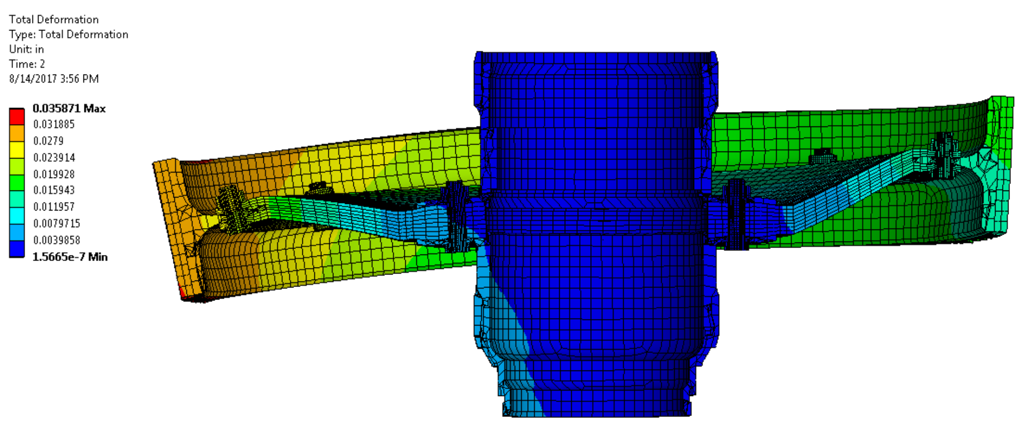


Figure 27: Exaggerated displacement on conceptual design 1 due to the teeth loads.

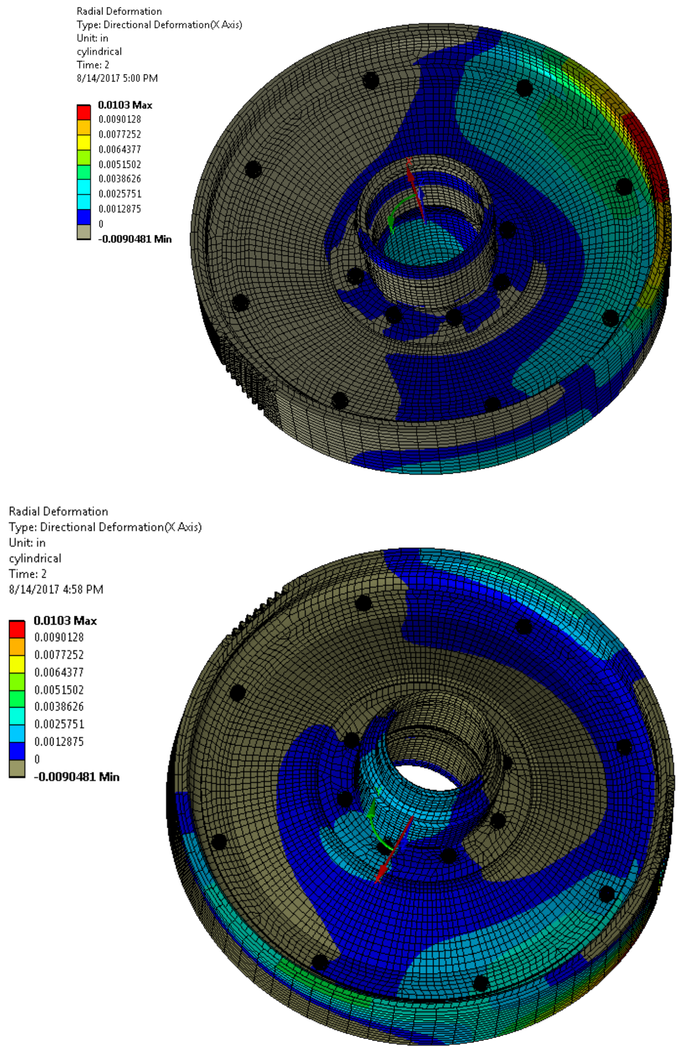


Figure 28: Radial deformation on conceptual design 1.

The steel baseline bull gear geometry was modeled to understand how the webs material affects the radial deformation in the web. Figure 29 shows the finite element mesh for the baseline bull gear. Like conceptual design 1, the baseline bull gear twists due to the teeth loads as see in Figure 30. This twisting also placed a large part of the web in compression as seen in Figure 31. For the baseline bull gear one wants the web to be in compression since the material is steel but for a composite web one wants most of the web to be in tension.

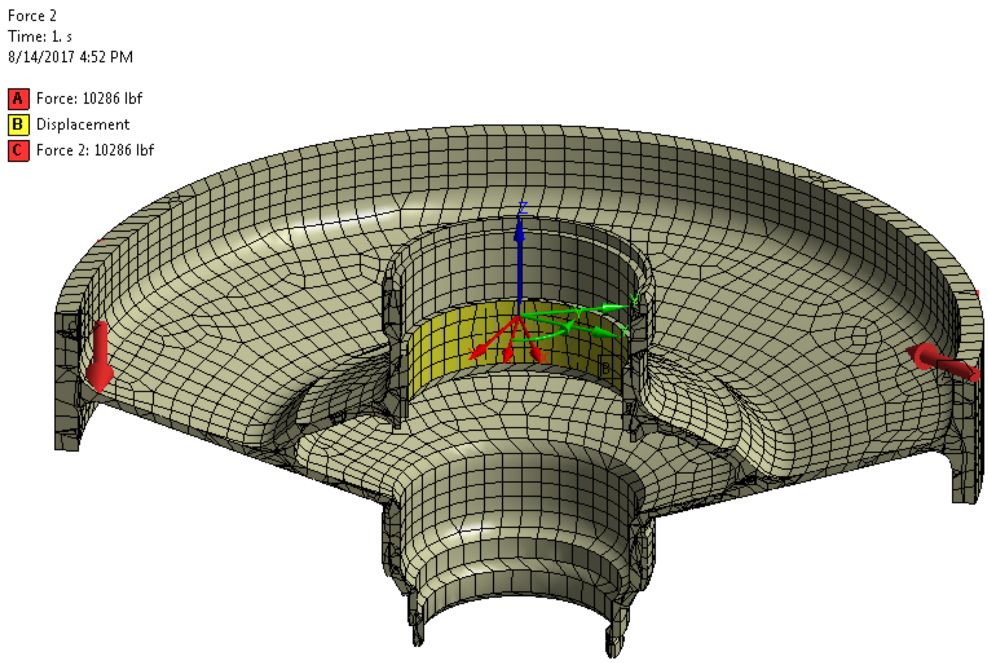


Figure 29: Mesh for the baseline bull gear.

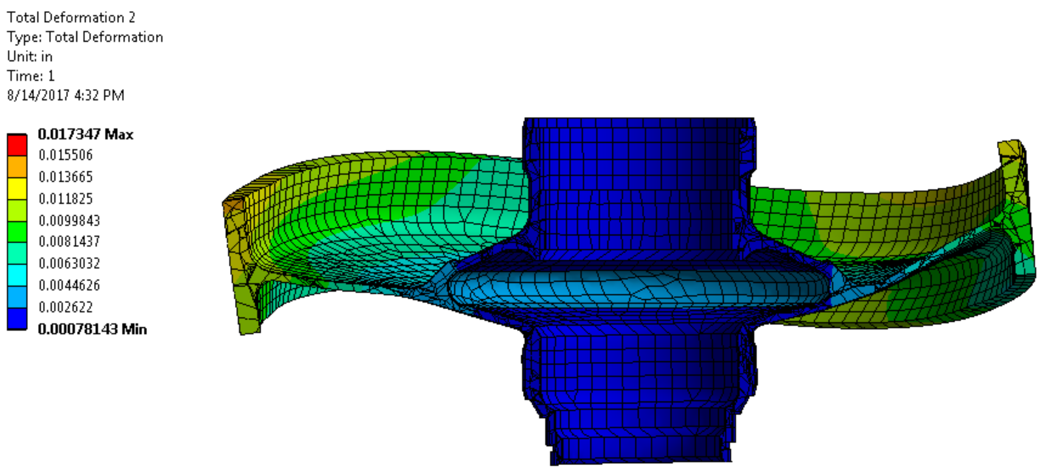


Figure 30: Total deformation on the baseline bull gear due to the teeth loads.

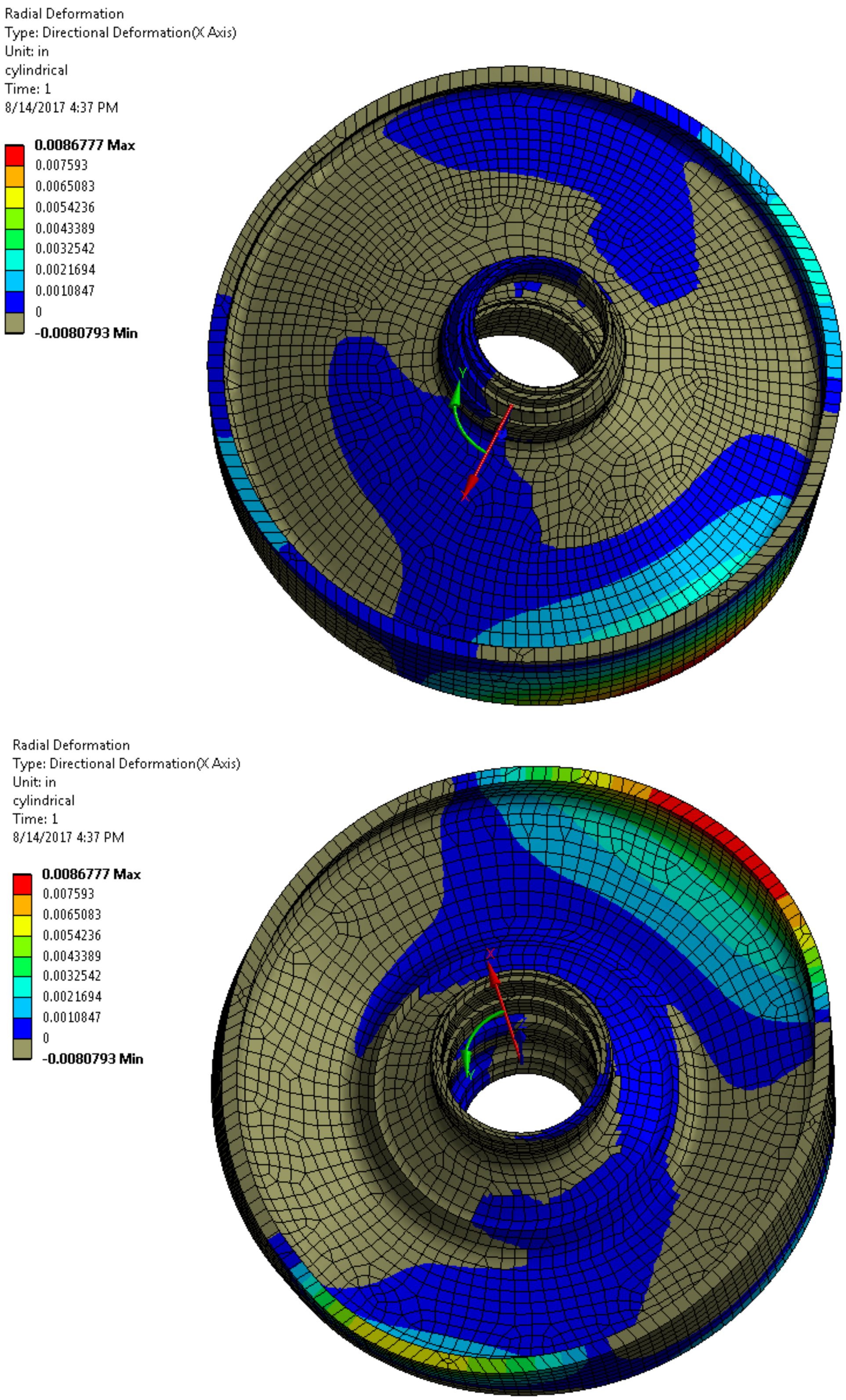


Figure 31: Radial deformation on the baseline bull gear due to the teeth loads.

Noticing that the web used in the NASA hybrid bull gear was flat (LaBerge, Kelsen E.; Handschuh, Robert F.; Roberts, Gary; Thorp, Scott;, 2016), the web in conceptual design 1 was made flat to determine if this would increase the amount of web in tension. The finite element mesh for this new configuration can be seen in Figure 32. Figure 33 shows the deformation on this flat web due to the teeth loads. The radial deformation of the bull gear can be seen on Figure 34.

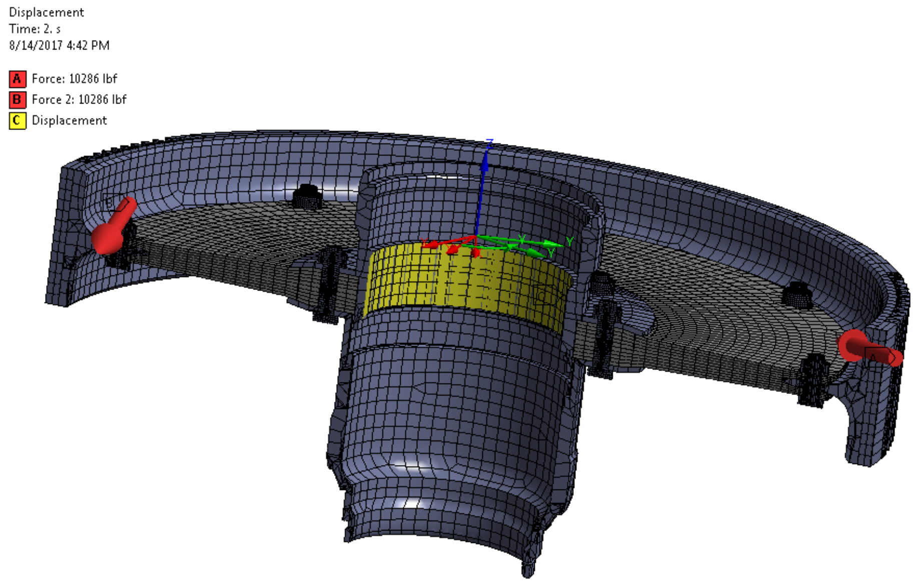


Figure 32: Mesh for conceptual design 2.

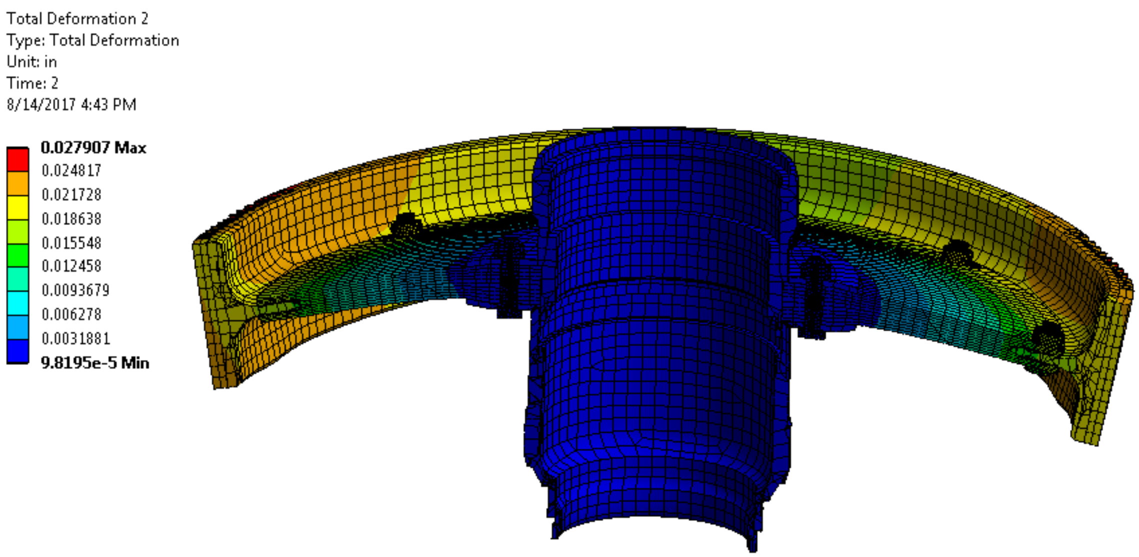
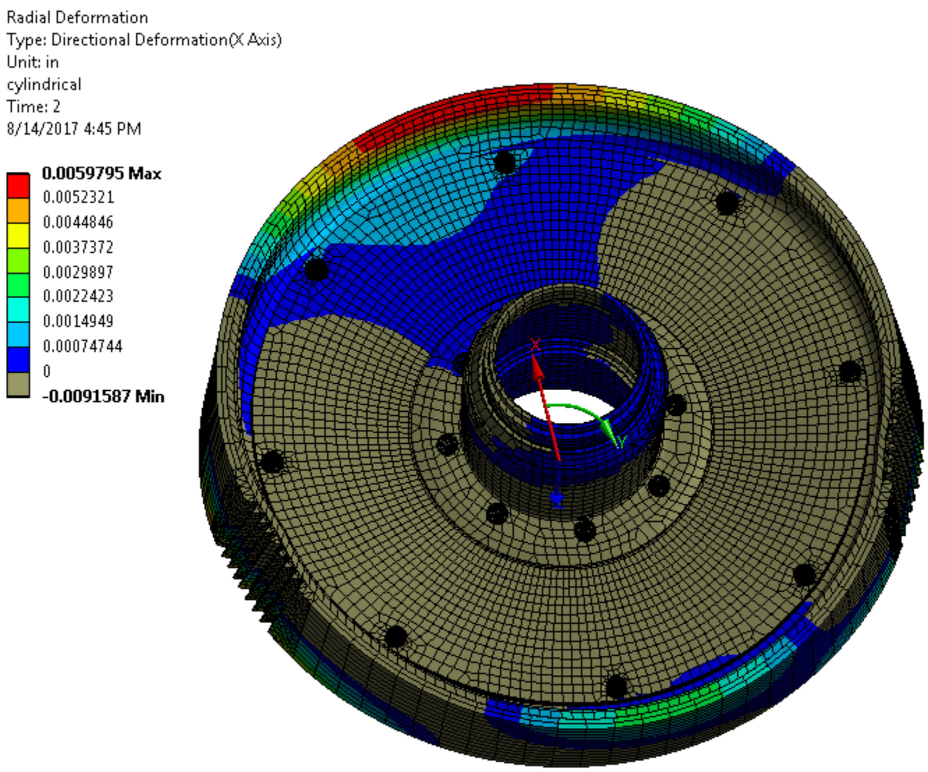


Figure 33: Deformation on conceptual design 2 due to the teeth loads.



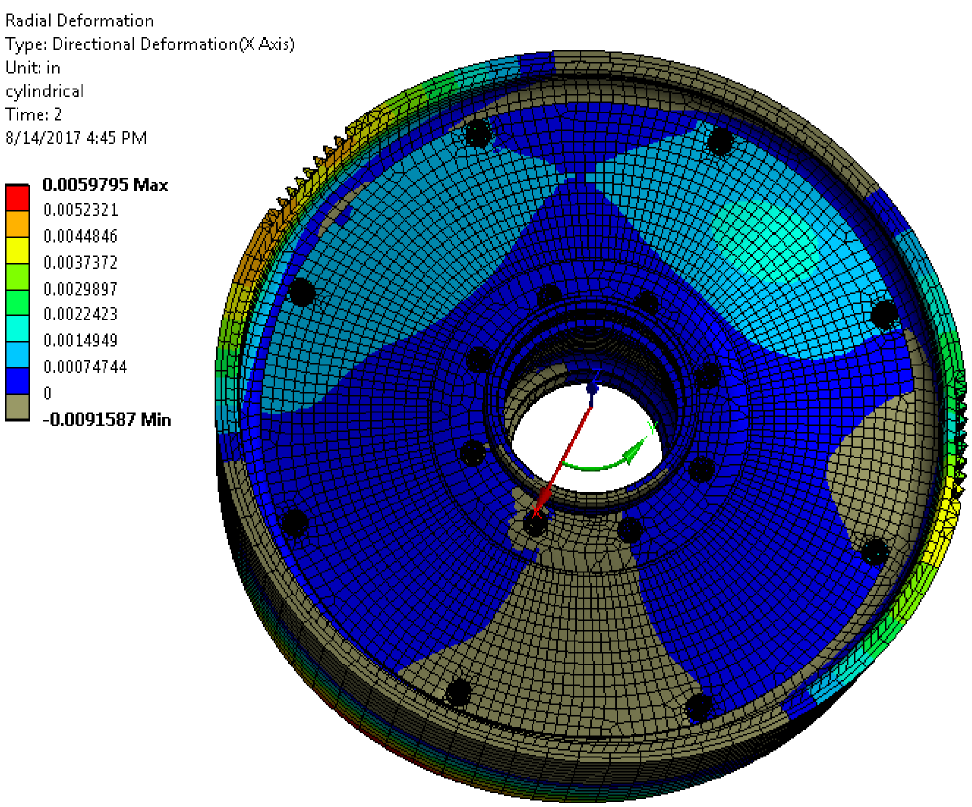


Figure 34: Radial deformation on conceptual design 2 due to the tooth loads.

Going from a contoured web to a flat web placed more of the web in tension as seen in Figure 35. This discovery lead to conceptual design 2 which uses a flat composite web.

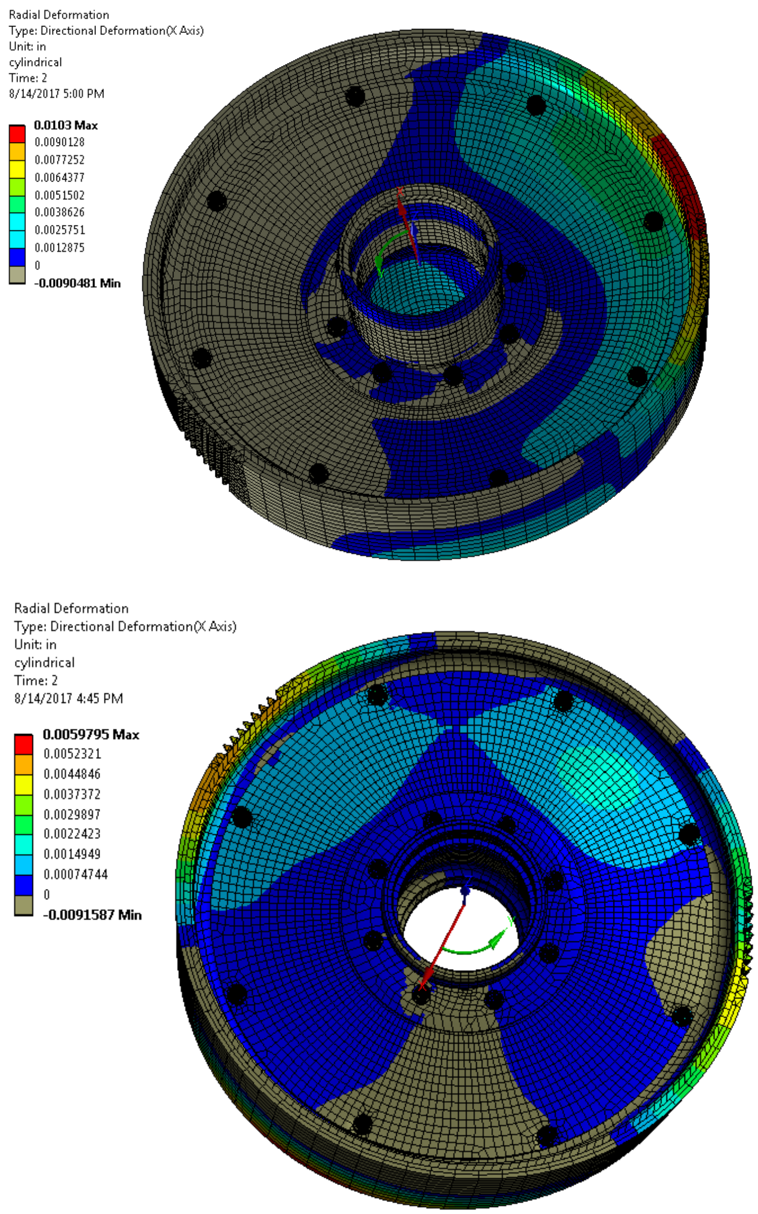


Figure 35: Comparing the radial deformation on conceptual design 1 (Top) and conceptual design 2 (Bottom).

v. Design of Conceptual Design 2

Conceptual design 2, similar to conceptual design 1, includes a metallic outer ring gear, two-piece composite web, two-piece metallic inner ring shaft, and mechanical fasteners both at the outer and inner diameter interfaces. An isometric view is shown in Figure 36 and a cross sectional view is shown in Figure 37. The design includes features required for integration in Drive System Configuration A.

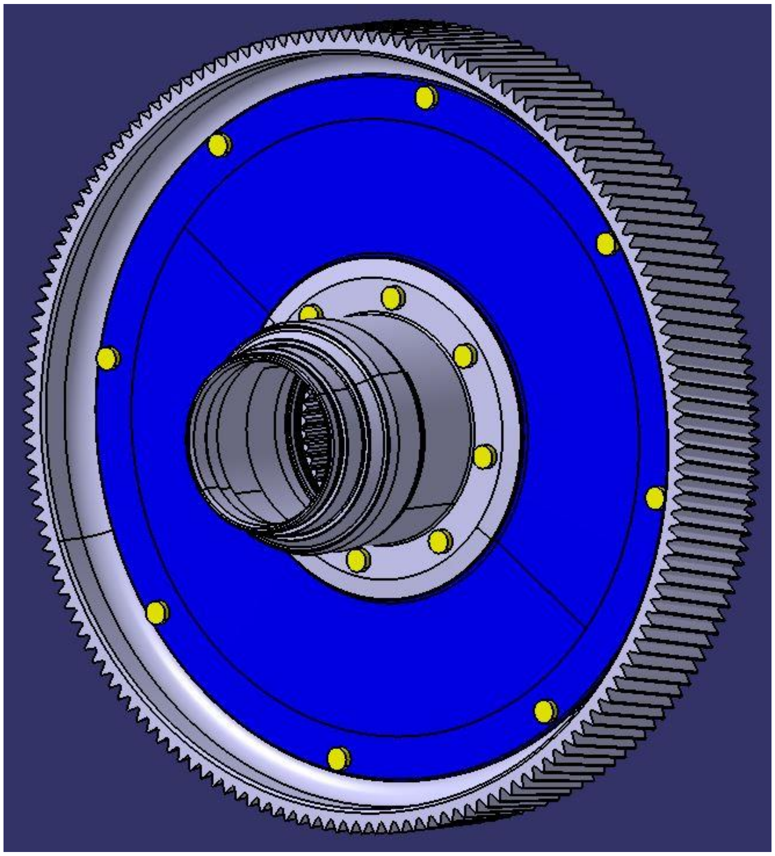


Figure 36: Isometric view of conceptual design 2.

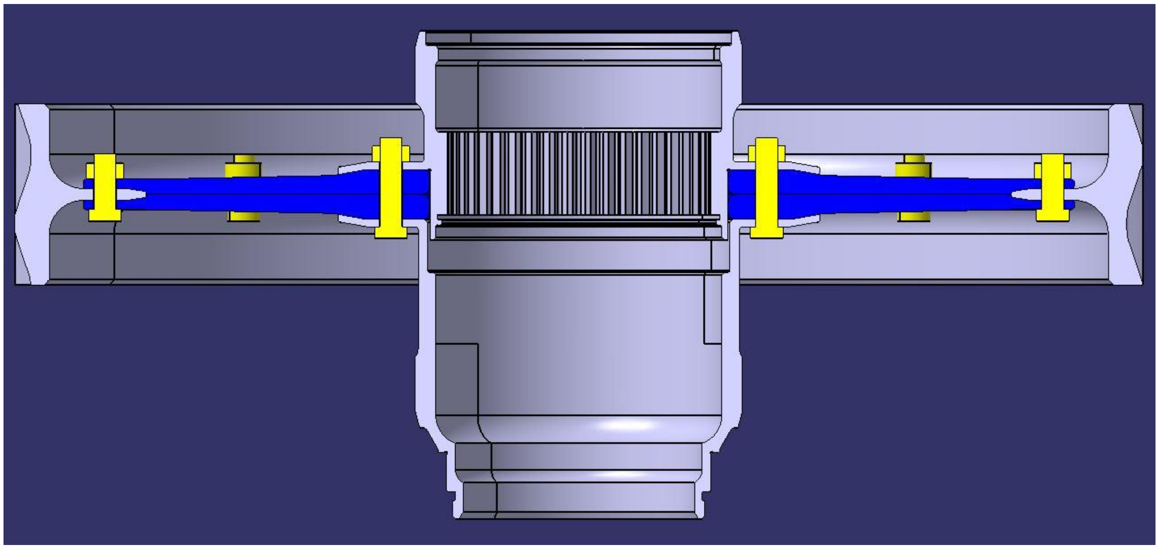


Figure 37: Cross sectional view of conceptual design 2.

With conceptual design 2, the two-piece composite web was designed to be flat rather than contoured as in conceptual design 1 to ensure that more of the web was in tension rather than compression. The location of the gear teeth, spline teeth, bearing raceways, and bearing journal remained as is due to the constraints of Drive System Configuration A. This required that the two inner ring shafts be modified to accommodate for the flat web, with the primary change being a translation of the contoured flanges. Given the constraints of Configuration A, conceptual design 2 maintains adequate clearance from adjacent components allowing for the integration of this conceptual design into the transmission.

For conceptual design 2, the same considerations as discussed for conceptual design 1 regarding the selection and processing of material for both the composite and metallic components applies. Also the same design considerations regarding the interfaces from conceptual design 1 apply to conceptual design 2.

Considering manufacturability, similar to conceptual design 1, conceptual design 2 is capable of being produced with current materials, technology, and processes. As with conceptual design 1, special consideration needs to be taken concerning the heat treatment of the metallic components and the fiber orientation with the composite components. Now, given the simplified geometry of the revised web, the processing is simpler than conceptual design 1. Conceptual design 2 is a feasible and simple design for integration of composite materials in a drive system configuration with current state of the art materials and processing.

vi. Detail Analysis Model Using ANSYS Composite Module

To correctly model the layup of the composite web, the ANSYS Composite PrePost (ACP) module was used (ANSYS Inc, 2017). With this module, the fiber orientation of each layer can be specified. This module also allows for the thickness of the composite to vary. Figure 38 is a copy of the ANSYS brochure where it describes the capabilities of the ACP module. This module makes it possible to model complex composite layups like the one for this gear web. Also, the module calculates the failure mechanism of the different layers using maximum stress, maximum strain, Tsai-Hill, Tsai-Wu and the other failure criteria described in Figure 39. Figure 40 shows the material properties needed for the different failure criteria. At the time of the analysis only the stress and strain limits for IM7 were available. More literature search and or testing will be needed to find the other material properties for the different failure criteria.

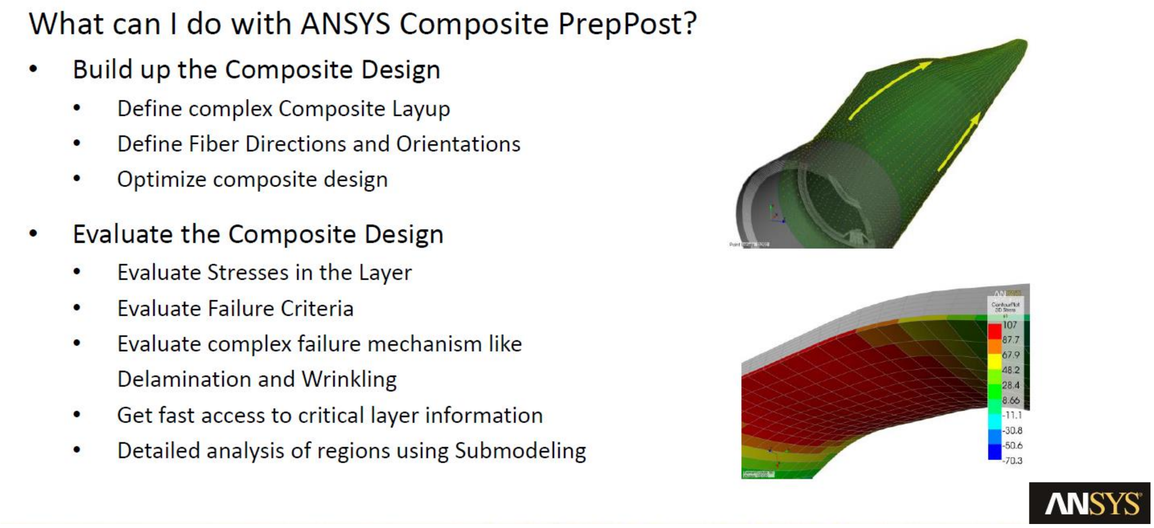


Figure 38: ANSYS brochure describing the capabilities in the ACP module.

Maximum Stress Failure Criteria

- Failure will occur when any one of the stress components exceeds the corresponding strength in that direction
- All stresses are independent. Occurring stresses in one direction wont affect the strength of the material in the other directions

Maximum Strain Failure Criteria

- Failure occurs when at least one of the strain components exceeds the ultimate strain

Tsai-Hill Failure Criteria

- Takes into account interactions between different failure modes
- Based on the von-Mises failure criteria for metals
- The Tsai-Hill failure criteria can not predict different failure modes (Fiber failure, matrix failure, fiber-matrix interface failure, …)

Tsai-Wu Failure Criteria

- Takes into account interactions between different failure modes
- Differences in tensile and compression strengths are considered
- Can not predict different failure modes (Fiber failure, matrix failure, fiber-matrix interface failure, …)
- Requires the definition of interaction parameters *(F_{12}, F_{23}, F_{13})*. The interaction parameters have to be defined by equibiaxial tests which are nearly impossible to perform. Therefore the interaction parameter are either defined by curve fitting or left to the default values of -1.

Figure 39: ANSYS brochure depicting the failure mechanism in the ACP module.

Property	Value	Unit
Density	0.052421	lbm in^-3
Orthotropic Secant Coefficient of Thermal Expansion		
Coefficient of Thermal Expansion		
Zero-Thermal-Strain Reference Temperature	68	F
Orthotropic Elasticity		
Young's Modulus X direction	8.5804E+06	psi
Young's Modulus Y direction	8.5804E+06	psi
Young's Modulus Z direction	1.0878E+06	psi
Poisson's Ratio XY	0.04	
Poisson's Ratio YZ	0.3	
Poisson's Ratio XZ	0.3	
Shear Modulus XY	2.5382E+06	psi
Shear Modulus YZ	3.916E+05	psi
Shear Modulus XZ	3.916E+05	psi
Orthotropic Stress Limits		
Tensile X direction	74404	psi
Tensile Y direction	74404	psi
Tensile Z direction	7251.9	psi
Compressive X direction	-63381	psi
Compressive Y direction	-63381	psi
Compressive Z direction	-21756	psi
Shear XY	17405	psi
Shear YZ	7977.1	psi
Shear XZ	7977.1	psi
Orthotropic Strain Limits		
Tensile X direction	0.0092	
Tensile Y direction	0.0092	
Tensile Z direction	0.0078	
Compressive X direction	-0.0084	
Compressive Y direction	-0.0084	
Compressive Z direction	-0.011	
Shear XY	0.02	
Shear YZ	0.015	
Shear XZ	0.015	
Tsai-Wu Constants		
Coupling Coefficient XY	-1	
Coupling Coefficient YZ	-1	
Coupling Coefficient XZ	-1	
Ply Type		
Type	Woven	

Figure 40: Example of the material properties needed by the ACP module to calculate the failure criteria of the different layers.

Modeling the composite layup required specifying a starting layer and a surface where the layup terminates as seen in Figure 41. The starting layer was copied 54 times and stacked on top of each other to represent the layers needed to fill the thickness of the web. Each layer extends to the termination surface where each layer is truncated as it bisects the termination surface.

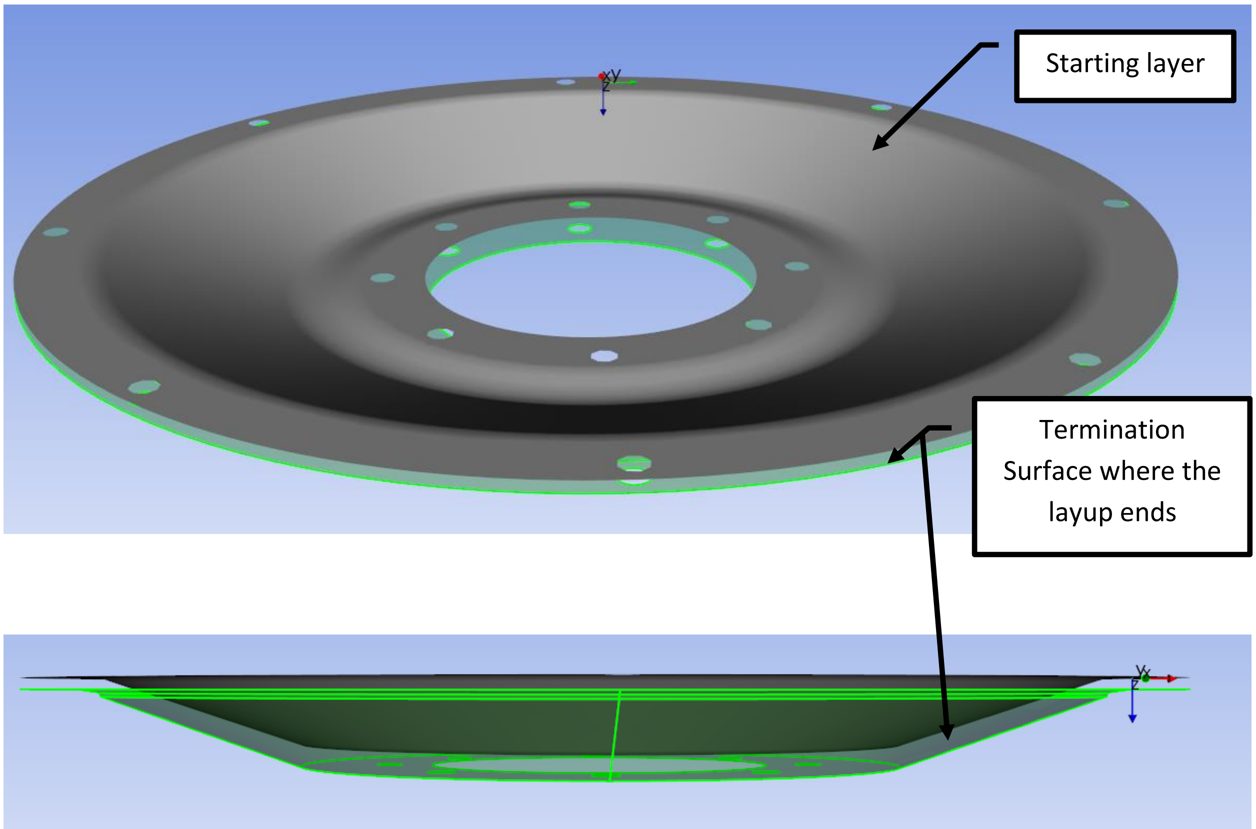


Figure 41: Surfaces used to define the composite layup.

In the ACP module, the tooling surfaces that define the boundaries of the composite geometry are specified by a starting and termination surface. The first layer is defined by the starting surface. This surface is repeated 54 times and stacked on top of each other to fill the volume between the starting and termination surface. Layers crossing the termination surface are terminated by this surface. Figure 42 shows how the layers are truncated at the termination layer.

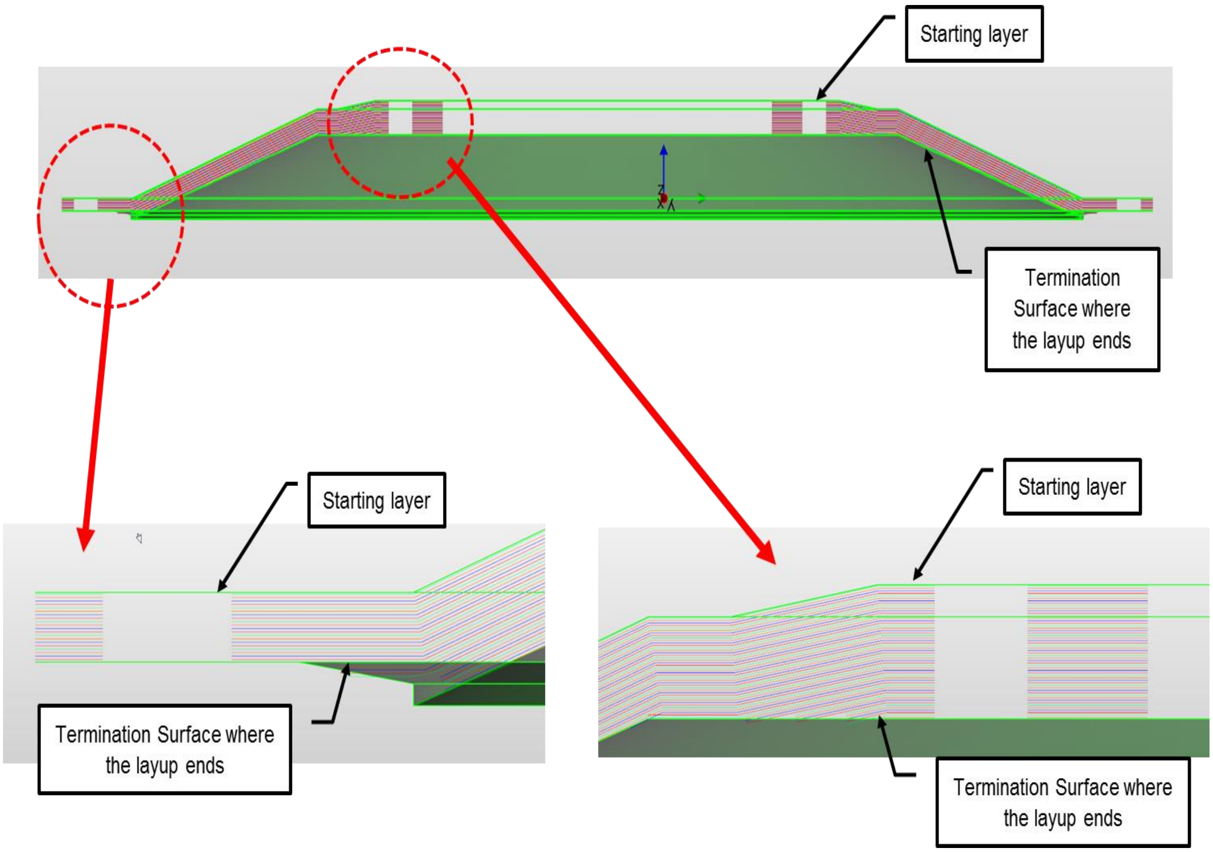


Figure 42: Cross section showing how the layers are truncated by the termination surface.

Orientation of the fibers in each layer can be specified. A coordinate system is specified for each layer and the fibers are oriented with respect to this coordinate system. In the initial model, the fibers in the first layer were oriented in the 0° orientation. The second layer was oriented in the 45° orientation. Third layer was oriented in the -45° orientation. The forth layer was oriented in the 90° orientation. This pattern was repeated until all 54 layers were specified. See Figure 43 for a visual description of the fiber orientation in the first four layers.

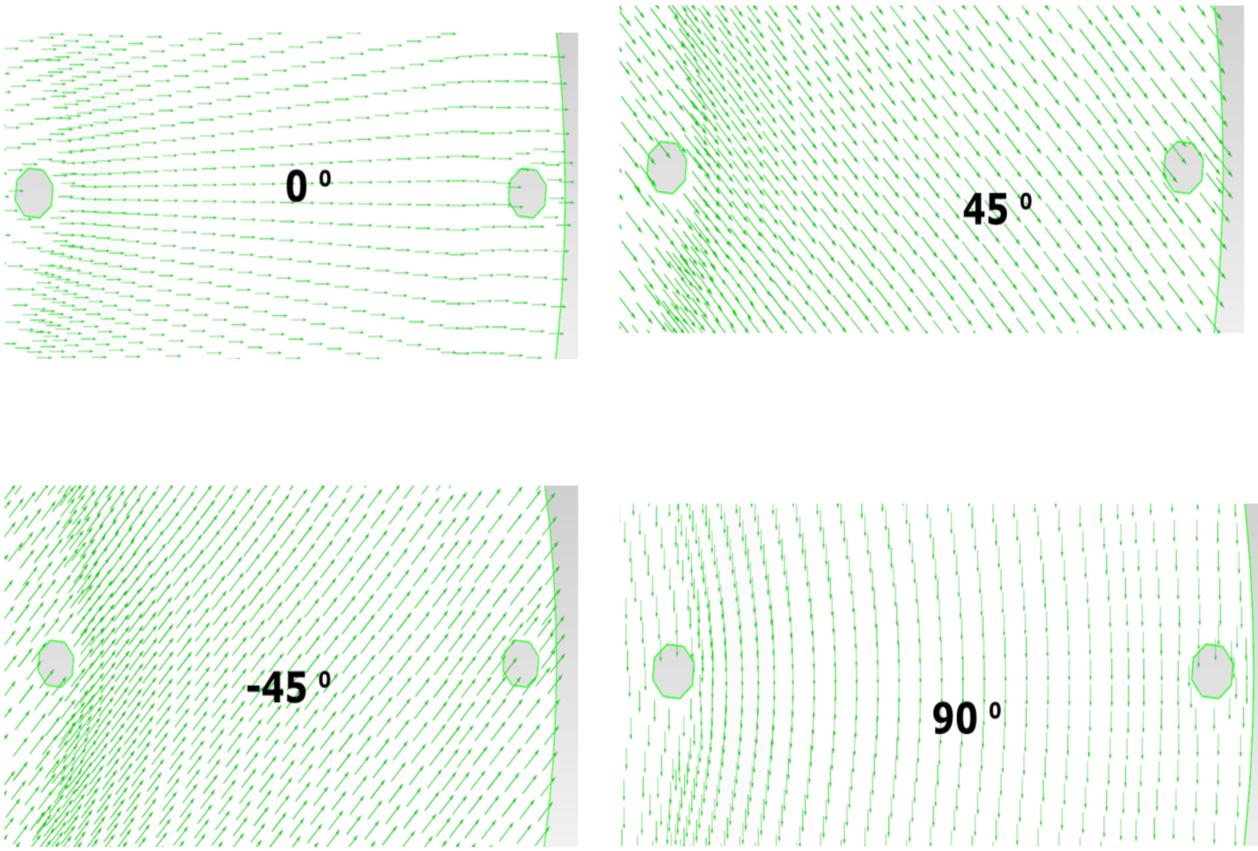


Figure 43: Orientation of the first four layers in the layup.

Sections of the composite web were created using the ANSYS ACP module and then assembled with the rest of the bull gear geometry to create a solid model of the hybrid bull gear. Figure 44 shows the mesh details for the top section of the composite web. The composite web was designed to replicate the shape of the metal web. This created a contoured composite web with a ticker section on the inner diameter where it attaches to the metallic flanges and a thinner section where it attaches to the outer metallic ring.

As described before, the composite web was designed to have a thicker section on the ID and a thinner section on the OD to replicated the geometry of the metallic bull gear. On Figure 44, one can see how the number of elements in the vertical direction vary to fill the volume between the starting and termination surface. Figure 45 shows the mesh for the composite and metal components assembled together to create the bull gear for conceptual design 1.

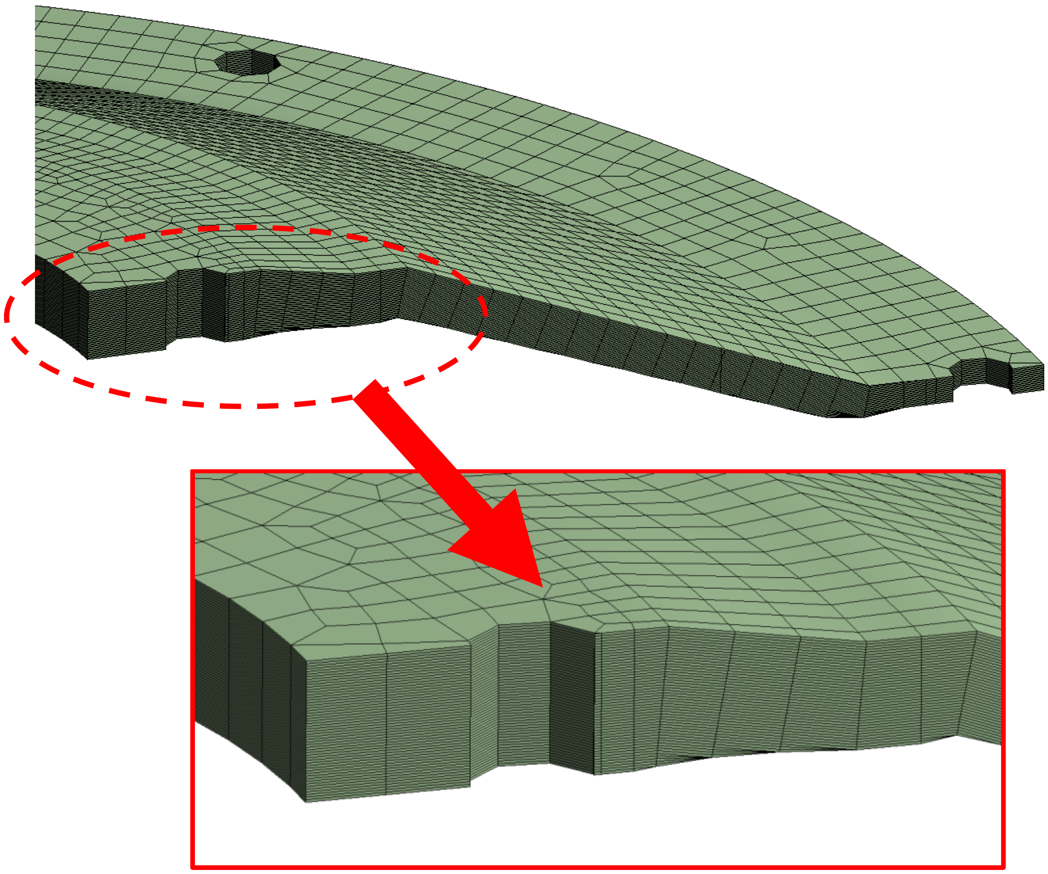


Figure 44: Mesh for the top section of the composite web in conceptual design 1.

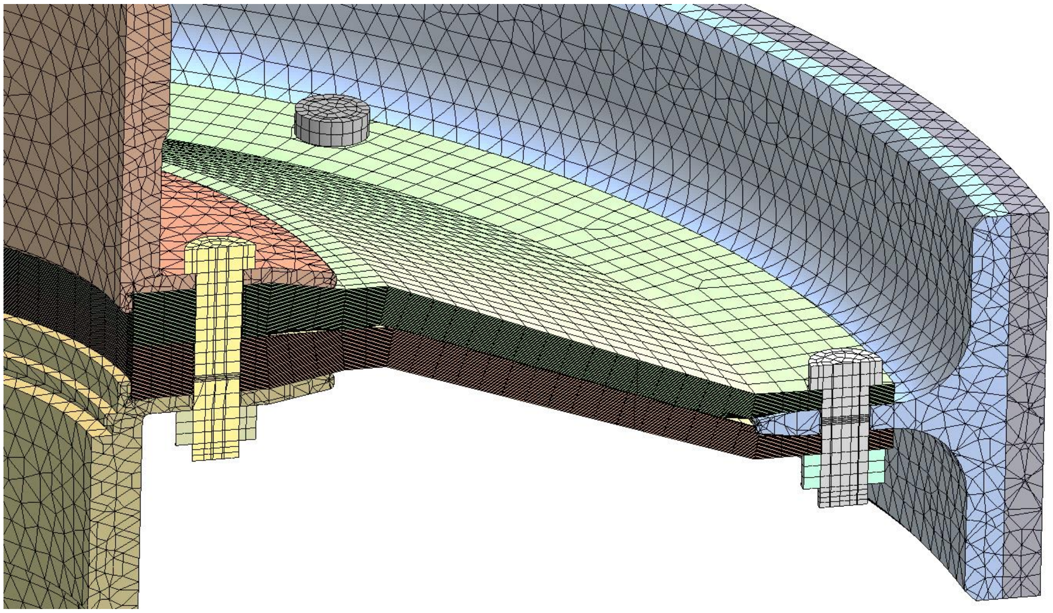


Figure 45: Cross section of the meshed assembly for conceptual design 1

With the geometry built using the ACP module, a more realistic analysis was performed on the composite gear. For the first model, it was assumed that the composite was attached to the metal using an adhesive. This was simulated with bonded contacts between the composite sections 1 and 2 and the metal parts of the bull gear (see Figure 46). Teeth loads described in Figure 23 and the restrains on the bearing surfaces previously described in Figure 24 were also applied to this model. The fiber layup described in Figure 43 was also used in this model.

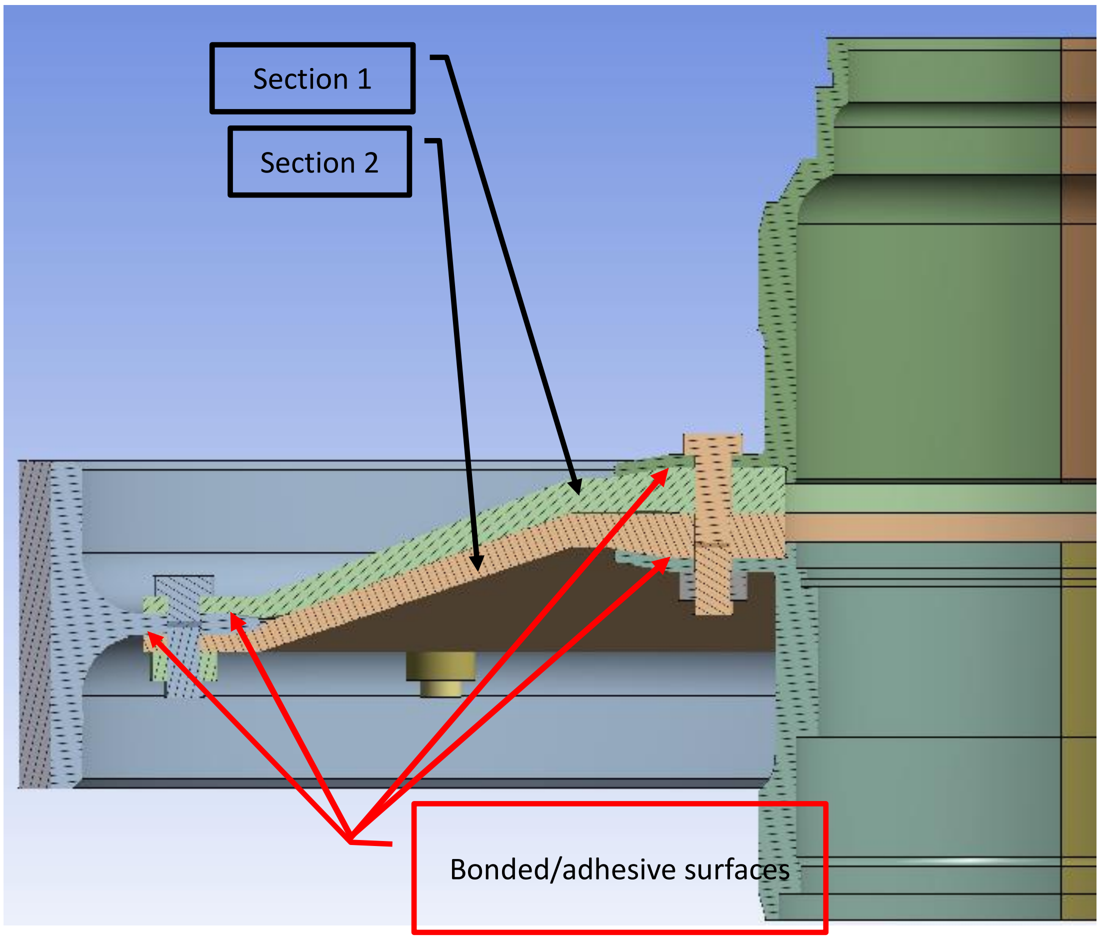


Figure 46: Geometry used to model conceptual design 1 with adhesive between the metal and composite.

As with the simplified model, a large part of the web is in compression as shown in Figure 47. Figure 48 shows the total deformation for this modeled geometry.

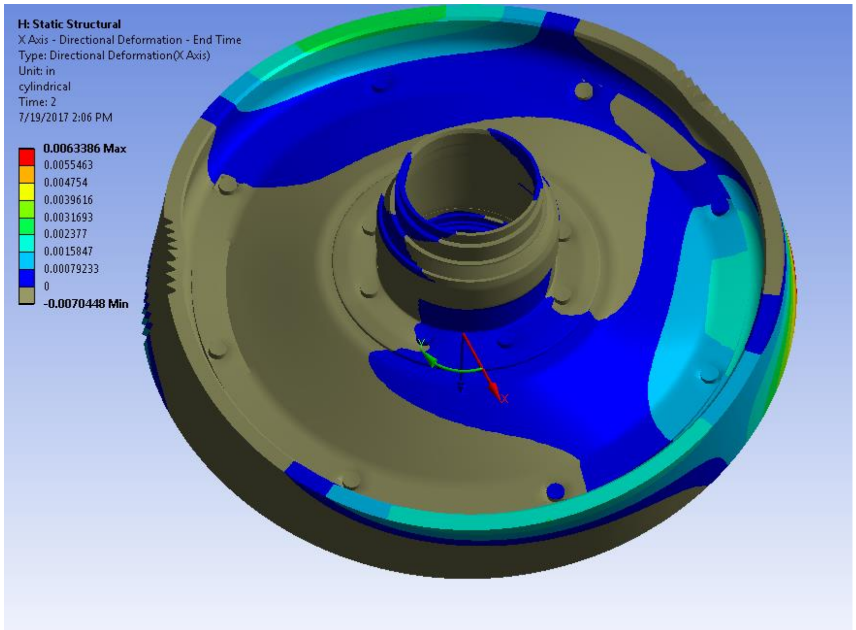


Figure 47: Radial deformation for conceptual design 1 using the ACP created geometry.

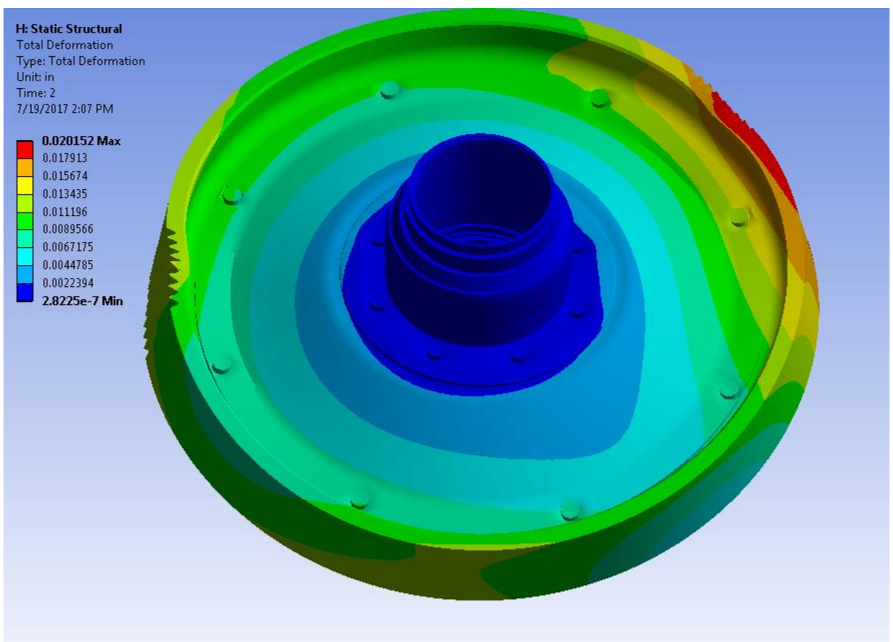


Figure 48: Total deformation for conceptual design 1 using the ACP created geometry.

The ANSYS ACP module is capable of predicting failure of the composite layers. For this analysis, the failure was depicted by the inverse reserve factor (IRF), which is the ultimate load divided by the ultimate strength. An IRF value greater than 1 predicts failure in the element in that layer. Plots of the IRF for sections 1 and 2 of the composite web predicts a maximum IRF factor of 0.76 which means no composite failure for this configuration (see Figure 49 and Figure 50).

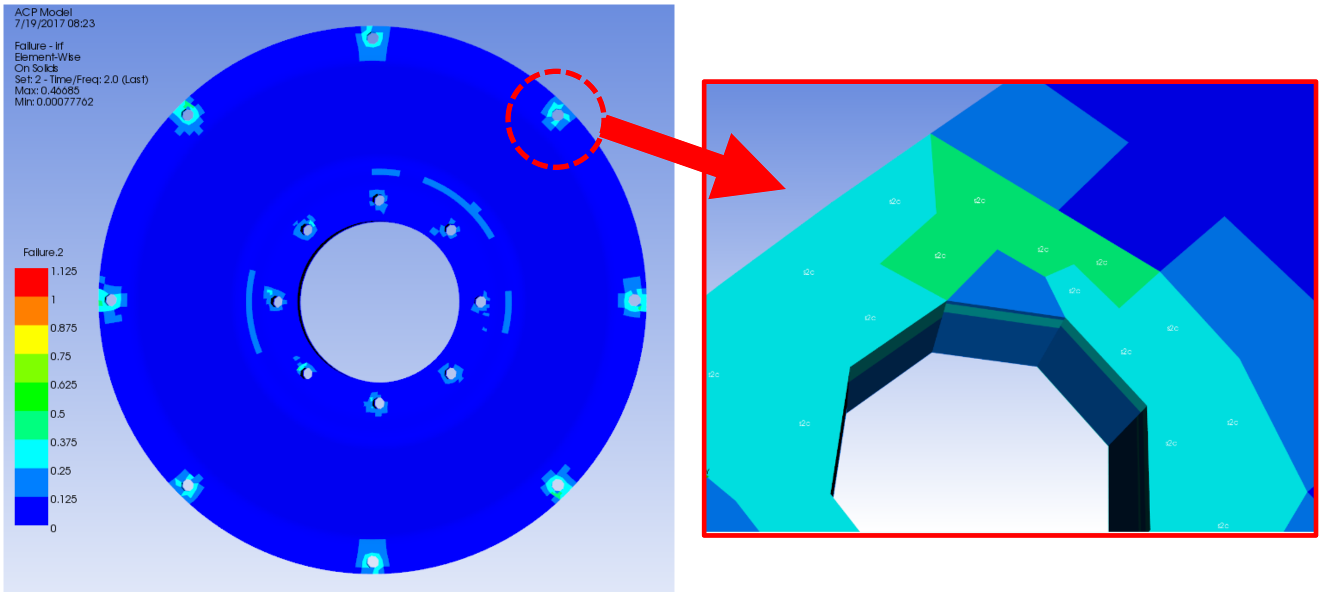


Figure 49: Inverse Reserve Factor for Section 1.

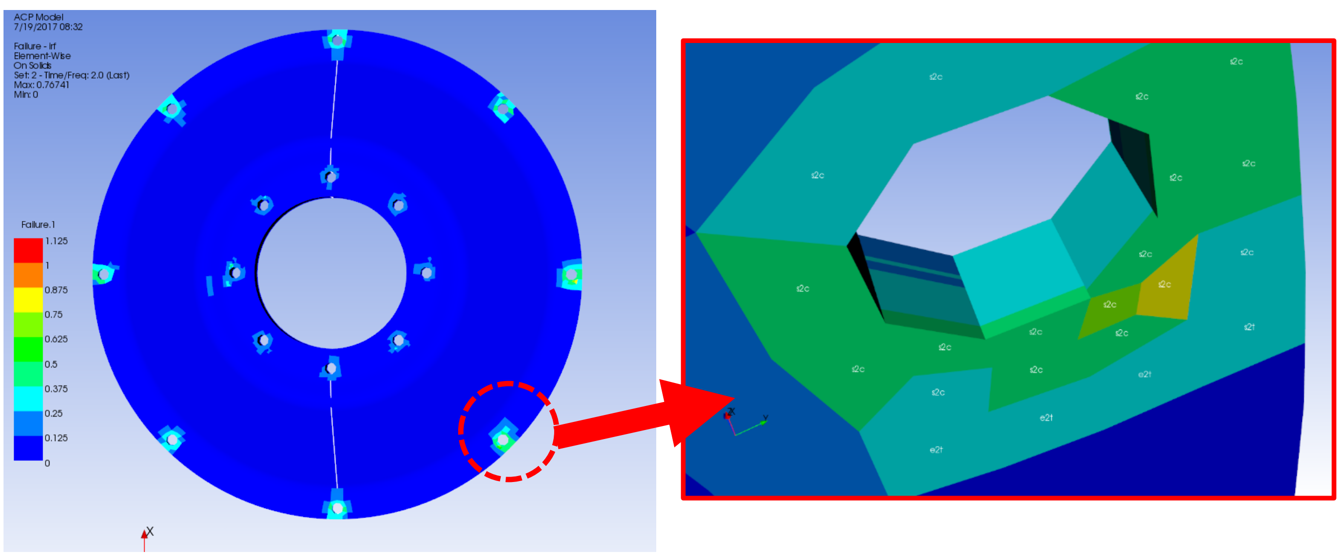


Figure 50: Inverse Reverse Factor for Section 2.

The next analysis assumed the adhesive bond between the epoxy and the metal had failed and the bolts must carry the load. This was simulated by creating sliding contact between the composite and the metal (see Figure 51). Plots of the IRF factor for sections 1 and 2 of the composite web predict a maximum IRF factor of 5.12 which means parts of the composite will fail. This failure occurs in the composite holes where the bolts transfer the loads (see Figure 49 and Figure 50). Also, notice how multiple layers in the composite fail.

If the bolts need to carrying the load, the composite sections around the holes must be modified to be able to carry the loads from the bolts. This can be accomplished by putting glass bushings in the composite holes which has been done with other composite components on rotorcraft. The details of this glass bushing need to be determined in future work.

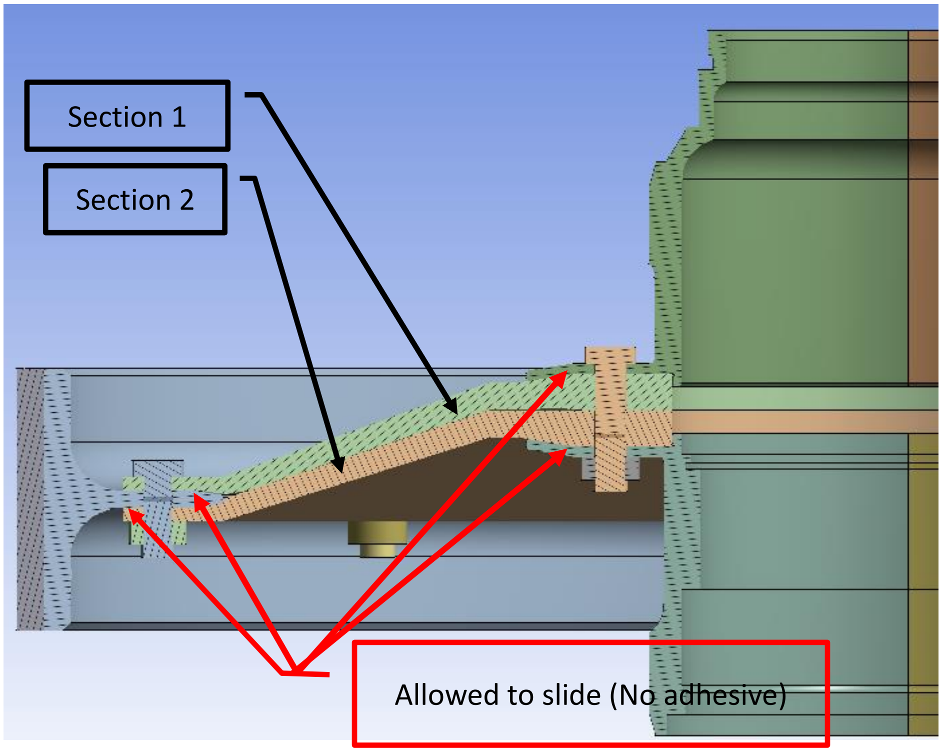


Figure 51: Total deformation for conceptual design 1 using the ACP created geometry and the bolts transfer the load between the composite and the steel.

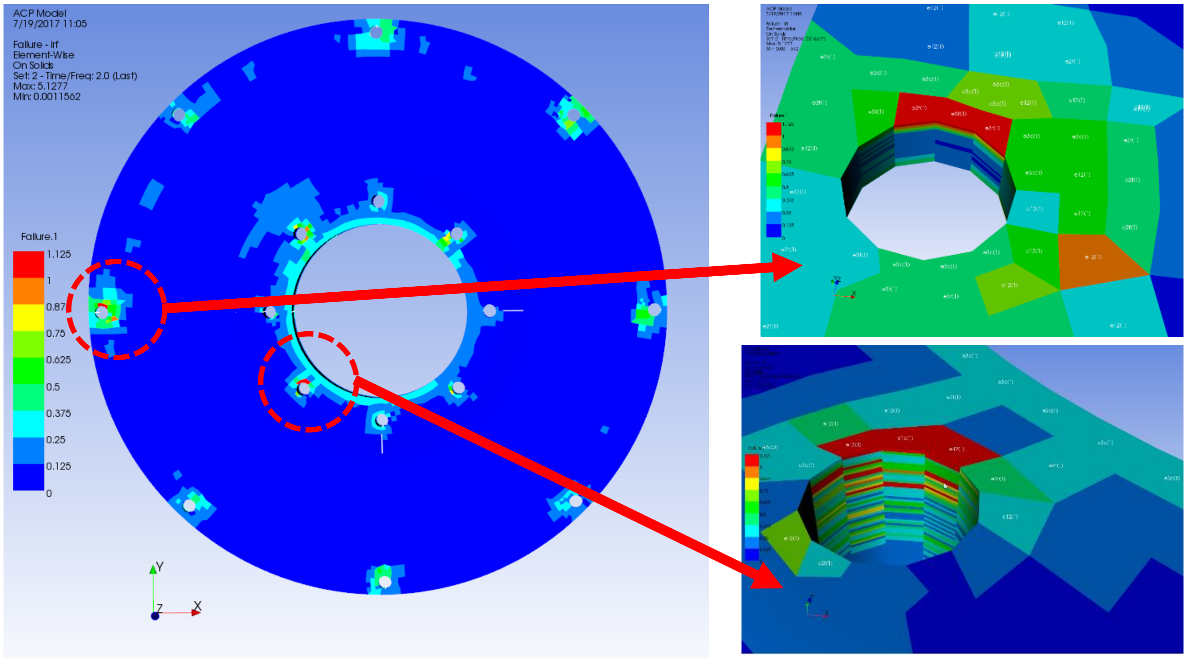


Figure 52: Inverse Reserve Factor for Section 1 in conceptual design 1.

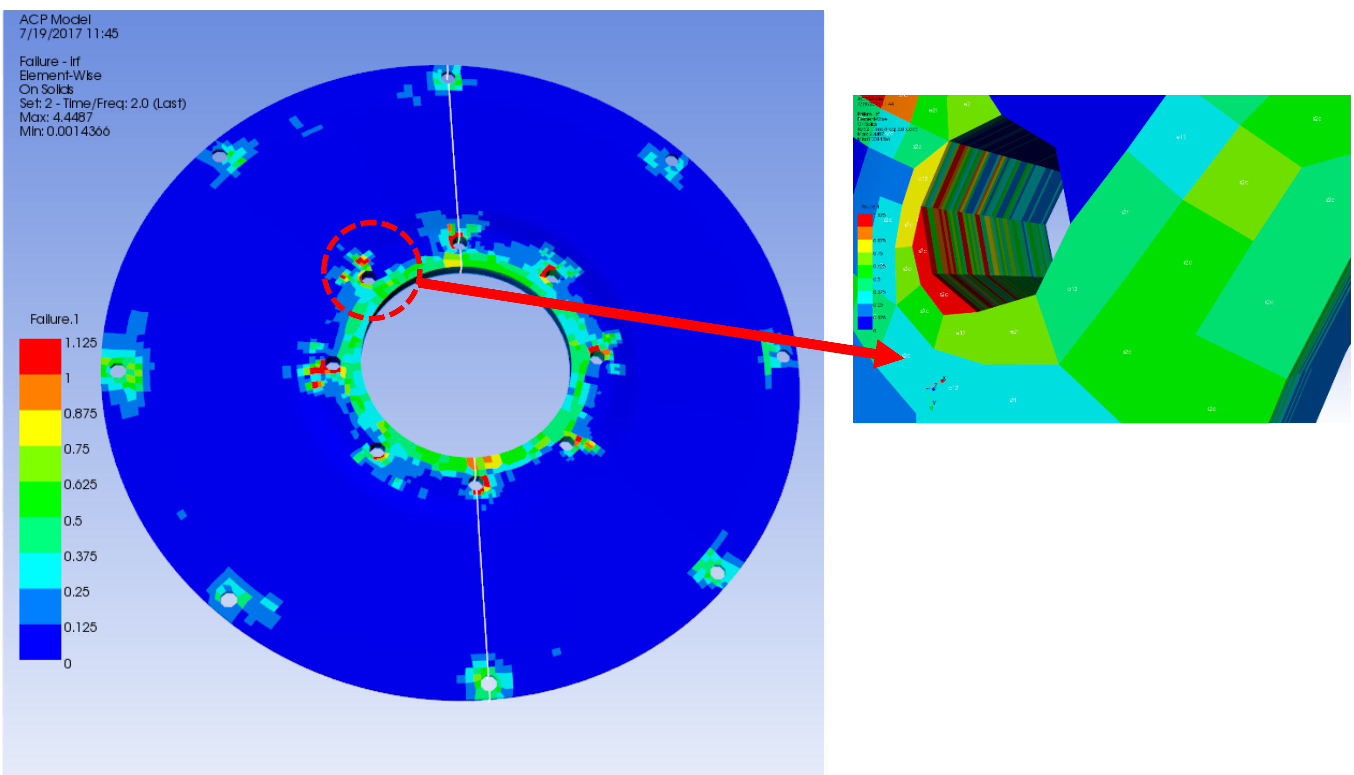


Figure 53: Inverse Reserve Factor for Section 2 in conceptual design 1.

Conceptual design 2 with the flat web was also modeled using the ACP module. For the first model, it was assumed that the composite was attached to the metal using an adhesive. This was simulated with bonded contacts between composite sections 1 and 2 and the metal parts of the bull gear. Teeth loads described in Figure 23 and the restrains on the bearing surfaces previously described in Figure 24 were also applied to this model. The fiber layup described in Figure 55 was also used in this model. Figure 56 shows the radial and total deformation for conceptual design 2.

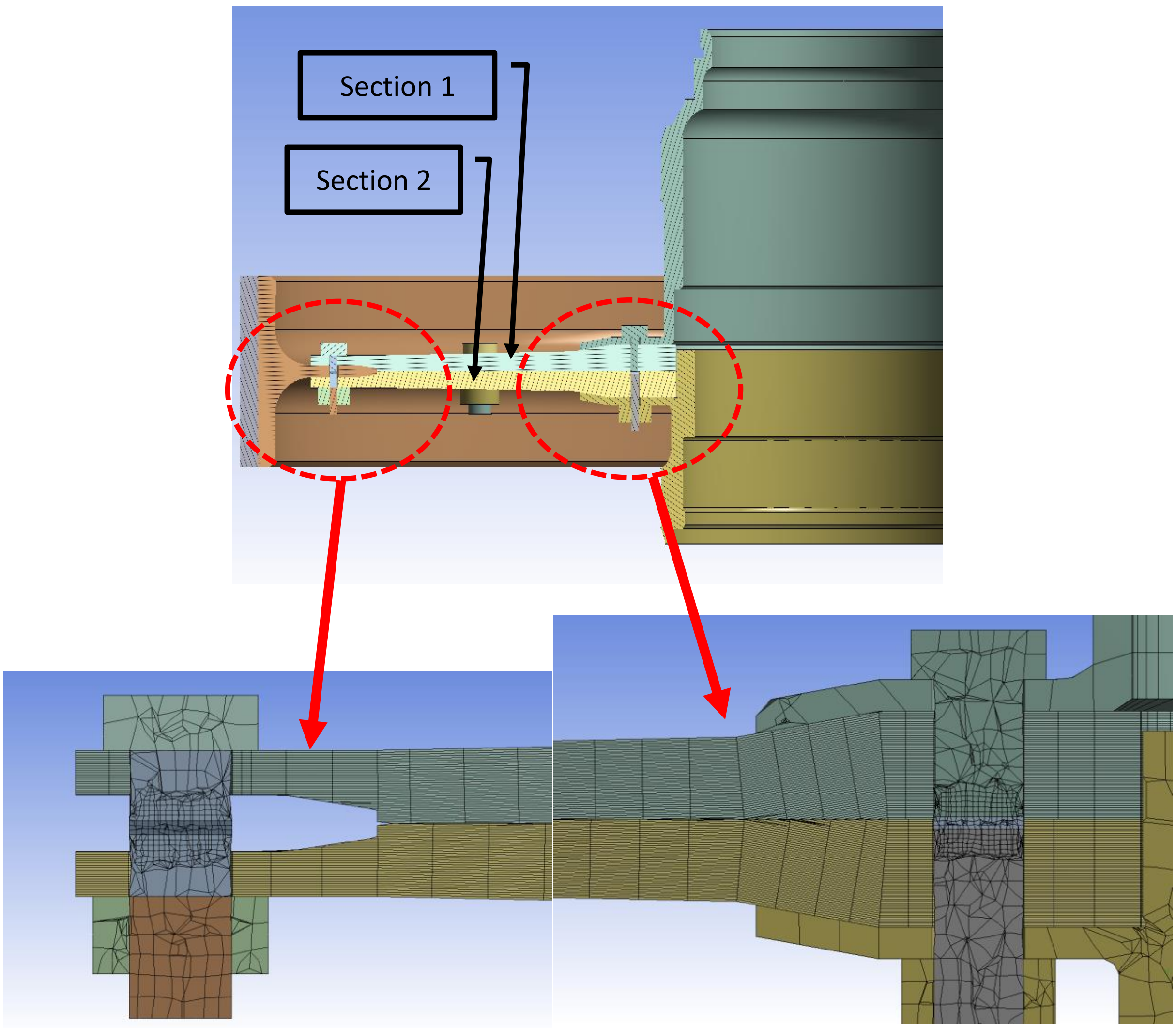


Figure 54: Geometry and mesh created for conceptual design 2 using the ACP module.

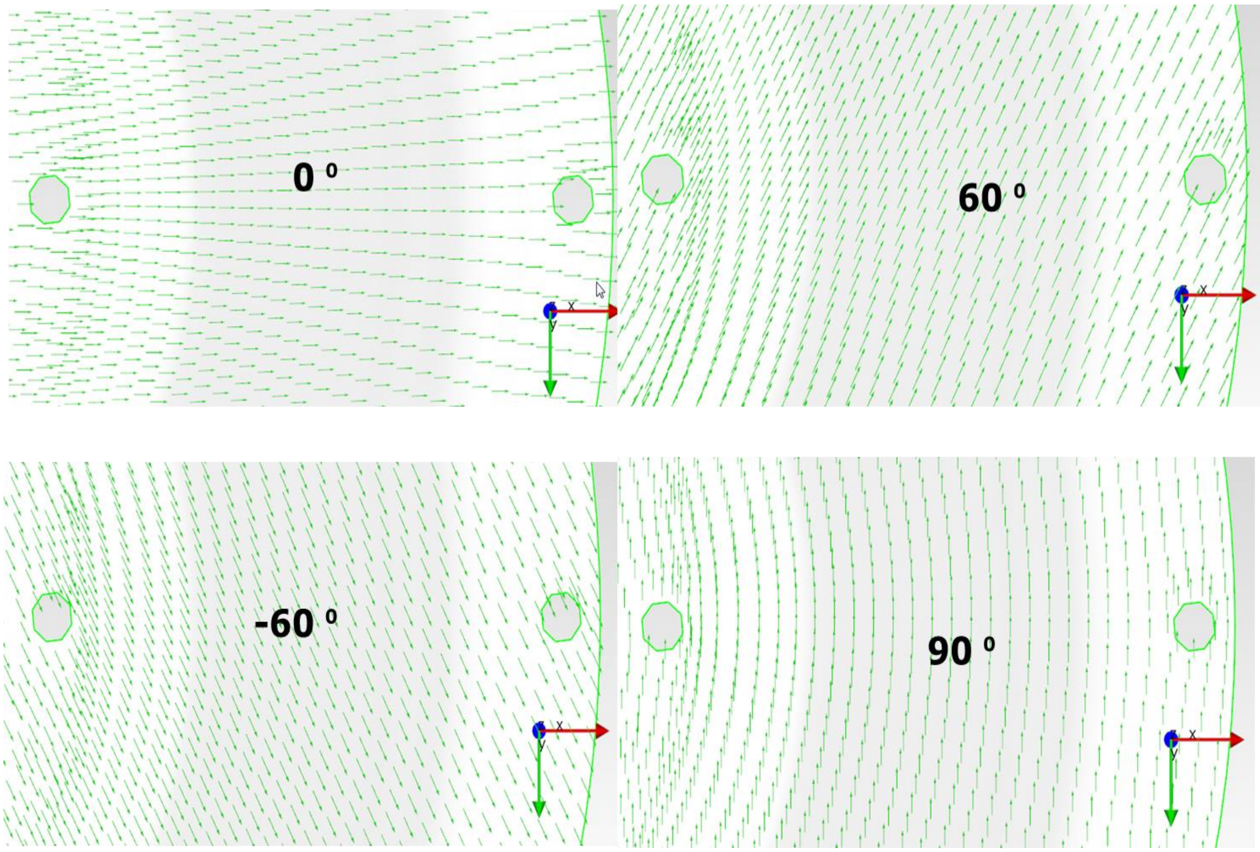


Figure 55: Fiber layout for the first 4 layers in the model of conceptual design 2.

Figure 56 through Figure 58 show the results for conceptual design 2. Radial and total deformation can be seen in Figure 56. Plots of the IRF for sections 1 and 2 of the composite web predicts a maximum IRF factor of 0.78 which means no composite failure for this configuration.

Due to time constraints, conceptual design 2 was not modeled with sliding contacts to simulate the adhesive failing and the bolts carrying the loads. The analysis for conceptual design 1 shows that the composite will fail at the holes and glass bushings or other modifications will be needed at the holes to better distribute the loads on the composite holes. This analysis can be performed on future work for conceptual design 2.

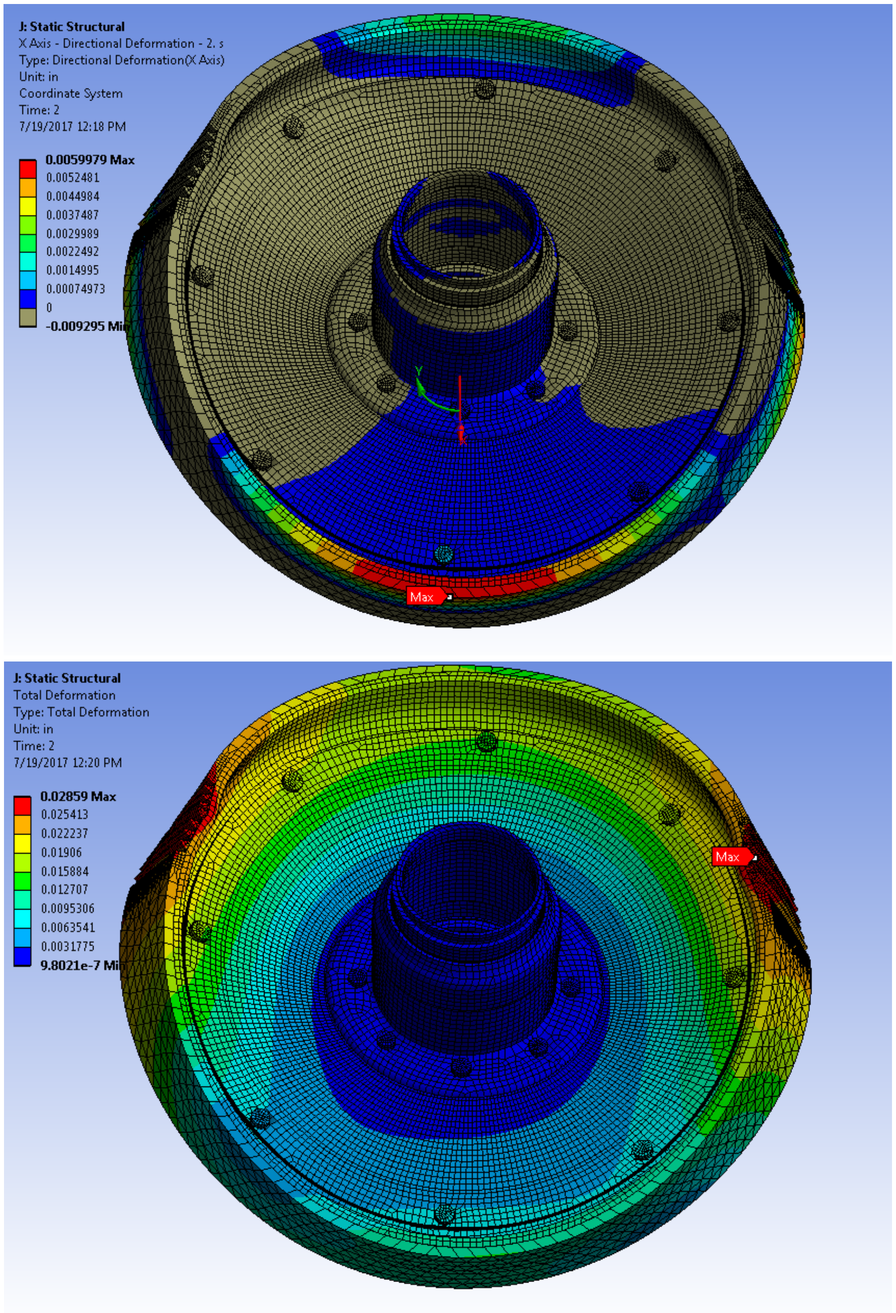


Figure 56: Top figure shows the radial deformation for conceptual design 2 using the ACP created geometry. The bottom figure shows the total deformation for conceptual design 2.

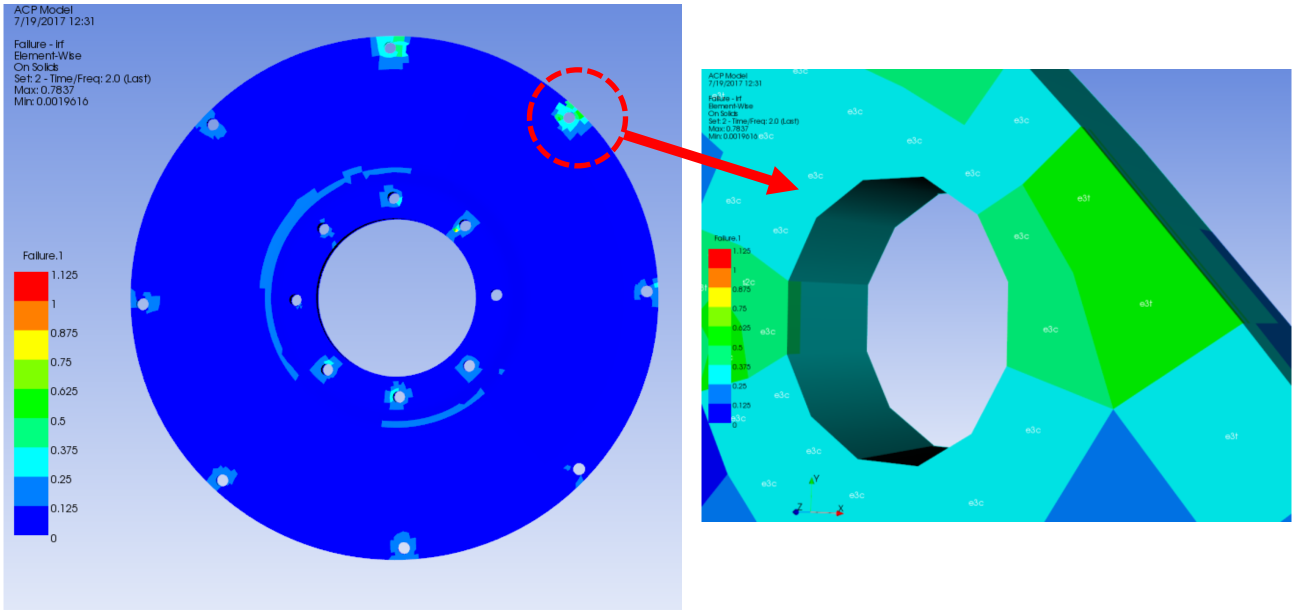


Figure 57: Inverse Reserve Factor for Section 1 in conceptual design 2.

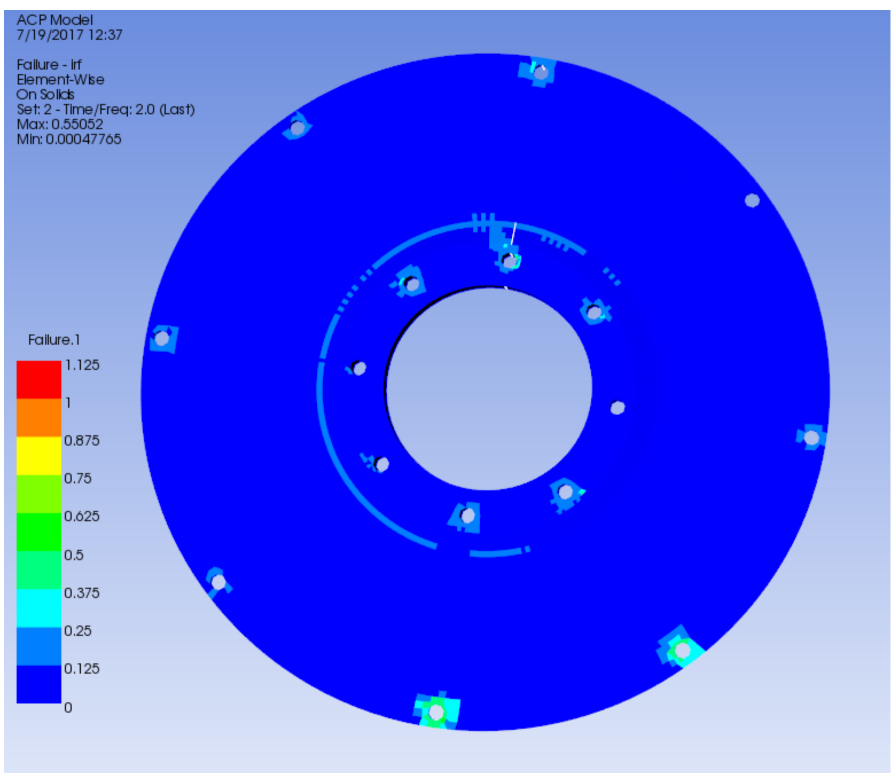


Figure 58: Inverse Reserve Factor for Section 2 in conceptual design 2.

IV. Advanced Concept

While the need for redundancy has been established for the integration of composite materials in power transmission gears, which was achieved through the use of mechanical fasteners in conceptual designs 1 and 2. The mechanical fasteners result in an increased weight which negatively impacts power/weight, and by having mechanical fasteners, a greater potential for foreign object debris (FOD) exists. To overcome the need for mechanical fasteners, a mechanical interlock shall be incorporated at the outer interface between the outer ring gear and the composite web. Similar to conceptual designs 1 and 2, the primary path of load transfer is achieved by adhesive at the interfaces, but in the instance where the integrity of the bond is compromised, the redundant load path offered by the mechanical interlock allows for the load to be transferred for an adequate amount of time for a rotorcraft to safely land.

In order to transfer the load between the outer ring gear and the composite web, a unique combination of geometry enables the implementation of a mechanical interlock at this interface. The mechanical interlock was incorporated into the baseline bull gear as shown in Figure 59. An exploded view of the advanced concept gear is shown in Figure 60. In looking at the isometric view in Figure 59 a subtle lobed profile is present at the interface between the outer ring gear and the composite web in the circumferential direction. The profile of this feature can be seen in greater detail in Figure 61. Looking at the exploded view in Figure 60 and the overview of the composite web in Figure 62, the secondary locking feature is shown. This feature incorporates protrusions on the composite web and indentions on the outer ring gear. These features nestle into one another as shown in Figure 63.

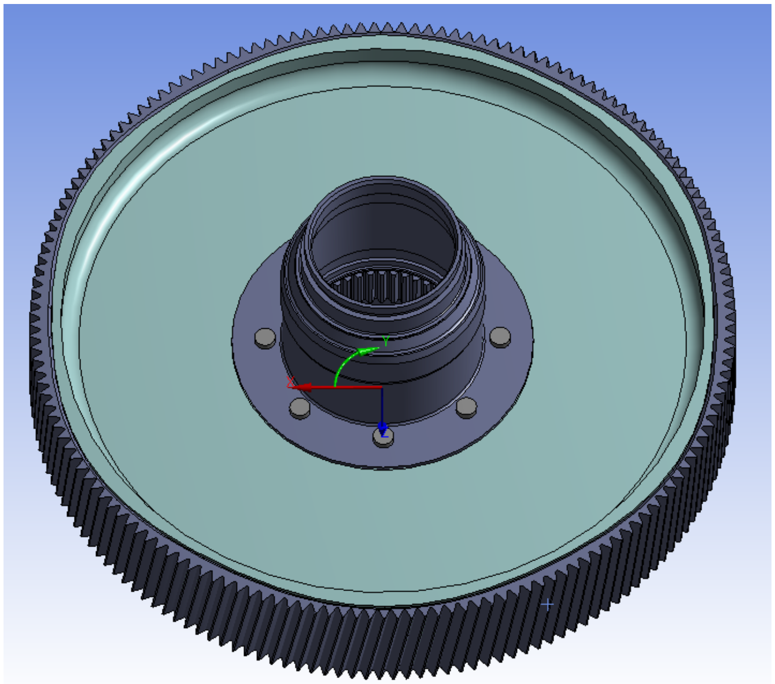


Figure 59: Isometric view of hybrid gear with mechanical interlock concept.

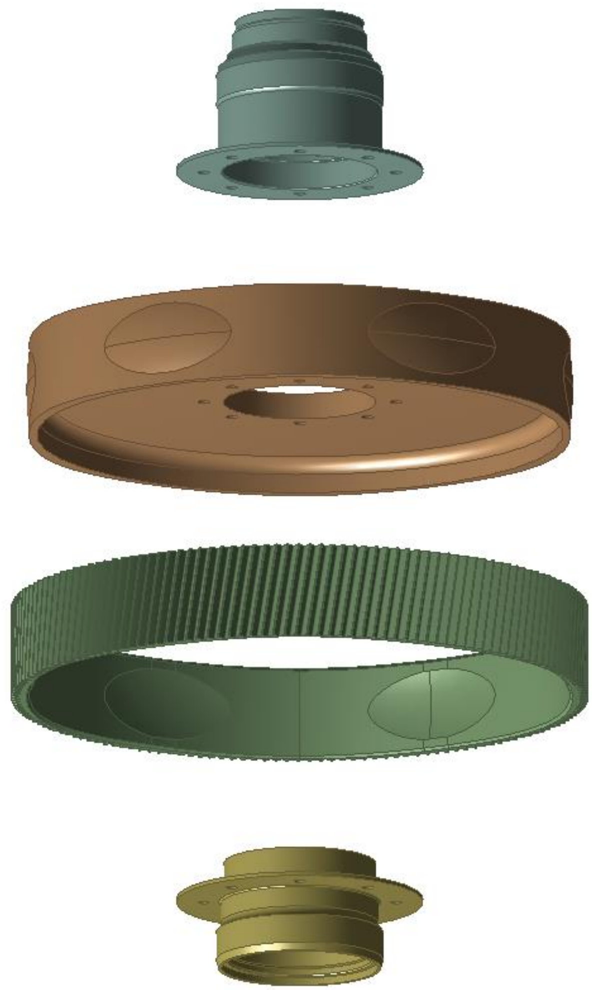


Figure 60: Exploded view of hybrid gear with mechanical interlock concept (mechanical fasteners at inner interface not shown).

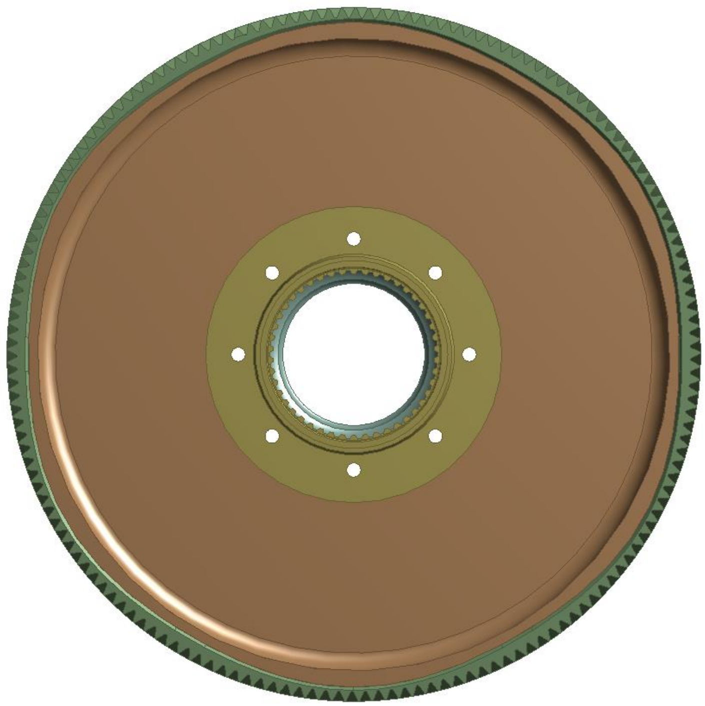


Figure 61: Top view of hybrid gear with mechanical interlock concept (mechanical fasteners at inner interface not shown).

Figure 62: Composite web with protrusions for mechanical interlocking capabilities of hybrid gear with mechanical interlock concept.

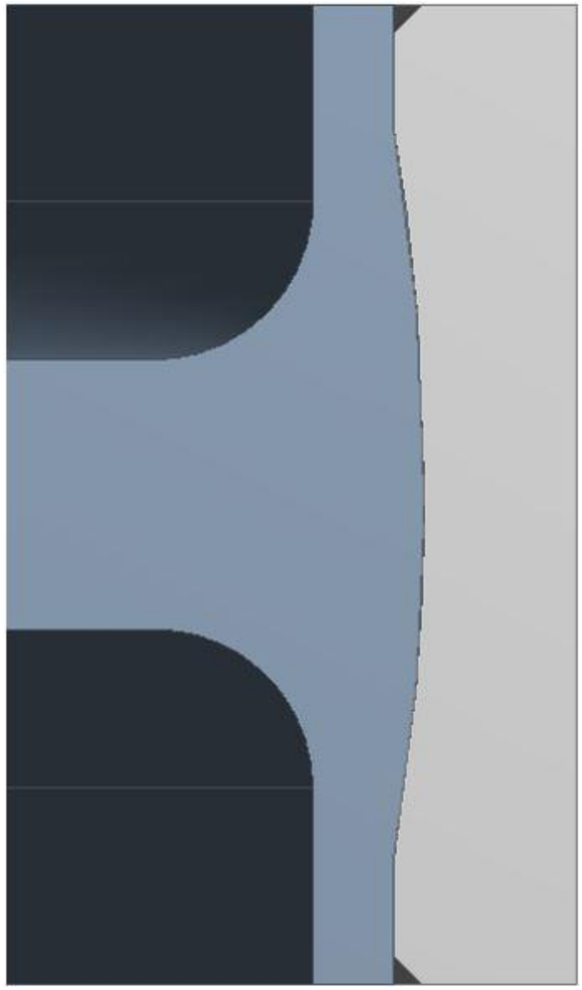


Figure 63: Detail cross sectional view of outer interface highlighting protrusion/indention of hybrid gear with mechanical interlock concept.

By incorporating both the lobed feature and the protrusion/indention feature at the interface between the composite and metallic components, a mechanical interlock is achieved that restrains an adequate number of degrees of freedom for the assembly. While only one configuration is shown above, multiple configurations are feasible. These configurations are possible due to the flexibility with the orientation, uniformity, frequency, and distribution of the protrusion/indention feature, the location of the protrusion and indention on either the metallic or composite structure, and the profile of the lobed feature.

In order to manufacture this gear, a co-cured process is likely required where the composite material and adhesive bond between the composite and metallic components are performed at the same time. Following curing, post machining would be performed. Post machining would include operations such as drilling the holes for the mechanical fasteners at the inner interface and final grinding of the gear teeth.

Overall this hybrid gear with a mechanical interlock at the outer interface benefits the performance of the transmission by reducing weight through a reduction in the amount of metallic material for the outer ring gear inner surfaces and removing the requirement for mechanical fasteners at the outer interface. This concept is lighter than the baseline design, redundant, and can be manufactured with current state of the art materials and processes.

V. Technical Challenges and Recommendations

While the benefits of incorporating composite materials in advanced drive system configurations are highly desirable, there are specific technical challenges that need to be addressed before such configurations can be implemented.

The primary challenge is due to the operational limitations with the composite material, especially at high temperatures. Current rotorcraft transmissions are capable of safely operating at temperatures well above the upper threshold of the composite materials. In order to meet the high operating temperatures required, a resin such as Cytec’s CYCOM 5250-4 bismaleimide can be used which has a service temperature up to 400°F. Components inside a transmission can operate at temperatures over 450°F and during a loss of lubrication event these temperatures can be well above 600°F.

To overcome these challenges, further development with composite materials are required. In addition to improved material property development, further considerations with heat rejection inside the transmission should be explored that would reduce the high operating temperatures. Other considerations would be location of the composite materials in the transmission as various zones can experience different temperatures due to proximity to various features of the transmission.

The secondary challenge with the above conceptual designs and advanced concept is the distortion with the outer ring gear component. Due to its size and shape, it is anticipated that during heat treatment with carburizing gear steel, distortion will occur based on past experiences. Given that weight improvement is critical, by removing the amount of metallic material being proposed, it increases the likelihood and extent of distortion to be observed. Even though the understanding of distortion is known going into heat treatment, predicting the extent and nature of the distortion will be difficult as well, making mitigation efforts challenging and iterative.

To overcome this challenge two paths are recommended. The first path would involve heat treatment trials with a carburizing gear steel, such as X53, where similar geometry is utilized to develop an adequate process and restraint tooling. The defined process and accompanying tooling will need to ensure a consistent outcome that can be accounted for during pre-heat treatment or post heat treatment operations. If the first path doesn’t yield an adequate solution, the use of a nitriding gear steel which has proven to be more stable with similar size and shape of gears from prior experience. While the processing time is longer for nitriding over carburizing, the likelihood of overcoming distortion is optimistic.

The third challenge with the above conceptual designs, advanced concept, and other possible hybrid gear designs is the means of fastening. Even though adhesive is the desired primary means of joining the composite and metallic components, the need for redundancy is essential. From the analysis performed during this project, it was determined that adhesive is capable of transferring the load under certain conditions, but no redundancy was present for the joints. For the conceptual design and the advanced concept at the inner interface, mechanical fasteners proved to be a viable solution for redundancy at the joints, but they do result in an increased weight that negatively impacts power/weight. For the advanced concept at the outer interface a mechanical interlock is proposed that would ensure redundancy while also resulting in reduced weight. Also when utilizing mechanical fasteners, the repeated bearing load at the joint is likely to result in damage to the joint over time. Special considerations with mitigating the fatigue at the joints is necessary.

To overcome these challenges, multiple options are recommended. Concerning the mechanical fasteners, it is recommended that multiple configurations be explored such as permanent fasteners like rivets given the likelihood that the assembly will be a matched set. Also it is recommended that tension bolts be investigated to see how they can help with edge distance to ensure the maximum amount of weight is removed from the assembly. As shown in the advanced concept with the mechanical interlock, it is recommended to pursue the use of mechanical interlocking features at the interfaces. The use of a mechanical interlock can be designed to overcome the thermal differences between the composite and metallic materials. With the load distribution at the holes for the mechanical fasteners, it is recommended that a glass liner be included at the fastener holes. Overall, a lot of research can and should be performed with the interface between the composite and metallic materials to optimize the way these two materials are joined.

The fourth challenge is determining the appropriate orientation of the composite structure. Conceptual designs 1 and 2 were modeled with different fiber orientation to understand how this affects the deformation and Inverse Reserve Factor for the two configurations. Conceptual design 1 was modeled with fiber pattern orientations of [0°,+45°,-45°,90°] and [0°,+60°,-60°,90°]. As can be seen in Figure 64 and Figure 65 the fiber orientation has a minimum effect on the deformation and IRF for conceptual design 1. Conceptual design 2 was also modeled with fiber pattern orientations of [0°,+45°,-45°,90°] and [0°,+60°,-60°,90°]. In conceptual design 2 the fiber pattern of [0°,+60°,-60°,90°] produced less deformation than the [0°,+45°,-45°,90°]. Fiber orientation has a minimum effect on the IRF (see Figure 65). Conceptual design 2 was also modeled with the fiber orientation patter of [0°,+60°,-60°,+60°,-60°, 90°]. These extra ±60° fibers had a minimum effect on the deformation but it did decrease the IRF factor for conceptual design 2.

The web geometry and fiber layout can be optimized using the ANSYS ACP module to minimize the bull gear deflections while keeping the composite fibers from failing. Furthermore, thermal loads can be applied to the model since the ACP module creates a composite/steel geometry that can slide past each other with sliding contacts.

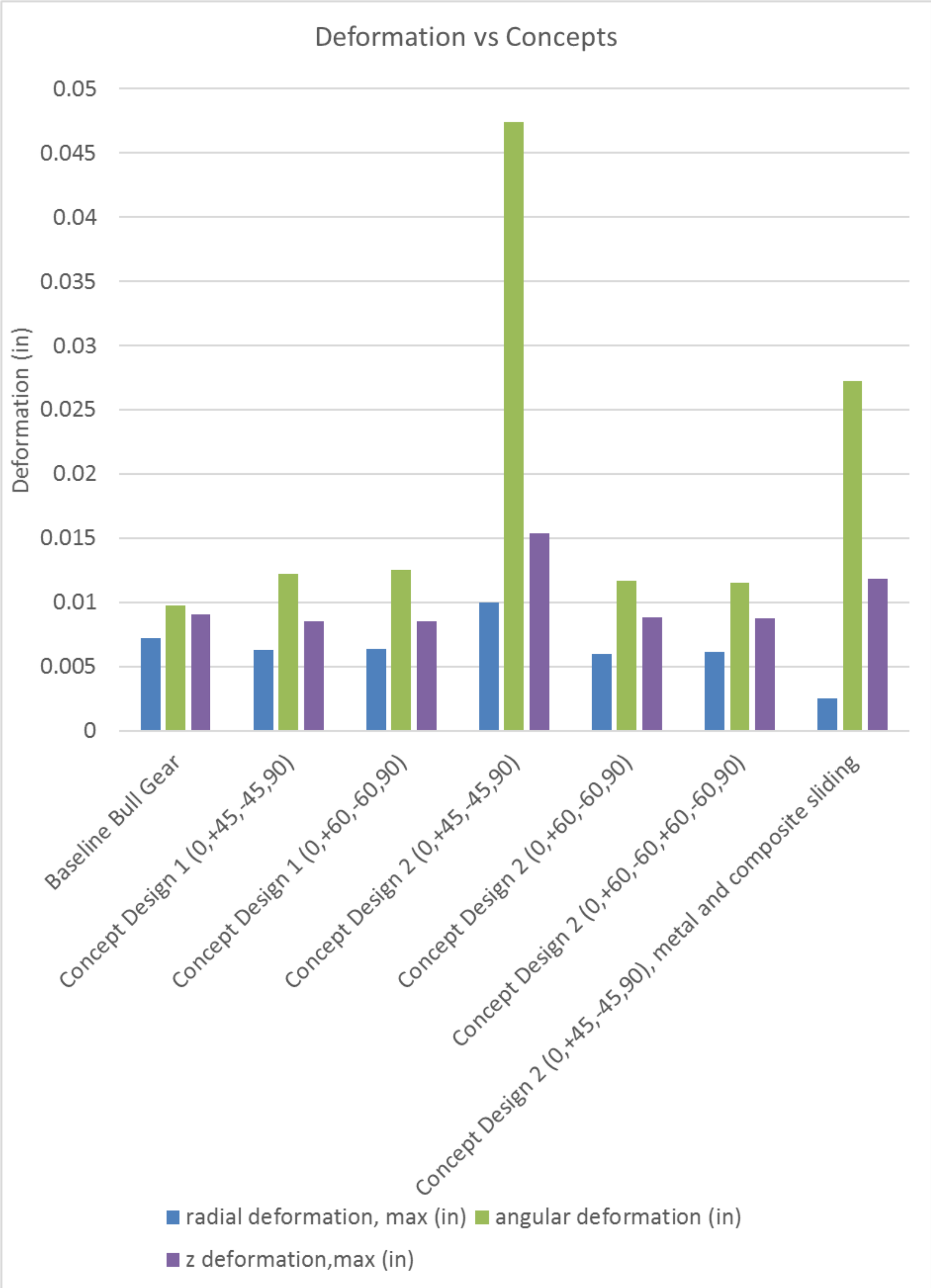


Figure 64: Deformation of conceptual designs 1 and 2 with different fiber orientations as compared to the baseline bull gear.

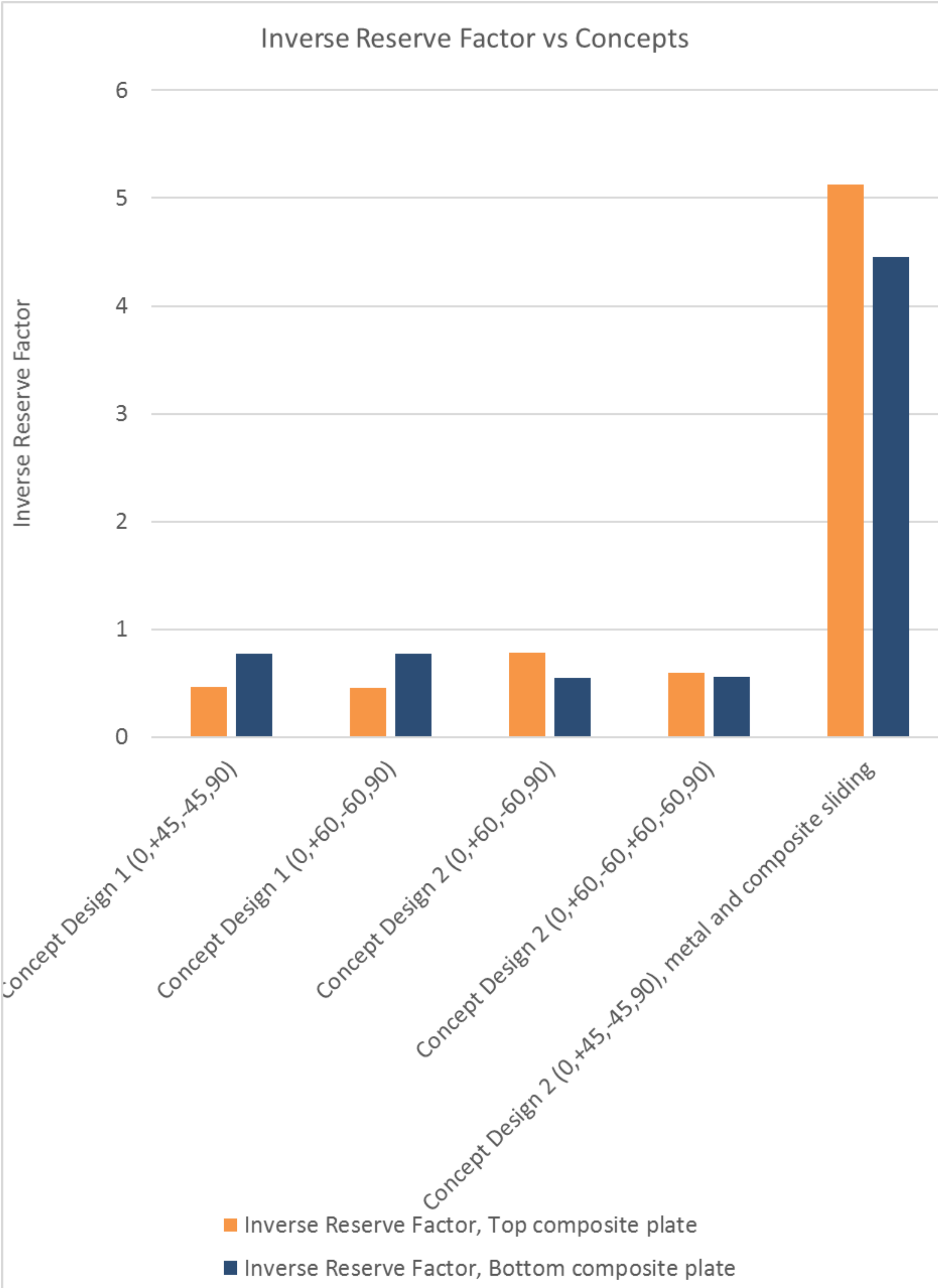


Figure 65: Inverse reserve factor for the two configurations with different fiber orientations.

The fifth challenge is certification. In order to integrate such technology in a rotorcraft drive system, the technology must be certifiable. The above technical challenges related to material properties and joint redundancy directly impact the ability to certify. These technical challenges are believed to be the primary constraints to certification to date.

Additional recommendations are to utilize topology optimization tools to guide the design of the composite web and mechanical interlock for the advanced concept and how integrated vehicle health monitoring could be incorporated to monitor the integrity of the bond between the composite and metallic components. These additional areas of recommendation are believed to largely influence the progression of composites in advanced drive systems.

VI. Conclusions

The integration of composite materials into advanced drive systems proves to be a promising approach to the improvement of performance as well as other potential areas, like manufacturing. At the onset of this project, a drive system configuration was identified as the baseline configuration to guide the development of our conceptual designs. Two conceptual designs were developed that allowed for the hybridized concepts to be integrated into the baseline configuration without the requirement of modifying additional components in the drive system. These conceptual designs were focused on the modification of the baseline bull gear, as this is the largest gear in the baseline drive system. The conceptual designs were designed to utilize currently available materials and processing.

The primary considerations that influenced the conceptual designs was weight reduction, redundancy, and manufacturability. Redundancy greatly influenced the other two considerations, especially weight reduction which can be seen in Table 3. With the need for a redundant load path if the adhesive at a joint is compromised, special considerations were taken at the interfaces between the composite and metallic components to ensure this requirement was achieved. These considerations resulted in a design that was heavier than the baseline design. Additional analysis is required to further refine the design, which is likely to improve the percentage of weight savings. In addition to the two conceptual designs, an advanced concept was developed that incorporated mechanical interlocking features at the outer composite/metallic interface. The mechanical interlocking features ensures a redundant design. While conceptual designs 1 and 2 resulted in a negative weight savings, the advanced concept resulted in a weight savings of 2% from the baseline design.

Table 3: Summary of weights for baseline design, conceptual designs 1 and 2, and the advanced concept.

Concept	Metal weight (lbs)	Composite weight (lbs)	Total weight (lbs)	Weight savings (lbs)	% Weight Savings
Baseline Bull Gear	52.05	----	52.05	0	0%
Conceptual Design 1	49.65	6.38	56.03	-3.98	-8%
Conceptual Design 2	49.75	6.38	56.13	-4.08	-8%
Conceptual Design 1, without bolts	48.56	6.38	54.94	-2.90	-6%
Conceptual Design 2, without bolts	48.66	6.38	55.04	-2.99	-6%
Advanced Concept	37.14	13.75	50.89	1.16	2%

Throughout the project, an analysis methodology was developed that allows for multiple considerations to be explored. This tool will help identify the key design performance contributors, optimized geometry, and optimized composite layup.

With the integration of composite material into drive systems, multiple technical challenges are present that require attention before the potential benefits can be captured. The primary technical challenges are: operational limitations of composite materials, heat treatment of outer metallic rings, joining of the composite and metallic components, orientation of carbon fibers, and certification. Each of these challenges requires specific considerations to overcome them. Multiple recommendations have been proposed which are believed to further advance the technology with the goal of capturing the potential benefits composite materials can have in future advanced drive systems.

VII. References

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