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RTAPS (Research and Technology for Aerospace Propulsion Systems): Simulation of Structural Loads within a Hybrid Gear Resulting From Loading at the Gear Teeth

Richard K. Naffin, Umut Ulun, Charles D Garmel, Nika McManus, Zhenning Hu,
Westin B. Ohlerking, and David E. Myers
The Boeing Company, Philadelphia, Pennsylvania

December 2017

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December 2017

Acknowledgments

Mark Robuck, Technical Fellow, Mechanical & Dynamic Systems: Mark Robuck is the team leader for the Mechanical and Dynamic Systems Design group. Mr. Robuck joined the Boeing Company in 1984 after working at Allison Gas Turbines, since that time he has been involved as lead designer for many drive system projects and R&D programs. These include the A160T UAV main rotor transmission, F22 AMAD gearbox, CH-47 tandem rotor drive system upgrades, ART R&D programs, the RDS-21 program, and the NRTC RITA projects. Mr. Robuck holds a Master of Engineering degree from Widener University, BSME from North Carolina State University, and a BFA Arts degree from Edinboro University. Mr. Robuck is registered as a Professional Engineer in the State of Pennsylvania. Scott Davidson, Gear Technology: Scott Davidson is the lead Gear Technology Engineer with 15 years experience in the helicopter industry. Mr. Davidson has provided drive system and component analysis to support numerous conceptual design studies for rotorcraft products, including CH-47, and other fixed wing and rotorcraft programs. Mr. Davidson has also developed enhanced capabilities in Boeing's analysis tools and procedures. Mr. Davidson holds a MS in Mechanical Engineering from Villanova University and a BSME from Drexel University.

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Background

NASA is investigating the practical usage of hybrid structures for rotorcraft gearing. A hybrid structure, in this sense, is a structure assembled from both metallic and composite material. The primary driver for utilizing hybrid structures for rotorcraft gearing is to reduce the drive system weight.

The hybrid structure concept featured in this study for rotorcraft gearing consists of a metallic gear tooth-rim, a web section manufactured from composite materials, and a metallic hub. The metallic gear tooth-rim is manufactured from conventional gear steel alloys, such as AISI 9310. The gear tooth-rim attaches to the outer diameter of the web section made from composite materials. The inner diameter of the composite web can then attach to a metallic hub, completing the assembly. It is assumed that areas of the shafting or hub where rolling element bearings may ride must remain as gear steel alloys for this study.

The interfaces between the metal and composite sections are considered critical design features for these hybrid structures. In addition, the methods for designing and fabricating the composite web and hub components will need to meet the critical load requirements for fully-loaded, rotating gearing. Such features could be tested and screened using (non-rotating) static tests to determine ultimate strength and also with cyclic loading tests to determine fatigue limits. Part of the focus for this study is a test rig capable of simulating realistic gear loads (including a range of tooth loads) and moments in a static environment. Such a test rig would be useful in screening various hybrid structure configurations for rotorcraft gearing prior to performing full dynamic testing of the gear components in a gearbox.

NASA contacted Boeing to assist in developing a practical static test rig for evaluating rotorcraft gearing consisting of hybrid structures. The investigation was broken into three components, as per the Statement of Work:

1. The Contractor, Boeing, shall provide a list of rotorcraft gear types and applications that would be suitable for analysis of structural loads. The gear types would be selected to represent a range of load conditions with varying levels or torque, thrust, radial, and centrifugal loads and overturning moment. A minimum of two gear types would be selected for detailed finite element analysis.

   For each selected gear type, the Contractor shall perform a static structural finite element analysis to determine stress and displacement throughout the gear using realistic boundary conditions at the hub ID and realistic gear tooth loads at the rim OD. Stresses and displacements shall be determined for the entire gear with emphasis on transition of the near field contact loads at the rim to far field stresses within the main body of the gear, as well as loads the hub ID boundary. The primary purpose of this analysis is to determine feasibility of designing a multi-axial structural test rig to impose the quasi-static loads. A simplified radial gear profile may be used for the analysis and data may be normalized so that results can be published. If time allots, the Contractor shall identify any dynamic or thermal issues that should be considered when interpreting results of the static structural analysis.

2. The Contractor shall use the results of the first part of the investigation to propose a conceptual design for a multi-axial test rig that could be used to simulate the load conditions as defined in the finite element analysis. A detailed description of the actuation, control, and data acquisition system is not required; however, the loads applied should be consistent with the capabilities of commercially available hydraulic systems. The Contractor shall perform static structural finite element analysis for each down-selected gear type using the loads applied by the test rig and compare to the resultant stresses/displacements to those predicted in the theoretical finite element analysis completed in the first part of investigation.

3. The Contractor shall investigate the feasibility of extending the performance capability of the test rig to simulate more realistic non-steady loads while not actually rotating the gear.

The results of the investigation outlined above are summarized in this report. Per the Statement of Work, the report shall include the following:

1. Summary of the gear type down-selection
2. Summary of the selected gear type finite element analysis, including a discussion of the critical load conditions.
3. A conceptual solid model of the multi-axial test rig
4. A comparison of the critical load conditions as discussed in the finite element analysis to those actually applied by the test rig.
5. A solid model showing the proposed test rig, along with a description of operation describing how the rotating loads will be applied.

Rotorcraft Gear Types

The investigation started off by screening various gear types and applications as possible candidates for a hybrid structure configuration. From the various gear configurations available, a few were considered for more detailed screenings, based upon their wider design and loading ranges. These included spiral bevel gears, accessory spur gears, and bull gears. The results of these detailed screenings are as follows:

1. A spiral bevel gear utilizing a mixed metallic/composite shaft is shown in Figure 1(b). Metallic features were retained for the web section, gear hub, and shafting surfaces where the rolling element bearings directly rode on the shaft. This configuration displayed a decrease in weight of 1.53 lb (adhesive and fastener weight is not included). However, this candidate was considered to be rather complex with very modest weight reduction and was not pursued in this study.
2. Accessory spur gears from various rotorcraft platforms were also considered as possible candidates. From the various accessory gears available, a few candidates are shown in the Figure 2. This gear type was considered to be much easier to manufacture using a hybrid structure configuration. In particular, idler gears that do not have a spline connection or have torque output at the gear hub could potentially be constructed with a metal rim and an all composite hub. The weight reduction for this component would be greatly reduced. However, since these gears are relatively small, the overall weight reduction for the drive system may still be small. Accessory gears could come in a range of sizes and applications and their loading range is typically small.
3. The third gear candidate for hybrid structure gears was a bull gear configuration (Figure 3). Bull gears are generally very large spur or helical gears used in high reduction, high load applications. Like the

accessory gears, the manufacturability of a hybrid structure configuration was considered possible. Bull gears are used in many rotorcraft systems and can also come in a range of sizes and applications.

At the end of the down selection stage, Boeing and NASA agreed to only select one gear type instead of two. The bull gear component was selected due its large hub and web section, which, if converted to composite material, would lead to a substantial weight savings. In addition, the bull gear would see higher loading conditions, where gear and hub materials are strained to their capacity, and are classified as critical components. Boeing then suggested the following hybrid structure configuration, as shown in Figure 4. Essentially, the configuration would consist of a metallic gear-tooth rim, composite web section, and a metallic gear hub/shaft.

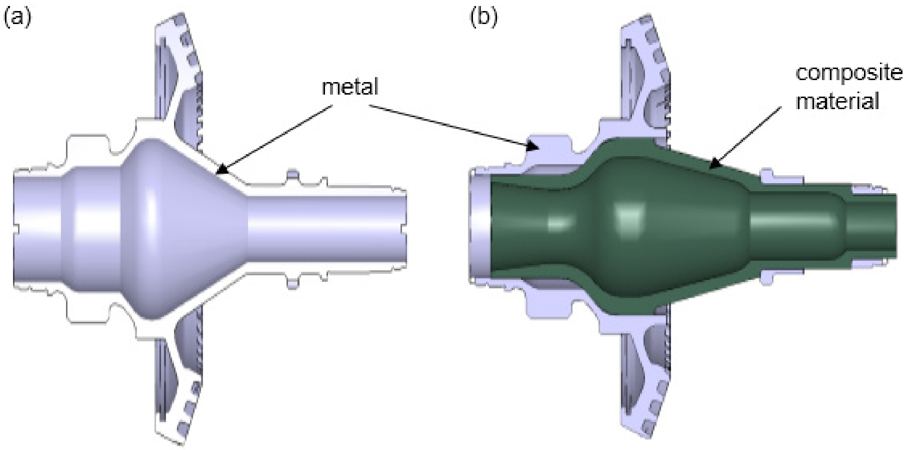


Figure 1.—Spiral Bevel Gear Candidate

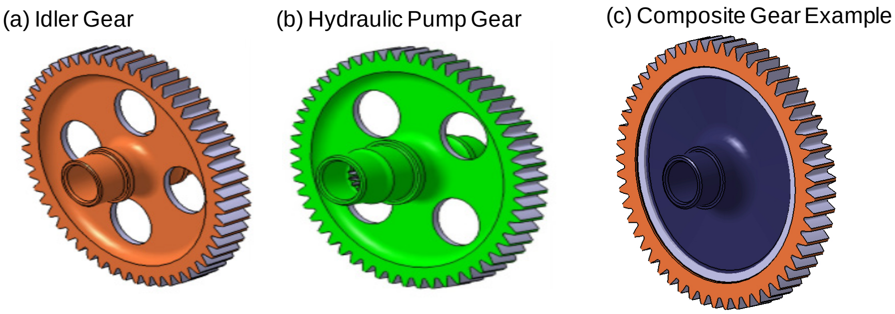

(a) Idler Gear
(b) Hydraulic Pump Gear
(c) Composite Gear Example

Figure 2.—Accessory Gear Candidates

Figure 3.—Bull Gear Candidate

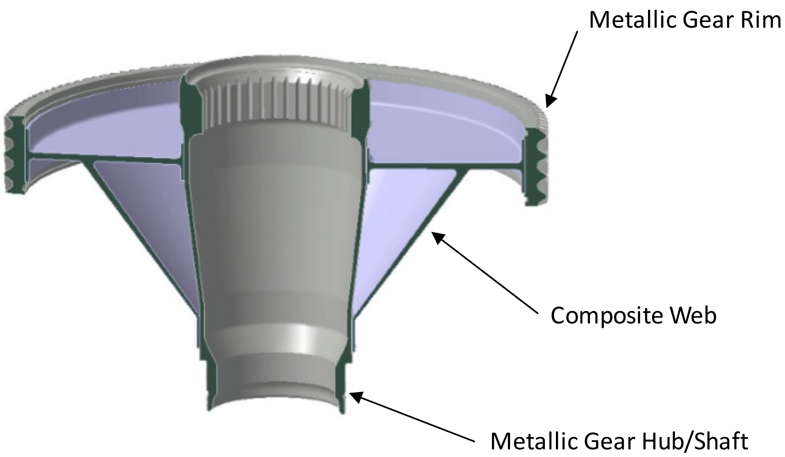


Figure 4.—Selected Gear Configuration – Hybrid Bull Gear

Finite Element Model

The helicopter bull gear subsystem analyzed in this project is comprised of a helical bull gear and two helical pinions to provide torque transfer from the engines to the epicyclic system mounted above. The bull gear in this system is a good candidate for a composite rim structure due to the size and potential weight savings for a hybrid configuration that replaces a large section of the rim with a composite material.

The helicopter helical bull gear and pinion arrangement was modeled in Transmission3D to provide NASA analysts with realistic dynamic gear tooth loading and backup structure stresses. The model was built as a modular system such that the geometry of the bull gear rim could be changed easily to provide a robust analysis tool. Loading and rpm were defined as similar to those of a typical helicopter transmission system.

Calyx is a contact solver specifically designed for use with precision elastic gear and spline teeth. The semi-analytical finite element approach taken internally generates a mesh at the surface of the contact bodies which significantly reduces computational time and allows the user to focus on geometry rather than element formulation. Transmission 3D is the program interface used to build the geometry of the bull gear arraignment internally to the program and analyzed the system using the Calyx contact solver.

The finite element model is comprised of two helical bull pinions and a helical bull gear. An overview of the Transmission 3D model is shown in Figure 5. The typical helical bull gear cross section is shown in Figure 6.

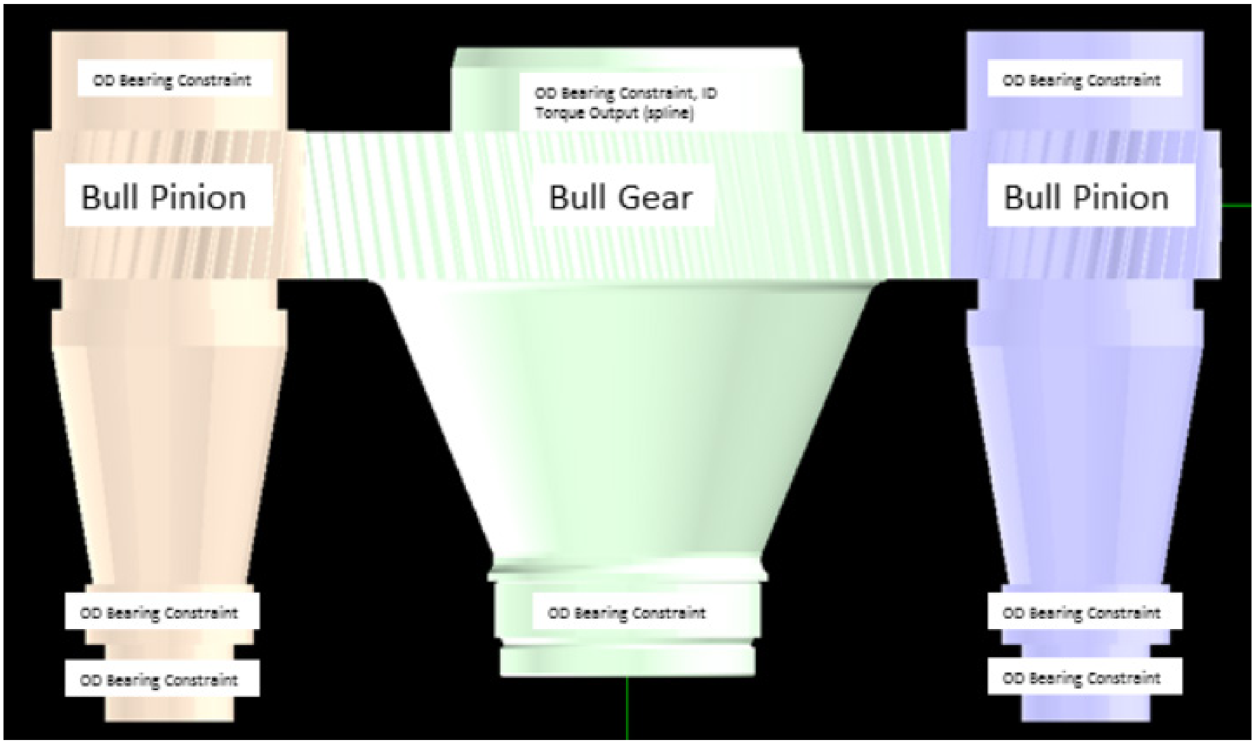


Figure 5.—Transmission3D Model Overview

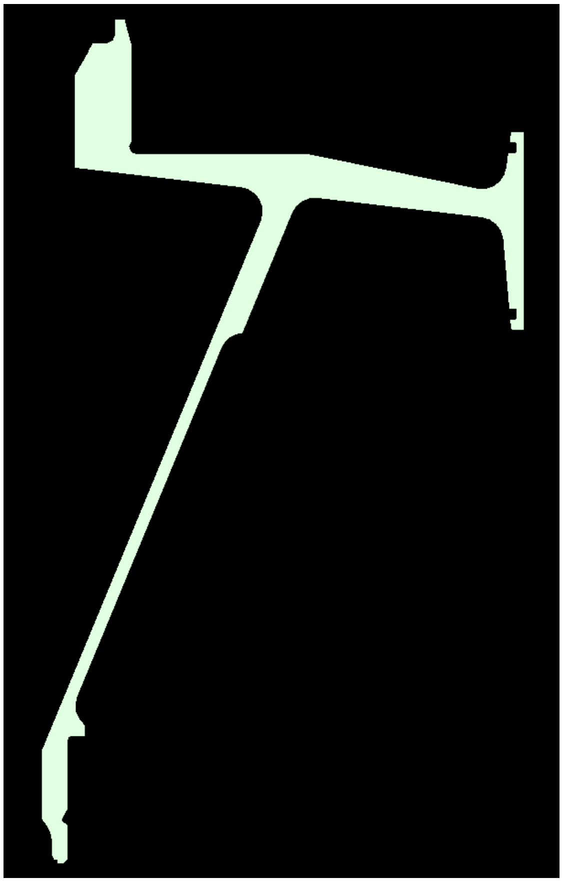


Figure 6.—Typical Isotropic Bull Gear Cross Section

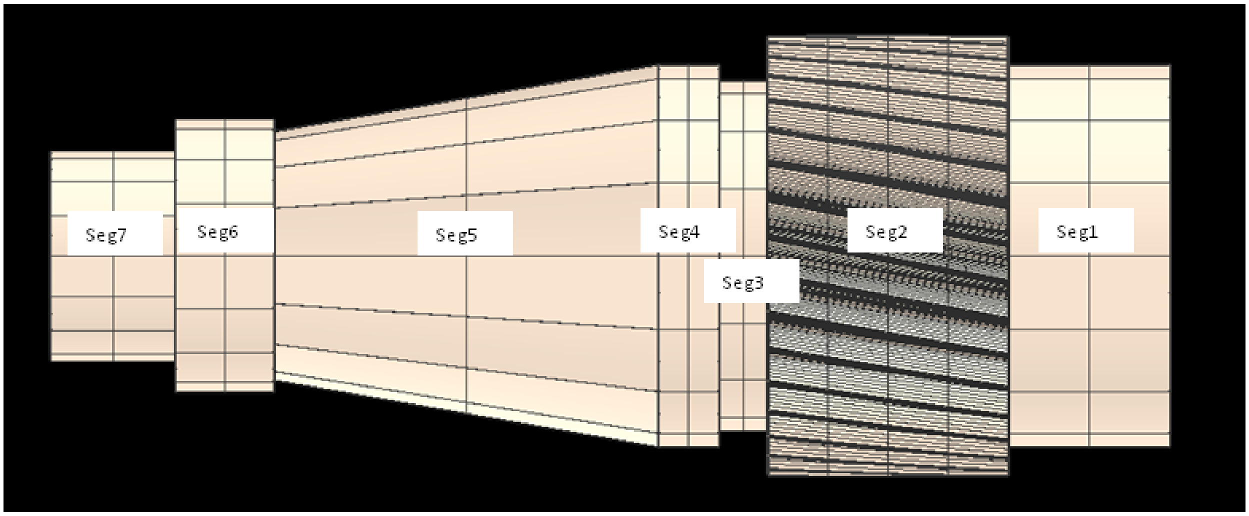


Figure 7.—Bull Pinion Segment

Bull Pinions

Gear tooth geometry was input into the tabular Sun1 of the Rotor menus to mimic typical helicopter tooth geometry. A large topland chamfer was added to the tooth modification used and produced a realistic contact pattern between both bull pinions and the bull gear. A coefficient of friction of 0.1 was used for both tooth contacts setup within Transmission3D.

The helical bull pinions and shafts, Figure 7, were built internally within Transmission3D. These pinions were comprised of seven separate shaft segments, two of which were constrained radially due to roller bearing positioning in the assembly, and one segment was constrained axially due to a ball bearing location. The torque was applied through the central segment (segment 4) of the bull pinions. Segment 2 of the bull pinions is the race for the helical gear teeth. It should be noted that the bull pinions in this model were not intended for use with stress analysis and therefore have a coarse mesh in an attempt to aide in fidelity of the bull gear itself.

Bull Gear

The bull gear is comprised of two shaft segments, an imported rim, and a backup structure/tooth segment. The upper shaft segment’s OD is constrained due to a roller bearing location, and ID is reacting the system torque from a splined connection. The lower shaft segment is constrained axially due to a ball bearing location. The teeth of the bull gear have a typical helicopter profile modification to aide in tooth contact.

Bull Gear Rim Geometry

The bull gear rim is loaded into the model as an Abaqus input file (.inp). This method allows the user to replace the bull gear rim quickly after creating a new geometry or element material definition or set in Abaqus and generating an input file. If the diameters of the bearing races and tooth backup structure remain the same, this new bull gear rim file should be easily loaded into the model. Transmission3D needs the following characteristics to be met for the Abaqus input file to be loaded properly:

1. All elements must be assigned a material property containing an isotropic Young’s Modulus, Mass Density and Poison’s Ratio.

2. All elements must be C3DXR, solid continuum reduced integration elements.
3. The assembly must have an end face constrained to the YZ plane. (This parameter can be altered if less than 141 segments are desired, see Rotor 2's Carrier – Sectoral Symmetry menu).
4. All elements must have a Jacobian ratio greater than 0.3.
5. All nodes on the primary side face (face that lies on YZ plane) must match the radial coordinates of those on the secondary side face.

This modular technique allows the user to analyze many different types of rim files in a relatively short period of time. Once the rim files are analyzed and an IGlass file is created from Transmission3D's PostProc menu, the user will be able to import the results of the backup structure deflection into Abaqus for easier post processing.

Time Step

The time steps chosen in this model are proportional to the nominal rpm of the bull gear. A typical Transmission3D model consists of 11 time steps (DELTATIME) that encompass a single pitch of rotation of the slowest turning member. The increment chosen is given by the following formula:

$$\Delta T = \frac{60}{S * N * \text{rpm}}$$

Where S is the desired number of time increments per single pitch of rotation (in this case, 10), and N is the number of teeth in the bull gear. A full pitch of the slowest turning member is typically used such that various information can be obtained for real-time contact between gear teeth, i.e., stress distributions in the web. Time step 11 contains the lowest margin of safety due to the formulation of the boundary condition displacements from Transmission3D in relation to Abaqus and should be considered a single margin of safety for the part. Arbitrary time steps are shown in the Transmission3D model in Figure 8, Figure 9, and Figure 10.

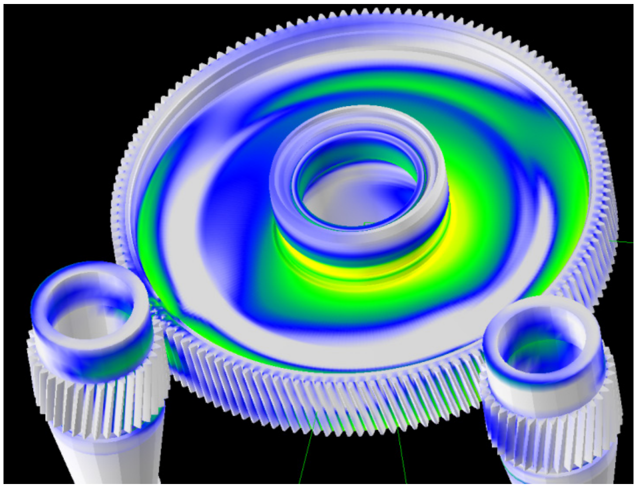


Figure 8.—Transmission3D iGlass Viewer – Step 1, Max Principal Stress Shown

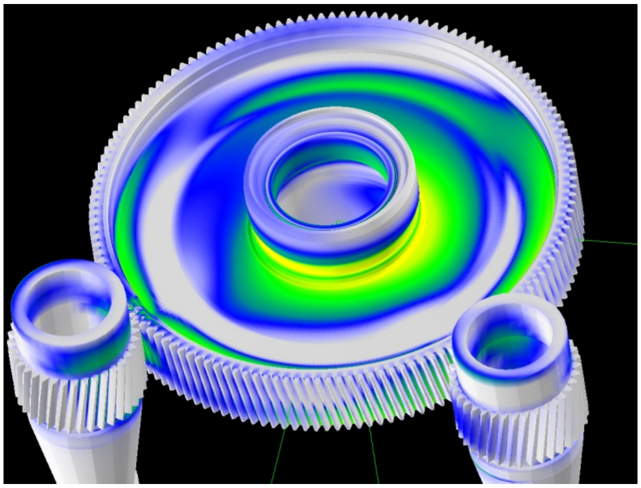


Figure 9.—Transmission3D iGlass Viewer - Step 5, Max Principal Stress Shown

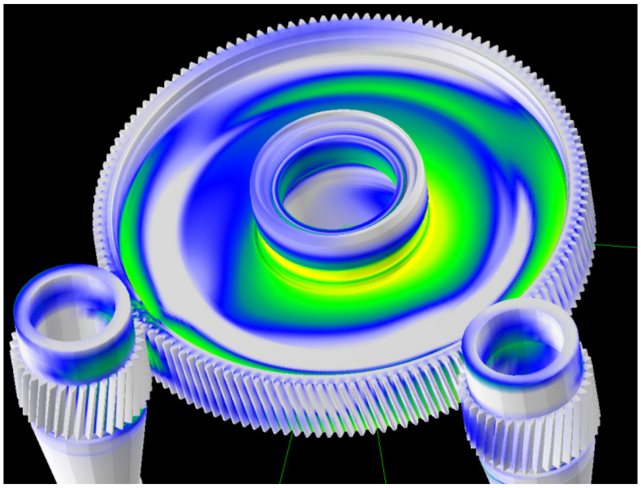
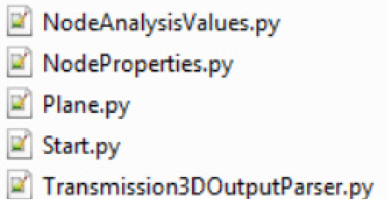


Figure 10.—Transmission3D iGlass Viewer - Step 11, Max Principal Stress Shown



NodeAnalysisValues.py
NodeProperties.py
Plane.py
Start.py
Transmission3DOutputParser.py

Figure 11.—Python scripts.

Converting Transmission 3D Models to Abaqus Models

Result files generated from the Transmission 3D were used to generate Abaqus models through a set of proprietary Abaqus Python scripts. The script files were used to import the rim section geometry along with the Transmission 3D displacement results at the rim surface. The imported rim section instances are structurally tied together in the Abaqus assembly. The displacement results are iterated over the rim section instances to produce 360° realistic gear tooth loading.

Gear Selection

Critical Load Conditions

The typical helicopter helical bull gear was modeled and analyzed in Abaqus, v6.13-3. In order to implement the representative boundary conditions, Transmission3D was used to analyze the bull gear model with the typical helicopter transmission system loads and rpm.

In Transmission3D, the gear model with the smeared composite material properties is used. Its nodal displacement results are queried throughout a single pitch of the bull gear tooth. The time allotted for a single bull gear tooth to move through mesh is divided by 10 to produce a total of 11 time steps for the model. Therefore there are 11 linear steps in Abaqus analysis.

The gear model with the smeared composite material properties served as a global model to impose its representative boundary conditions onto the model built with the BMS8-276 Carbon Fiber Reinforced Polymer (CFRP).

The BMS8-276 CFRP tape material properties are:

- The mass density: 0.056 lb/in.^{3}
- E1 = 20,600,000 psi
- E2 = E3 = 1,113,000 psi
- ν12 = ν13 = 0.340, ν23 = 0.530

The BMS8-276 CFRP composite properties are:

- The layup: 0°/±45°/90° percentage: 25/50/25
- E1 = E2 = 7,717,000 psi
- The Poisson’s Ratio: 0.318
- The mass density: 0.056 lb/in.^{3}
- Max tension strain: 0.0183 in./in.
- Min compression strain: –0.0106 in./in.

The outer edges maintained its 9310 CEVM Steel material properties:

- Young’s Modulus: 30,000,000 psi
- The Poisson’s Ratio: 0.300
- The mass density: 0.280 lb/in.^{3}
- Yield Stress: 132,000 psi
- Ultimate Stress: 150,000 psi

The BMS8-276 CFRP/Steel Hybrid bull gear consists of steel rims and CFRP webs. Its cross section is shown in Figure 12. The cross sections are revolved 141 times and tied to complete the bull gear circular configuration. The Steel bull gear cross section used for weight comparison is shown in Figure 13.

The weight for the BMS8-276 CFRP/Steel Hybrid bull gear is 21.28 lb and for the Steel bull gear is 43.05 lb. The volume for the BMS8-276 CFRP/Steel Hybrid bull gear is 135.22 in.^{3} and for the Steel bull gear is 153.74 in.^{3}. Their weight and volume comparison is listed at Table 1.

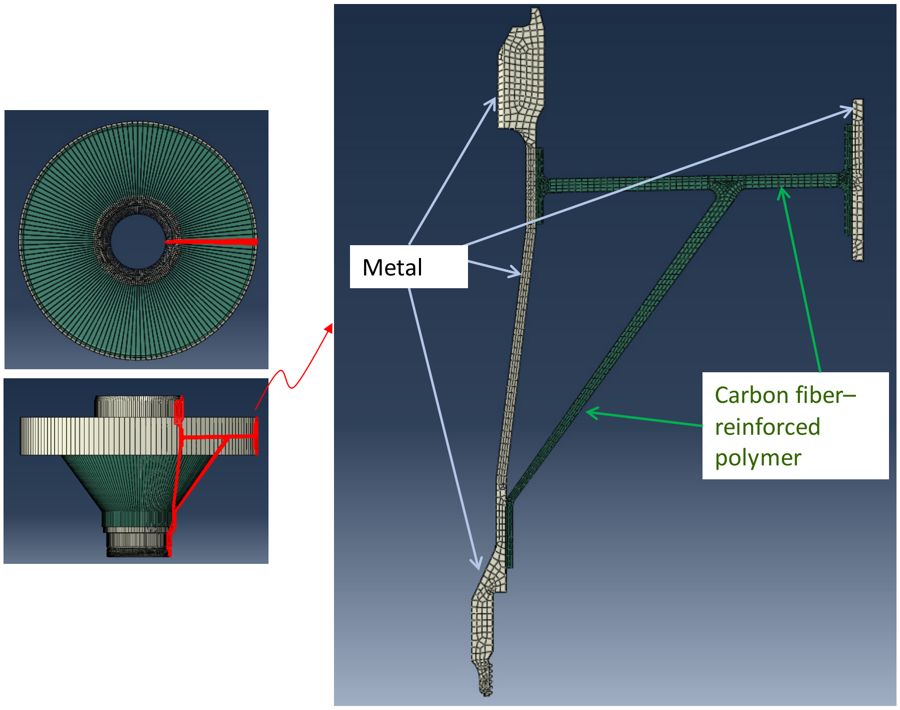


Figure 12.—The BMS8-276 CFRP/Steel Hybrid Bull Gear Cross Section

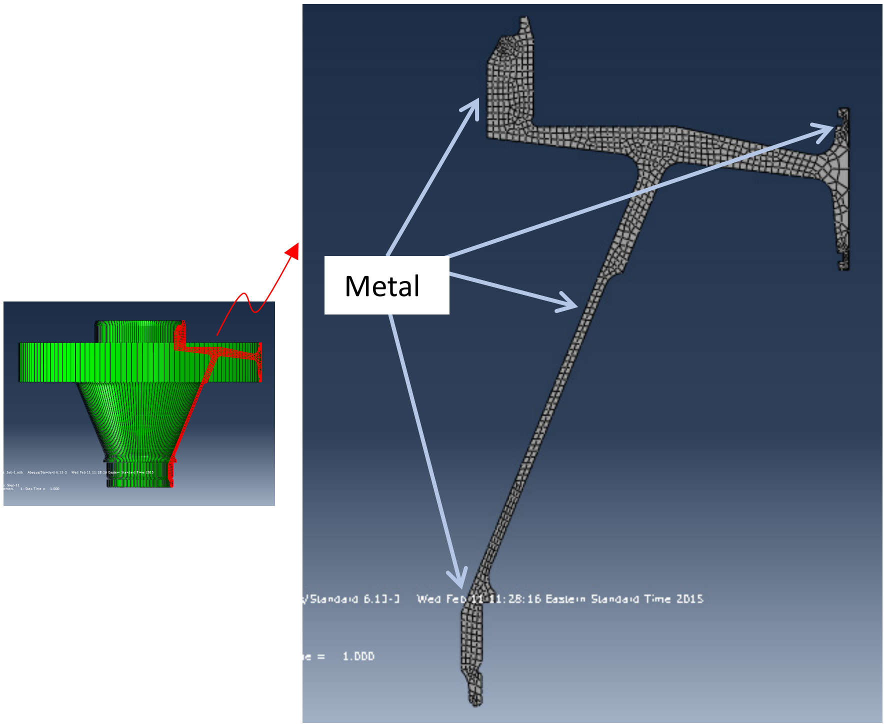


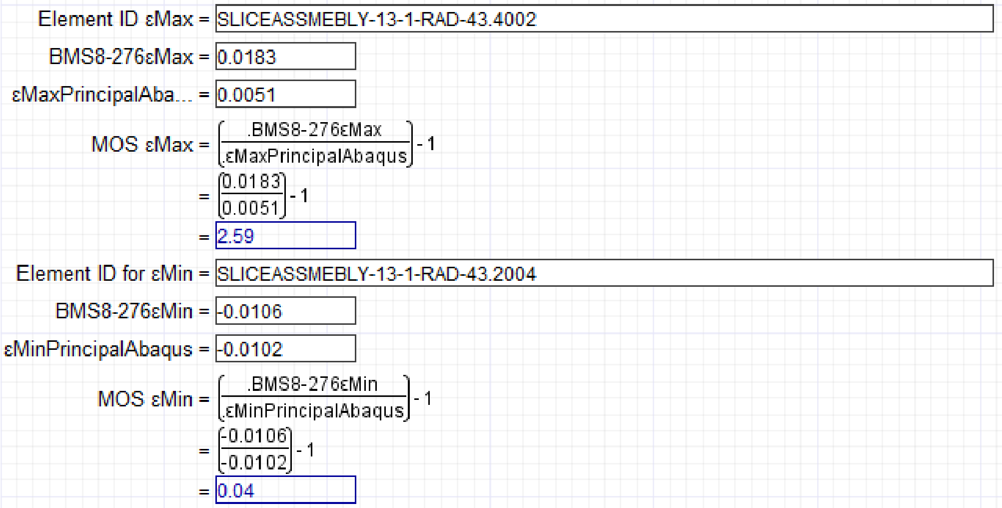
Figure 13.—The Steel Bull Gear Cross Section

TABLE 1.—BMS8-276 CFRP/STEEL HYBRID BULL GEAR VERSUS STEEL BULL GEAR WEIGHT COMPARISON

	Steel bull gear	CFRP/steel hybrid bull gear	Difference (%)
Weight (lb)	43.05	21.28	–50.6
Volume (in.^{3})	153.74	135.22	–12.0

Hybrid Gear Structural Strength

The Margin of Safety calculation using the BMS 8-276 CFRP allowables is shown in Figure 14. Figure 15 and Figure 16 show the BMS8-276 CFRP/Steel Hybrid bull gear model Max and Min Principal Strain, respectively, as well as the corresponding critical locations for step 11. Figure 17 and Figure 18 show the Steel model Max and Min Principal Strain, respectively, as well as the corresponding critical locations for step 11. Figure 19 and Figure 20 show the stresses for the BMS8-276 CFRP/Steel Hybrid bull gear model and the Steel model, respectively.



Element ID εMax = SLICEASSMEBLY-13-1-RAD-43.4002

BMS8-276εMax = 0.0183

εMaxPrincipalAba... = 0.0051

$$\text{MOS } \varepsilon\text{Max} = \left(\frac{\text{BMS8-276}\varepsilon\text{Max}}{\varepsilon\text{MaxPrincipalAbaqus}}\right) - 1$$

$$= \left(\frac{0.0183}{0.0051}\right) - 1$$

$$= 2.59$$

Element ID for εMin = SLICEASSMEBLY-13-1-RAD-43.2004

BMS8-276εMin = -0.0106

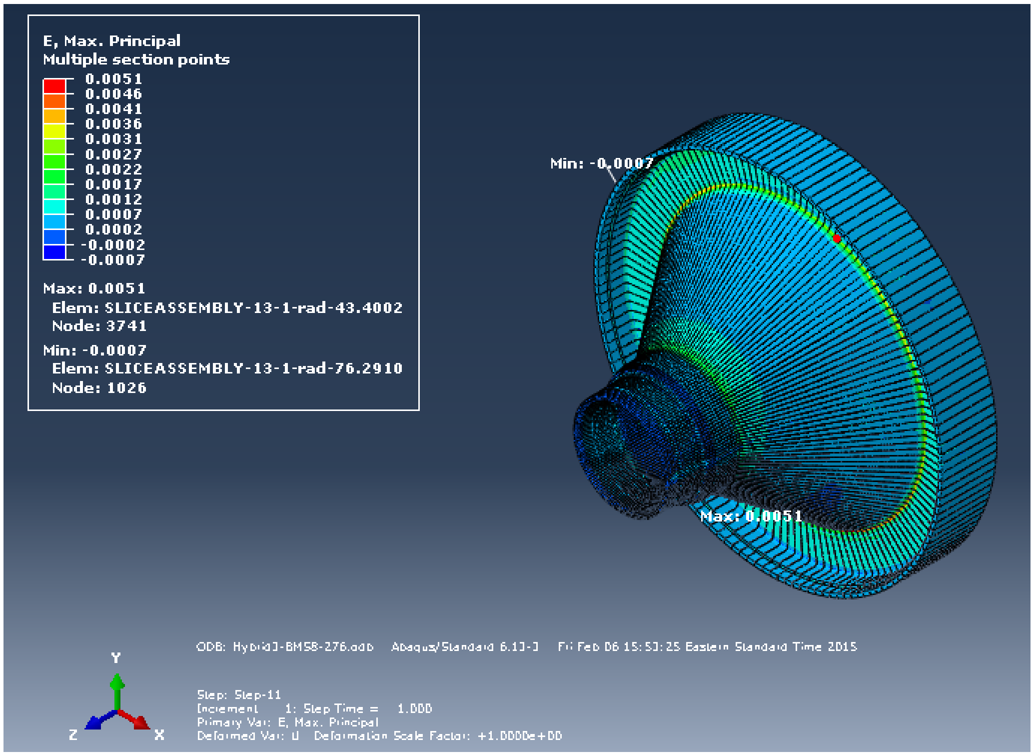
εMinPrincipalAbaqus = -0.0102

$$\text{MOS } \varepsilon\text{Min} = \left(\frac{\text{BMS8-276}\varepsilon\text{Min}}{\varepsilon\text{MinPrincipalAbaqus}}\right) - 1$$

$$= \left(\frac{-0.0106}{-0.0102}\right) - 1$$

$$= 0.04$$

Figure 14.—Margin of Safety Calculation Using BMS8-276 CFRP Allowables



```
ODB: Hybrid3-BMS8-276.odb    Abaqus/Standard 6.13-3    Fri Feb 06 15:53:25 Eastern Standard Time 2015

Step: Step-11
Increment      1: Step Time =    1.000
Primary Var: E, Max. Principal
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

Figure 15.—BMS8-276 CFRP/Steel Hybrid Bull Gear Model Max Principal Strain (in./in.) and the Corresponding Critical Locations for Step 11.

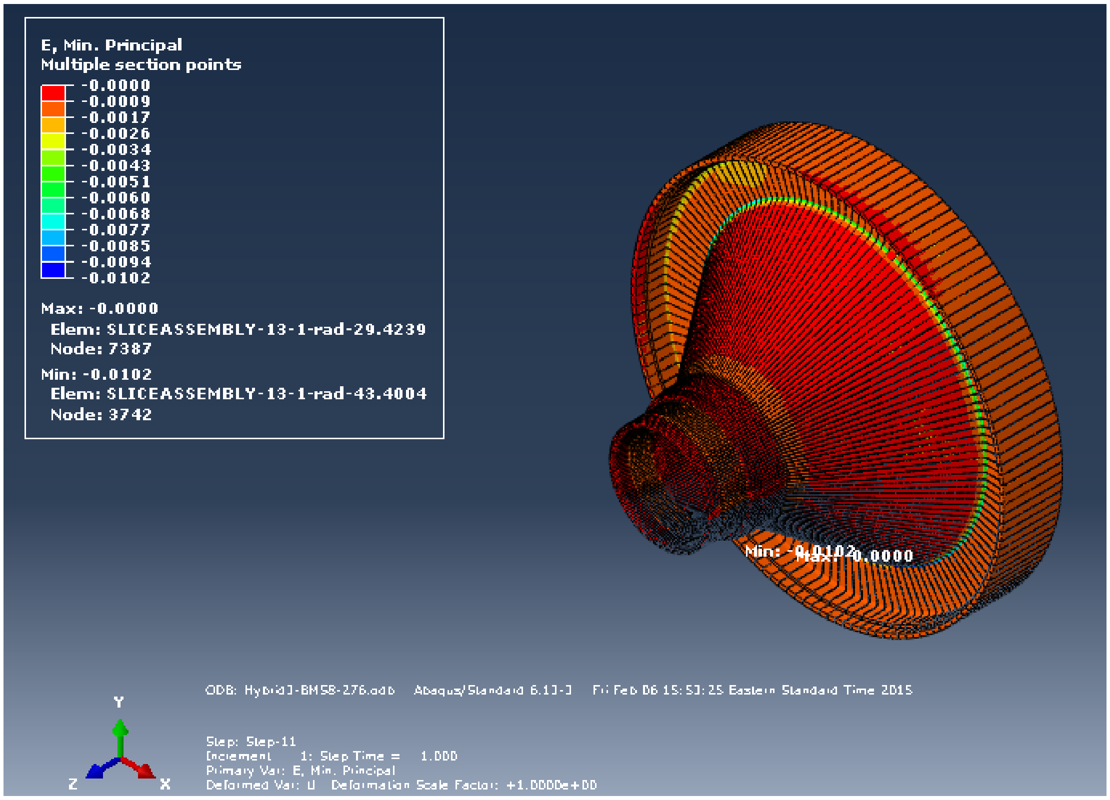


Figure 16.—BMS8-276 CFRP/Steel Hybrid Bull Gear Model Min Principal Strain (in./in.) and the Corresponding Critical Locations for Step 11.

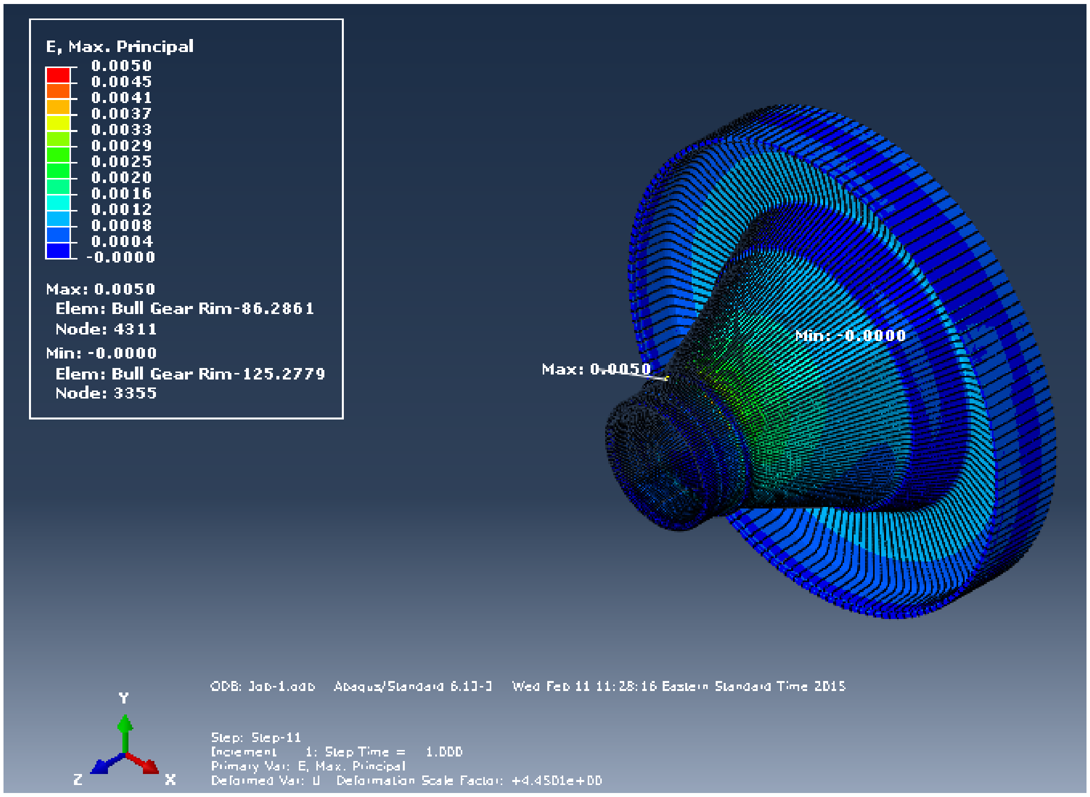


Figure 17.—The Steel Model Max Principal Strain (in./in.) and the Corresponding Critical Locations for Step 11.

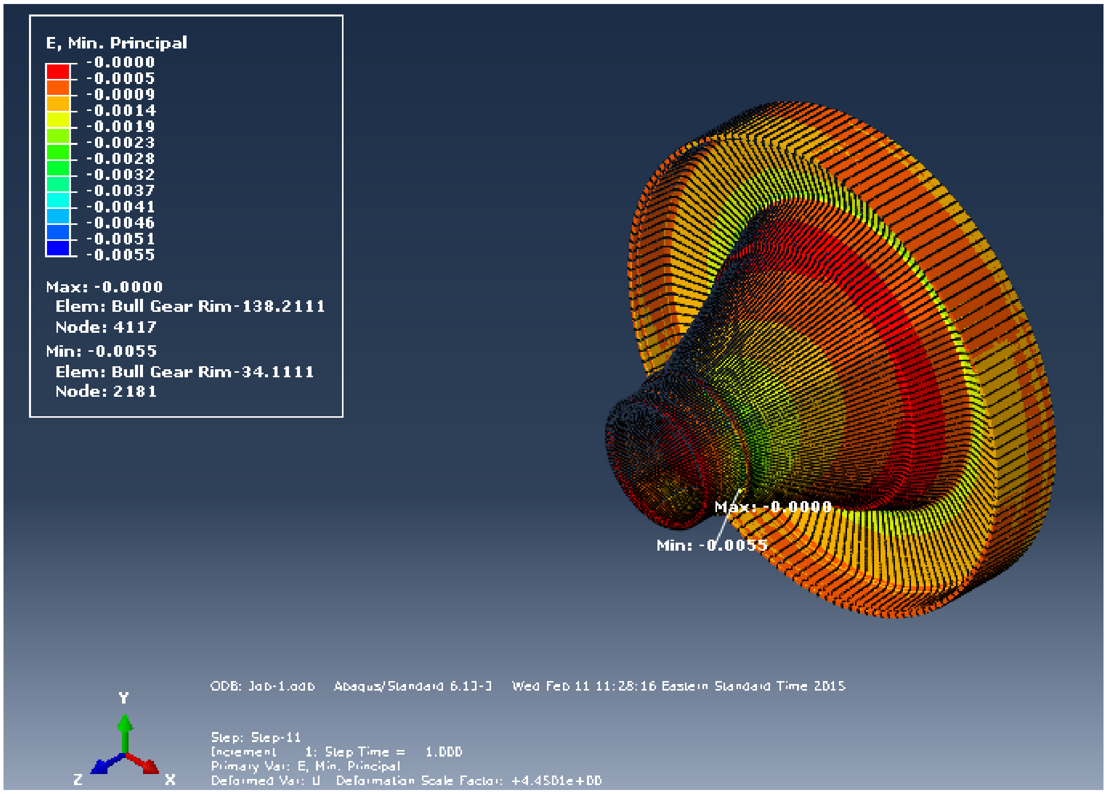


Figure 18.—The Steel Model Min Principal Strain (in./in.) and the Corresponding Critical Locations for Step 11.

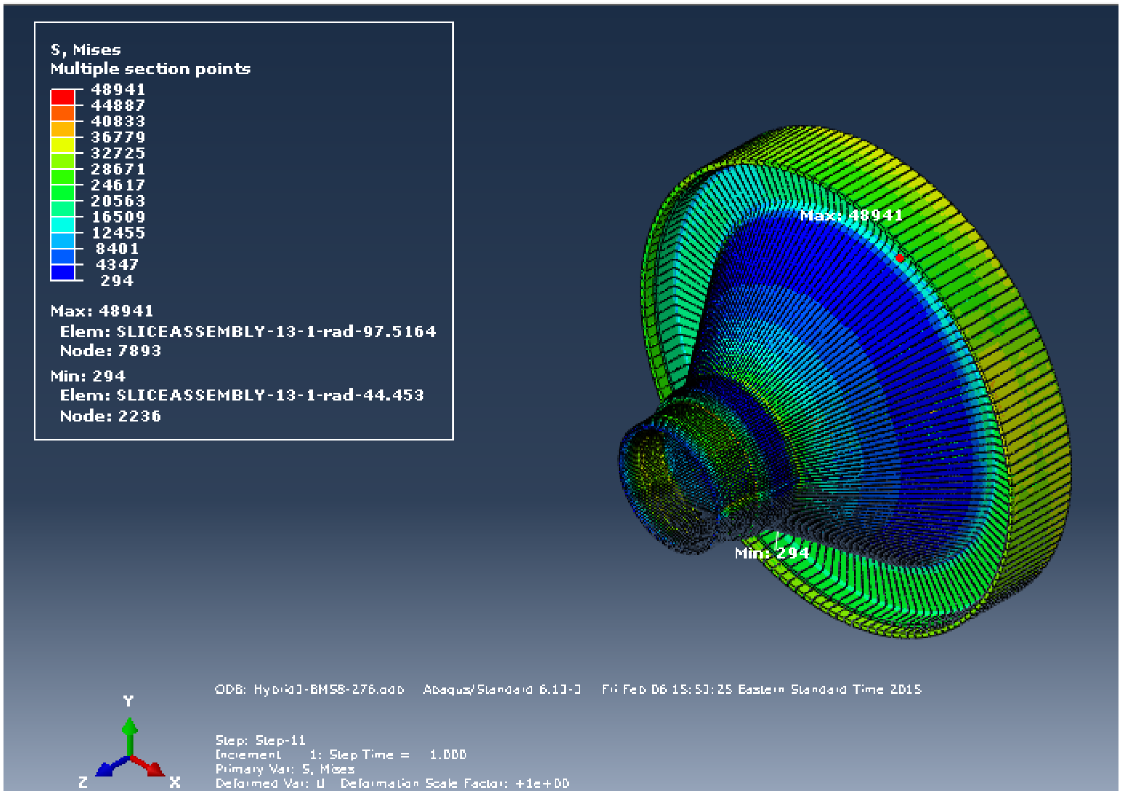


Figure 19.—Stress (psi) for the BMS8-276 CFRP/Steel Hybrid Bull Gear Model.

Table 2 shows the BMS8-276 CFRP/Steel Hybrid bull gear model Margin of Safety compilation for 11 steps. All steps have positive margins. The minimum acceptable Margin of Safety for structural analysis is 0. The most critical step is Step 11, which has the smallest Margin of Safety 0.04. The area with the smallest Margin of Safety is located in the center noodle region of the rim slice, Figure 21. Table 3 shows the BMS8-276 CFRP/Steel Hybrid bull gear model Margin of Safety for 11 steps in the center noodle region.

Steel-CFRP Interface Bond Force

The gear model consists of 141 slices and each slice has three bond interfaces. Their locations are identified at Figure 22. The bond forces per square inch are checked at Step 11 between the metal and CFRP interfaces. The Step 11 has the smallest strain margin thus it is believed to generate the most critical bond force. Figure 23 and Figure 24 shows the hybrid gear CFRP portion max and min principle strains, respectively. Their bond interfaces are identified. Figure 25 shows the Slice 89's principle strains. The bond force is averaged by the interface area. Figure 26 shows the bond force per area calculation at the Slice 89 bond interface 2. All 141 x 3 = 423 bond interfaces are checked. The largest normal force (pull-out force) per area is 2129 psi, and the largest shear force per area is 2232 psi as listed at Table 4.

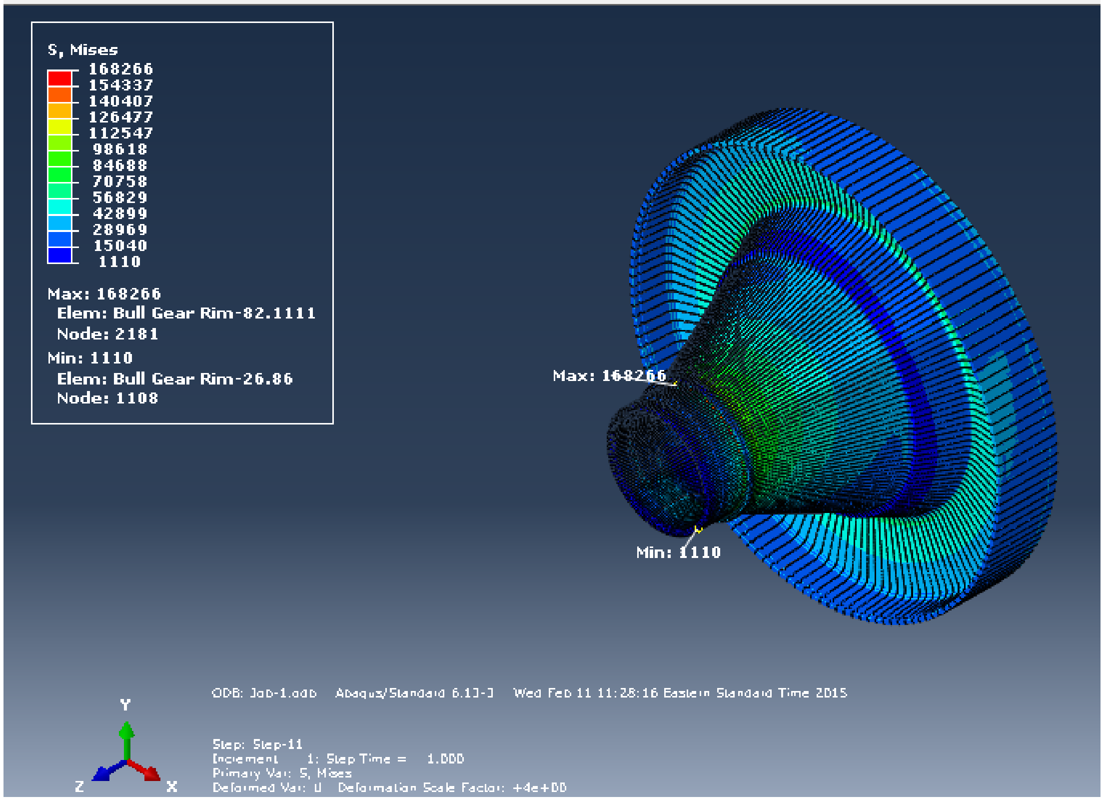


Figure 20.—Stress (psi) for the Steel Model.

TABLE 2.—BMS8-276 CFRP/STEEL HYBRID BULL GEAR MODEL MARGIN OF SAFETY COMPLICATION FOR 11 STEPS

Step	εmax principal	Margin of safety	Step	εmin principal	Margin of safety
1	0.00484	2.78	1	–0.00494	1.15
2	0.00478	2.83	2	–0.00493	1.15
3	0.00476	2.84	3	–0.00510	1.08
4	0.00469	2.90	4	–0.00513	1.07
5	0.00460	2.98	5	–0.00546	0.94
6	0.00445	3.11	6	–0.00571	0.86
7	0.00429	3.27	7	–0.00607	0.75
8	0.00411	3.45	8	–0.00673	0.58
9	0.00391	3.68	9	–0.00734	0.44
10	0.00421	3.35	10	–0.00854	0.24
11	0.00507	2.61	11	–0.01024	0.04

TABLE 3.—BMS8-276 CFRP/STEEL HYBRID BULL GEAR MODEL MARGIN OF SAFETY COMPILATION FOR 11 STEPS IN THE CENTER NOODLE REGION

Step	εMax Principal	Margin Of Safety	Step	εMin Principal	Margin Of Safety
1	0.00484	2.78	1	–0.00226	3.69
2	0.00478	2.83	2	–0.00227	3.67
3	0.00459	2.99	3	–0.00233	3.55
4	0.00422	3.34	4	–0.00238	3.45
5	0.00379	3.83	5	–0.00281	2.77
6	0.00324	4.65	6	–0.00358	1.96
7	0.00262	5.98	7	–0.00453	1.34
8	0.00277	5.61	8	–0.00568	0.87
9	0.00344	4.32	9	–0.00701	0.51
10	0.00421	3.35	10	–0.00854	0.24
11	0.00507	2.61	11	–0.01024	0.04

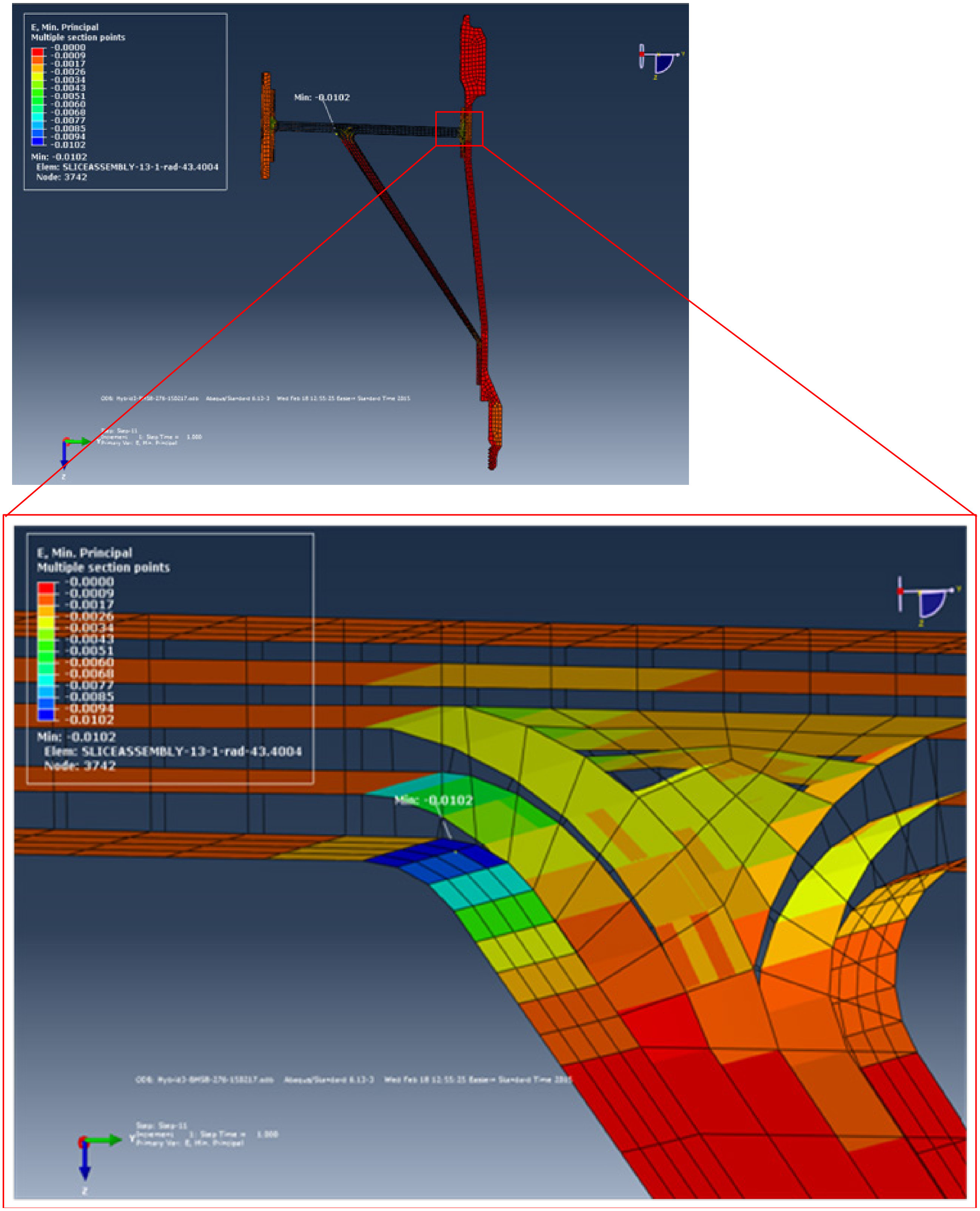


Figure 21.—Slice 43 Illustrates the Smallest Margin of Safety Location.

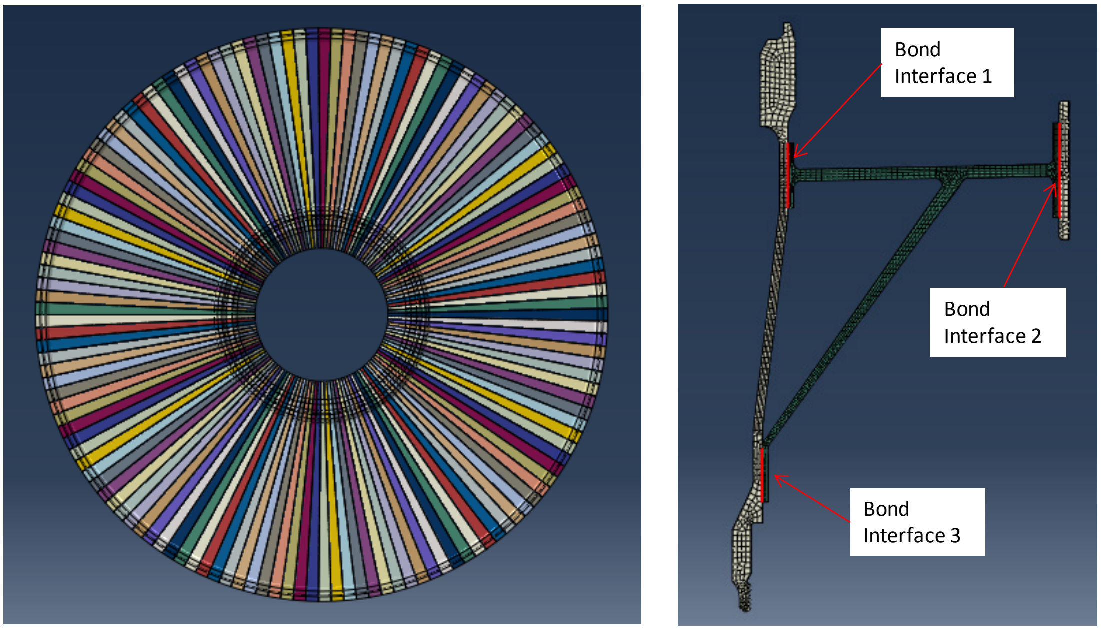


Figure 22.—141 Slices of the Hybrid Bull Gear (Left) and Steel-CFRP Interfaces Per Slice (Right).

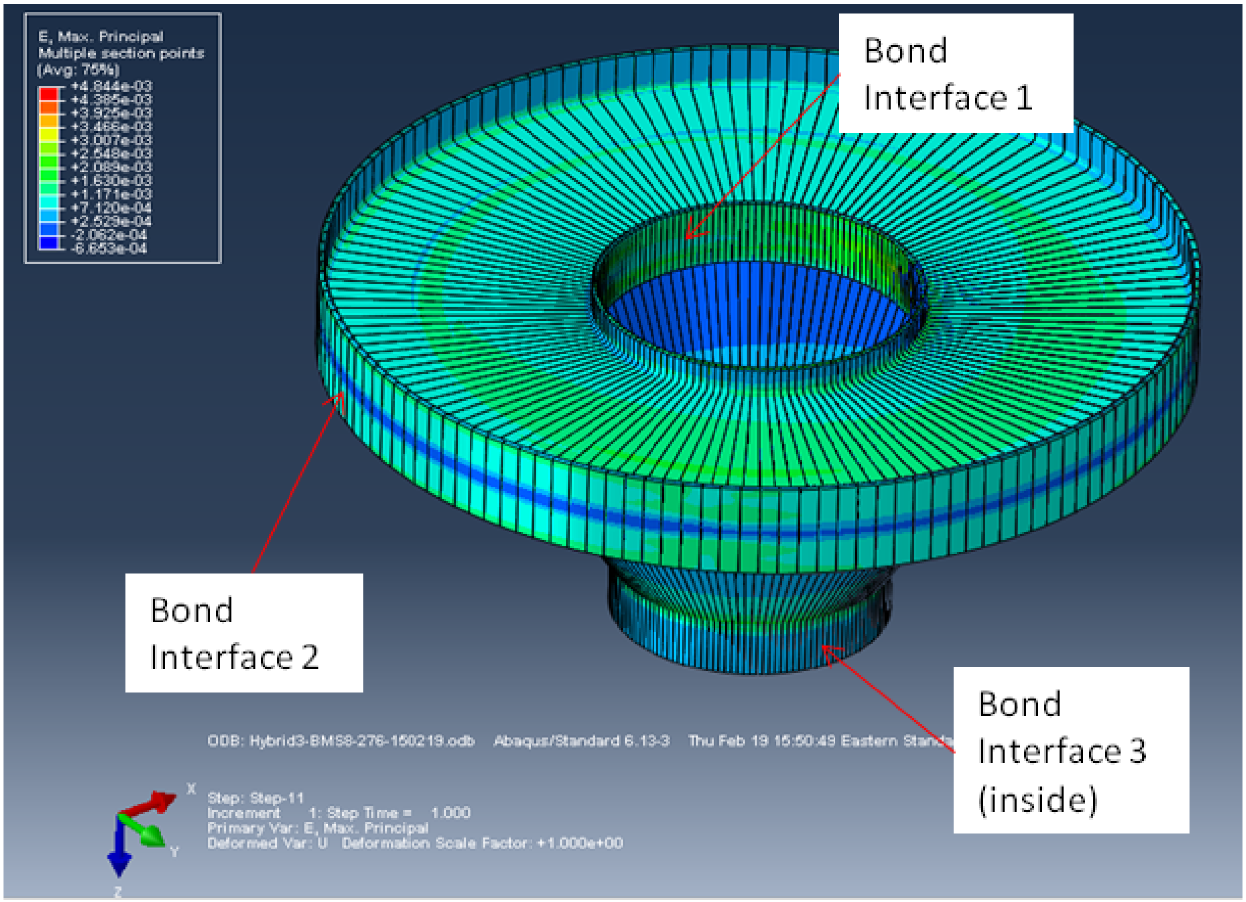


Figure 23.—Hybrid Bull Gear CFRP Portion Max Principle Strain (in./in.) at Step 11.

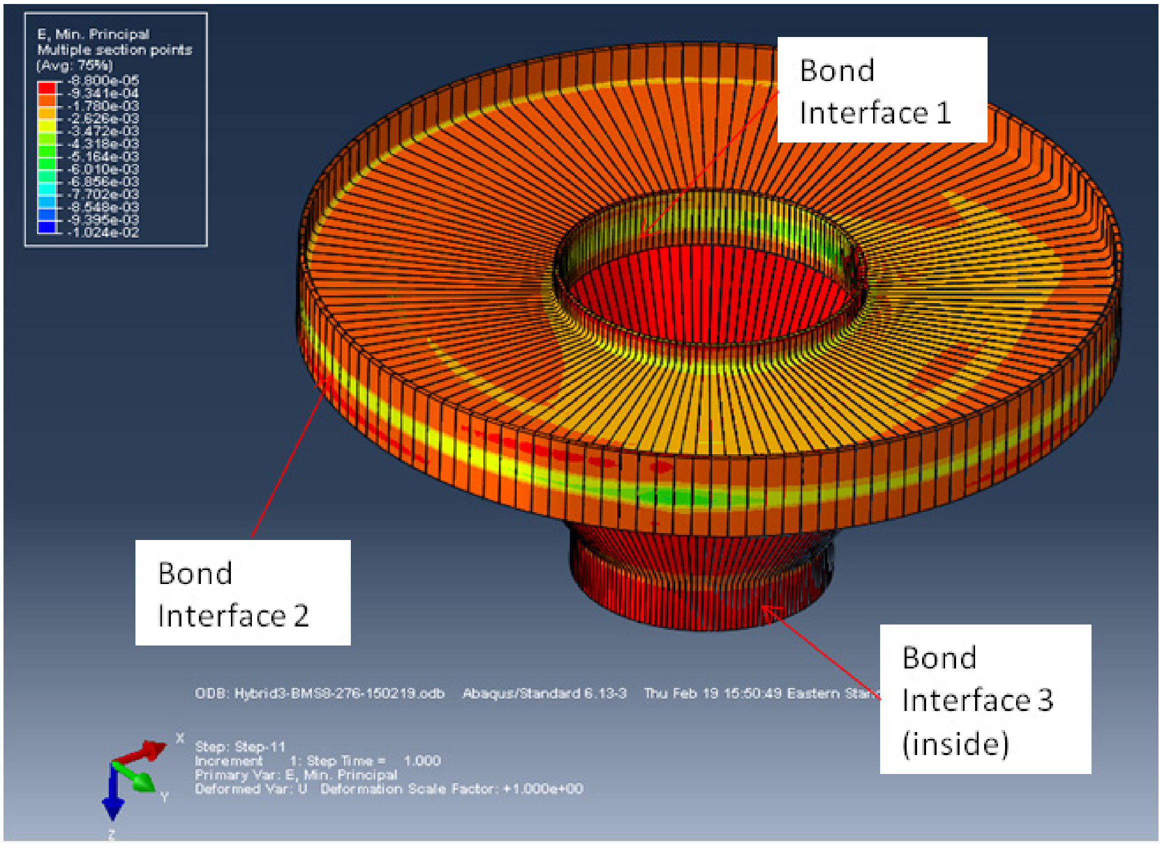


Figure 24.—Hybrid Bull Gear CFRP Portion Min Principle Strain (in./in.) at Step 11.

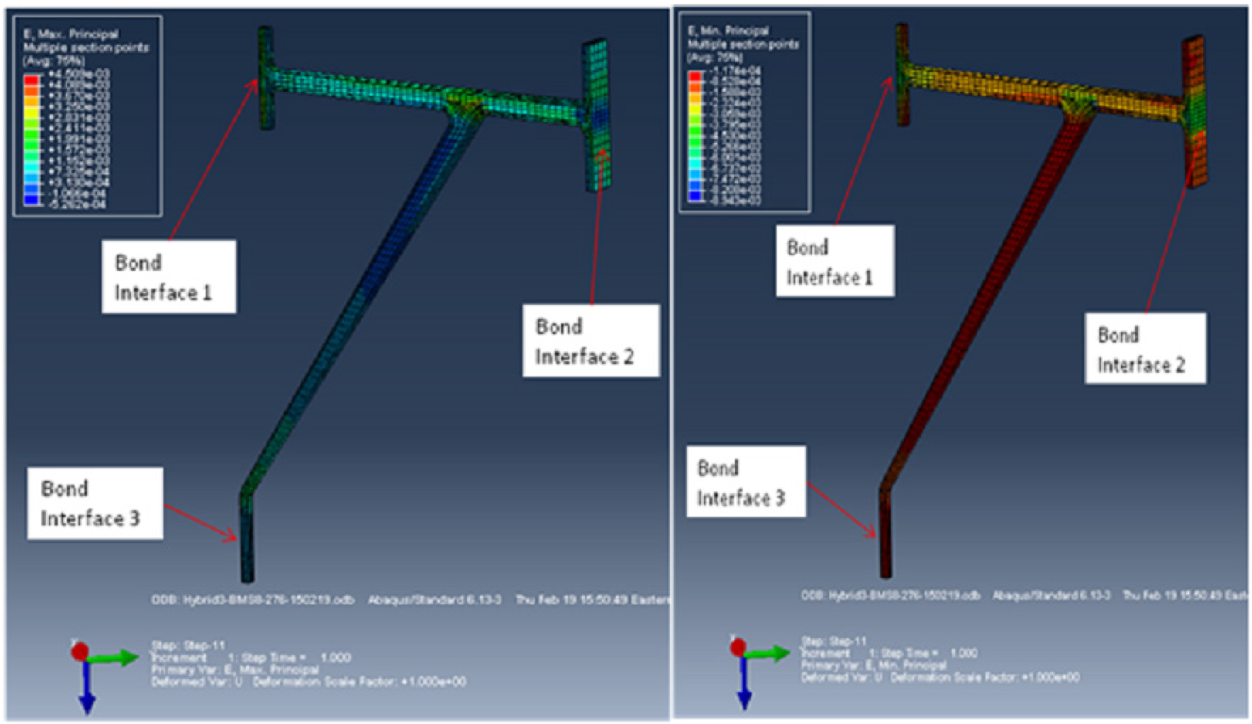
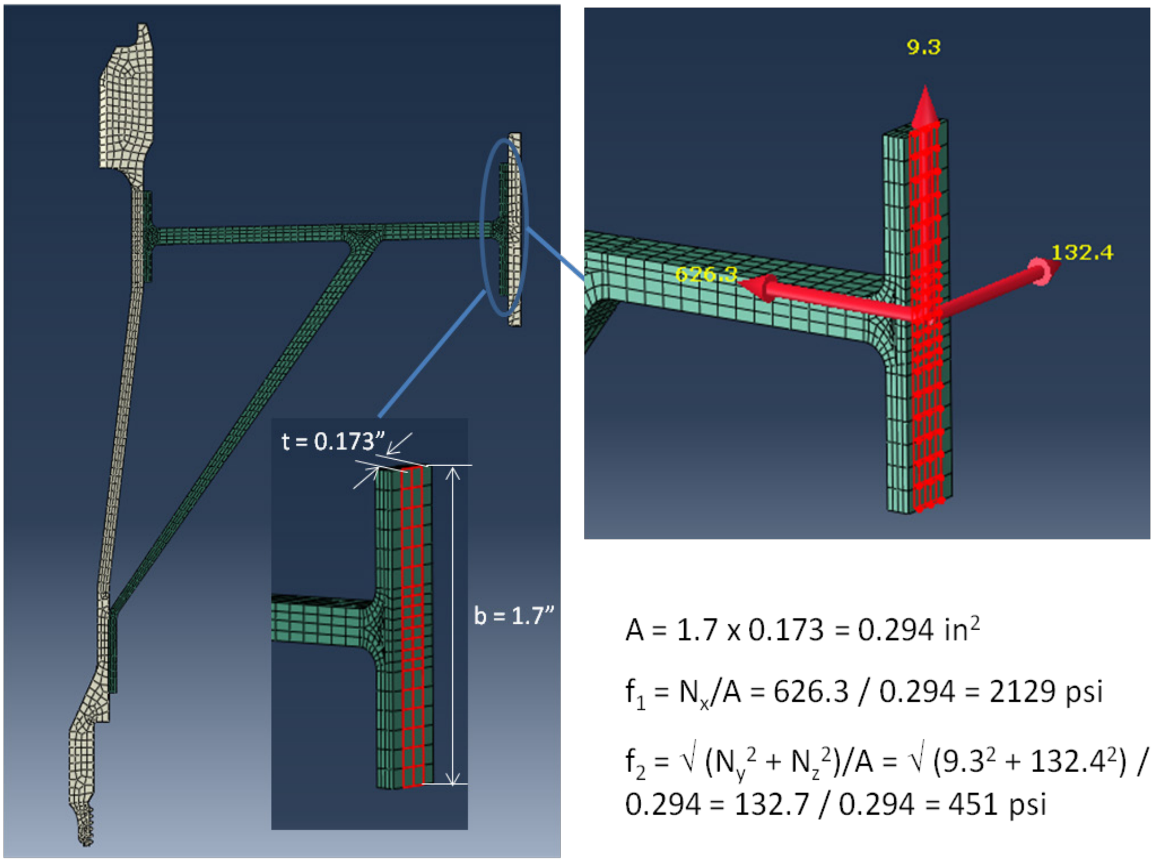


Figure 25.—Slice 89 of Hybrid Bull Gear CFRP Portion Max (Upper) and Min (Lower) Principle Strain (in./in.) at Step 11.



$$A = 1.7 \times 0.173 = 0.294\ \text{in}^2$$

$$f_1 = N_x/A = 626.3 / 0.294 = 2129\ \text{psi}$$

$$f_2 = \sqrt{(N_y^2 + N_z^2)}/A = \sqrt{(9.3^2 + 132.4^2)} / 0.294 = 132.7 / 0.294 = 451\ \text{psi}$$

Figure 26.—Slice 89 of Hybrid Bond Interface 2 Forces Per Area at Step 11.

TABLE 4.—MAXIMUM AVERAGE BOND FORCE PER AREA AT BOND INTERFACES AT STEP 11

Bond interface	Max average normal force per area (psi)	Max average shear force per area (psi)
1	1571	2235
2	2129	754
3	203	477

The bond is not modeled in the analysis model. The calculated bond forces at bond interfaces are required strength that the adhesive must provide. This sets the minimum spec requirement, when selecting the brand/type of adhesives to use. For this gear project, the adhesive’s minimum normal strength is 2129 psi, and minimum shear strength is 2232 psi. For example, a literature search at internet finds out a type of epoxy adhesive at www.epotek.com can meet the shear strength requirements. Its application guide can be found on their web site and its strength table at page 26 shows that this epoxy adhesive’s high end product can provide shear strength 2500 to 4000 psi (from the lap shear test), completely satisfying 2232 psi requirement.

Parallel Axis Power Gears Test Stand

Description

At the beginning of the investigation, it was proposed to develop a static, multi-axial test rig. The down selected gear would be installed statically (non-rotating) into the test rig and have quasi-static loads applied it. Boeing was to develop a technique that would apply a simulated rotating load onto the non-rotating component.

During the investigation, NASA and Boeing discussed and developed concepts for the test apparatus. The test rig evolved into a dynamic test rig that would allow the down selected gear (the bull gear) to rotate freely through a limited range of motion that includes several complete tooth loading and unloading cycles. The concept that resulted is called the Parallel Axis Power Gears Test Stand.

The basic concept of this test rig is simple. The test gear piece shall be mounted between two support structures and be allowed to rotate via rolling element bearings mounted into the support structure. The test gear piece shall mesh with a driving pinion similarly supported on a parallel axis. The driving pinion is rotated using a ROTAC drive motor, while torque is applied to the test gear piece via a ROTAC torque motor.

Because the test rig allows the gear test pieces to rotate, loading conditions similar to actual operating conditions may be applied to the gear mesh of the gear test piece. This will allow NASA to screen different configurations of the hybrid structure bull gear as if the component was installed into an actual gearbox. Since the gears are allowed limited rotation, there is no need to model additional testing hardware that would have applied a rotating load onto the component, as originally suggested.

Details of the test rig design are as follows:

The Parallel Axis Power Gears Test Stand shown in Figure 27 to Figure 29 will have two identical ROTAC Motors (Rotation Axis to mimic Production Gearbox), one Helical Bull Gear (with Composite Rim (Web)), one Helical Pinion Gear (all metallic), two adaptable quill shafts, and flight worthy hardware such as rolling element bearings, spanner nuts, etc. The support structure of the test rig will consist of two, 1 in. thick base plates each supporting a 1 in. thick parallel axis support structure. Each support structure is additionally supported by six triangular support gussets made out of ½ in. thick plate. Additional plates are used to cover the testing zone of the stand. A general parts list describing key hardware components is shown in Table 5. The rolling element bearings listed are standard catalog bearings that are similar to aircraft components. Further refinement of the bearings will be required during detailed design. Other details such as bolting, liners, interference fits, chamfers, and fillets would need to be cleaned up or further defined during a more detailed design phase.

It was decided early on that NASA's future testing of hybrid gears would primarily focus on various bull gear configurations only. Therefore, the Parallel Axis Power Gears Test Stand is not considered a multi-axial rig. In its current format, the test stand can only accommodate a limited range of bull gear sizes. Specifically, the bull gear axis of rotation must be approximately 10.481 in. from the pinion axis of rotation. The parallel axis supports are not adjustable at this point. Future development would be required to add adjustable supports that would allow variation in the distance between the two axes of rotation.

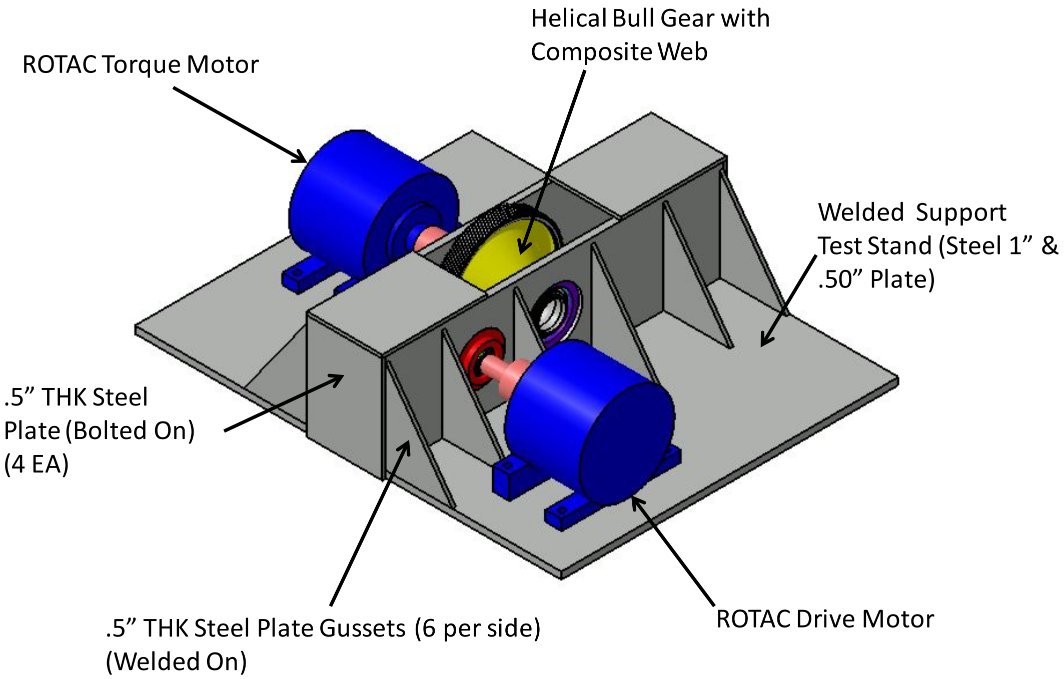


Figure 27.—Parallel Axis Power Gears Test Stand.

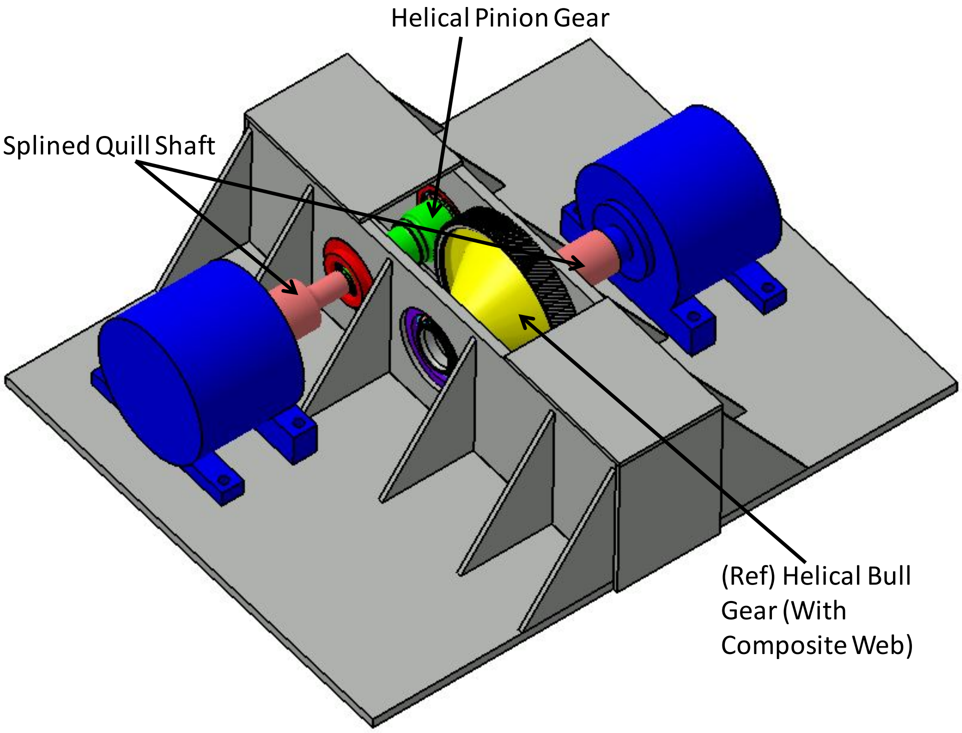


Figure 28.—Parallel Axis Power Gears Test Stand.

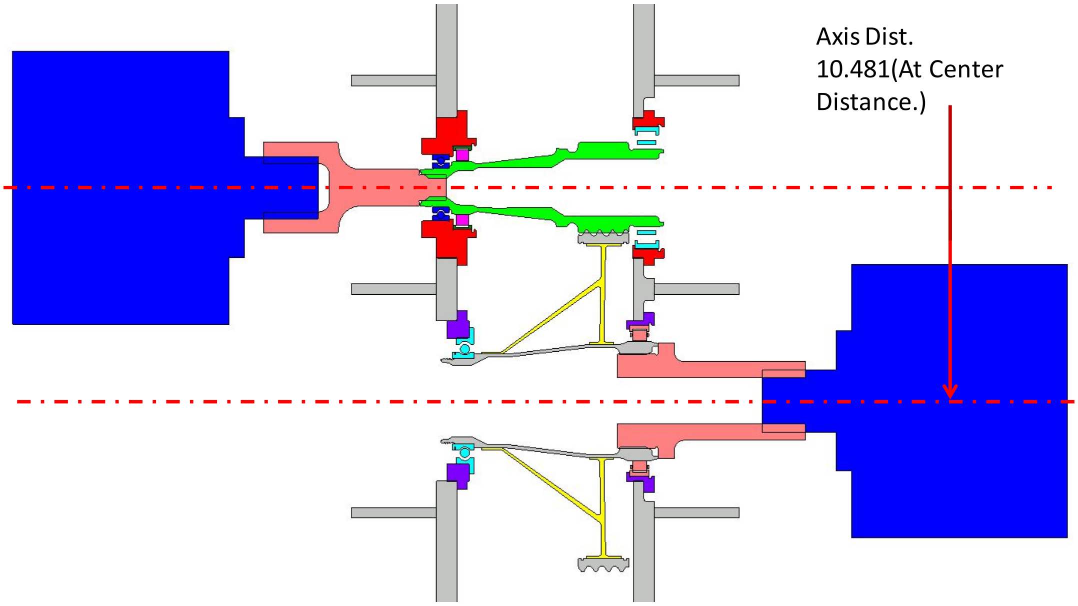


Figure 29.—Parallel Axis Power Gears Test Stand (Section Cut).

TABLE 5.—KEY HARDWARE COMPONENTS OF PARALLEL AXIS POWER GEARS TEST STAND

Component Name	Description	Quantity
ROTAC Drive Motor	Model #26R17, Single Vane, 280° Rotation 3,000 psi, Torque = 45,600 in.-lb	1
ROTAC Torque Motor	Model #26R31, Double Vane, 100° Rotation 3,000 psi, Torque = 174,900 in.-lb	1
*Drive Shaft	Ext Np15T, Int per SAE J498b-1969 Int 26T	1
*Torque Shaft	Ext Ng37T, Int per SAE J498b-1969 Int 26T	1
Test Stand Base Plates	1 in. THK Steel Plate (Floor Space TBD)	2
Parallel Axis Support Plates	1 in. THK Steel Plate (Dimensions TBD)	2
Support Gussets	½ in. THK Steel Plate (Dimensions TBD)	12
Support Covers	½ in. THK Steel Plate (Dimensions TBD)	4
Bearing, Roller – Cluster Gear	Timken RUSH 212	1
Bearing, Roller – Cluster Gear	Timken RUSH 218	1
Bearing, Roller – Helical Gear	Timken RUSH 028	1
Bearing, Ball – Cluster Gear	Timken HTH 211	1
Bearing, Ball – Helical Gear	Timken HTDH 022	1

*Components listed are specific to the baseline testing configuration of the effort.

Appendices

All appendices mentioned below can be found on the supplemental DVD.

Appendix	Description	Files
Appendix A	NASA RTAPS Test Stand	-ST54156 Top Product.CATPart -Internal Gear Profile.xlsx -Helical Gear – Input Design Table.xlsx -**CATPart files for all associated sub-level components**
Appendix B	Transmission3D Session File and Post Processing	-HybridDesign2.ses -IGlass-BullGear-CompositeRim-AIO.IGL -RimDepthAnalysisScript-AIO.txt -RimDepthAnalysisScriptRun.bat -ScriptResults_Step_1.csv thru ScriptResults_Step_11.csv.
Appendix C	Hybrid Composite Gear ABAQUS Input File	Hybrid3-composite-1-steel-150429.inp