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A Design Methodology for Optimizing and Integrating Composite Materials in Gear Structures

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Summary

The application of composite materials to gear structures is complex because of the gear shape, the need for precise dimensional tolerances, and the complex dynamic load condition. Methods are presented in this work to design and optimize an integrated composite hub-web structure that can be used as part of a hybrid composite-steel gear. The composite hub-web structure is a planar structure with a large decrease in thickness from the hub to the rim. Methods for design and optimization of this variable-thickness structure are presented along with a method for forming braided prepreg material to conform to the shape of this structure. A layered approach is presented that integrates cut plies or filler materials for thickness buildup with continuous-fiber layers for the primary load path. An additional gear design concept is presented that has an axially extended continuous-fiber composite structure that can be combined with the planar structure. A proposed optimization methodology is introduced where an optimized design is output for each type of optimization simulation. Through this process, composite knowledge can be incorporated in the optimization, and more control is given over the design during the process. The methods in this study provide a tool for designing and optimizing composite structures for gears and other high-power-density applications.

Introduction

Previous work has described hybrid gears in which composite material replaces the web section of a steel gear in order to provide lower weight (Refs. 1 to 6). Earlier work (Refs. 1 to 5) used a composite web section of constant thickness with mechanical interlocking between the composite web and the steel hub and rim sections. More recent work (Ref. 6) has used small thickness variations to provide greater thickness of the composite web in the region near the hub in order to account for stress concentration at smaller radii. In this report, a much larger increase in thickness is considered in order to replace the steel hub section of the gear with composite material. Fabrication of a structure with large thickness variation by the stacking of flat unidirectional ply layers introduces potential weak spots at ply terminations and potential defects such as wrinkling. This work considers the use of formable continuous-fiber layers to provide strength for the primary load path with cut plies or other formable material between the continuous-fiber layers to provide thickness buildup. Optimization simulations were performed to help the design process, and forming trials of a triaxial braided prepreg were completed to determine feasibility of fabricating the complex shapes needed for the continuous-fiber composite layers. The use of biaxial braided continuous-fiber layers in more complex gear structures having an extended axial gear body is also considered.

Design and Optimization of Composite Gear Web

The composite structure to be designed and optimized is an integrated hub-web structure in the shape of an annular ring having opening in the center hub location and a large decrease in thickness radially from the hub to the rim. For simplicity, this structure will be referred to as a “composite web” in the remainder of this paper. The design approach for fabricating the composite web is to use a formable continuous-fiber composite material in discrete layers separated by filler materials. A (0/+60/–60) triaxial braid architecture is used for the continuous-fiber composite material because of the quasi-isotropic stiffness. A prepreg form of the triaxial braid is used to provide precise fiber location and to provide the potential for forming of plies into the shapes needed for the continuous composite layers. Figure 1 shows one ply of the triaxially braided material where the fiber tows in the 0°, +60°, and –60° directions are illustrated. Each individual fiber within the layer provides a continuous load path that terminates on either the inside or outside diameter of the annular ring with no fiber terminations internal to the structure.

An initial design for a hybrid gear using the composite web and steel rim is shown in Figure 2. The sectioned view presented in Figure 2 indicates the three components of the composite web, which are the continuous composite layers, the cut filler composite layers, and the flat composite base. Dimensions are 13.37 in. (33.96 cm) in diameter and 2.675 in. (6.794 cm) thick at the center. The six continuous composite layers each consist of three formed plies that provide a direct load transfer path between the input shaft and the gear rim. Each continuous composite ply has a flat ring region at the outer radius for the bolted connection between the web and rim and a flat region at the center bore. The cut filler layers provide the large thickness buildup in the structure, but do not extend into the bolted connection. The outer filler layers each have 25 composite plies, whereas the inner filler layers each have 22 composite plies. The thickness buildup near the bore provides more material for the higher stresses at smaller radii and also provides a large through-thickness surface area for the shaft connection, which prevents compression failure. The design in Figure 2 shows a polygon geometry for connecting to a shaft, although alternative approaches could be considered.

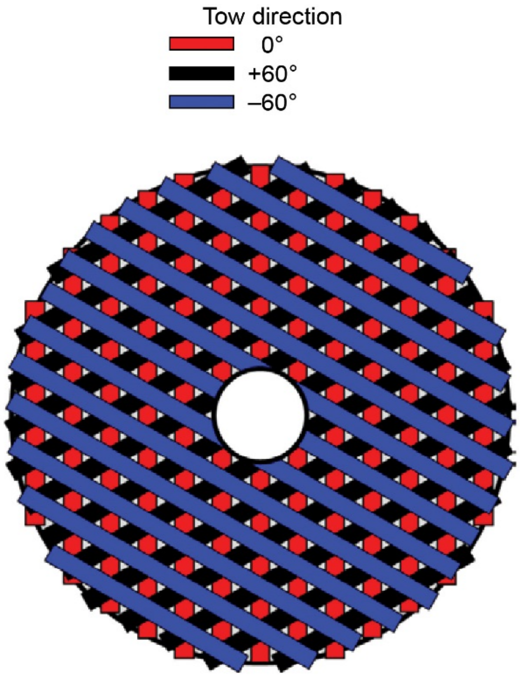

Figure 1.—Single layer of triaxial braid fiber preform in annular ring.

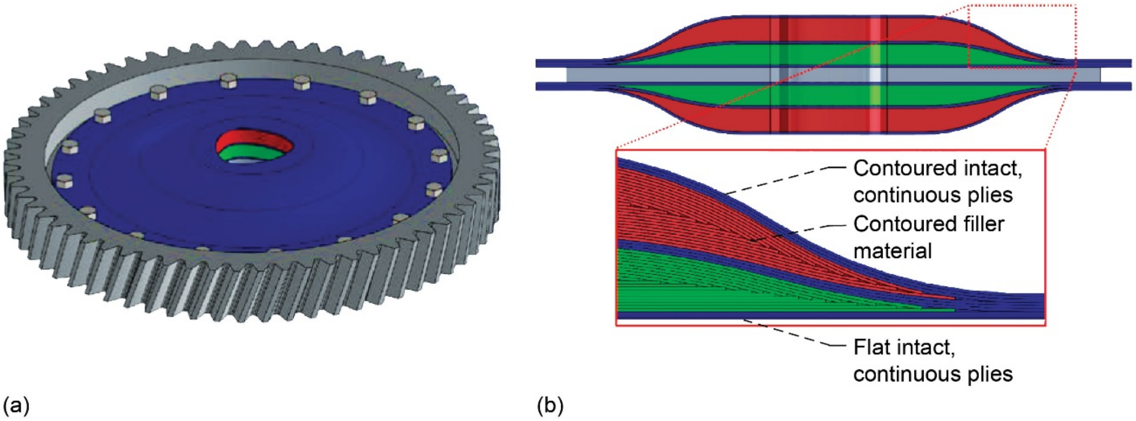

Figure 2.—Planar composite gear concept. (a) Model. (b) Sectioned view showing inner layout of composite plies.

Model and Optimization Simulations

A model of the hybrid gear design having a steel rim attached to the composite web was developed using HyperWorks^{TM} (Altair Engineering, Inc.) (Figure 3). The model includes both the web and rim to accurately simulate the distribution of the loading associated with meshing of the gear teeth and the interactions between the web and the rim. A T700/TC275 (Toray Industries, Inc.) triaxially braided carbon fiber/epoxy composite material was used for the composite web, and steel was used for the gear rim. The composite web is defined as an orthotropic bulk volume, using the HyperWorks^{TM} MAT9ORT solid element formulation, rather than individual plies in order to optimize the overall shape of the web. The gear rim is simplified by removing the teeth from the outer surface to reduce the size of the model and the computational expense of the simulations. The model is capable of reproducing the forces induced in the gear box of the Helical Gear Facility at the NASA Glenn Research Center, which are 7,050 lbf (31,360 N) in the tangential direction (torque), 2,650 lbf (11,788 N) in the radial direction (gear separation), and 1,500 lbf (6,672 N) in the axial direction (thrust). However, a 1.5 multiplier is used for the loading conditions in the model to ensure durability of the design. Currently, the model uses loading conditions that replicate a single helical gear configuration to optimize the more severe application of the bull gear, but the loading can be easily altered to simulate a double helical gear configuration. The loading is applied to a single, vertical line of nodes on the outer surface of the gear rim, and a fixed constraint is applied to the inner surface of the polygon bore. In order to simulate the bolted connection between the two parts of the gear, a bolted connector function is used within the software that applies a system of rigid-body elements in each bolt hole to hold the two parts together. The present bolted connection does not account for pressure induced by the tightening of the bolts, but future models will take this into consideration. In addition to the bolted connection, three contacts are defined on each surface between the gear rim and the web to incorporate any interactions that occur because of radial compression or bending moments.

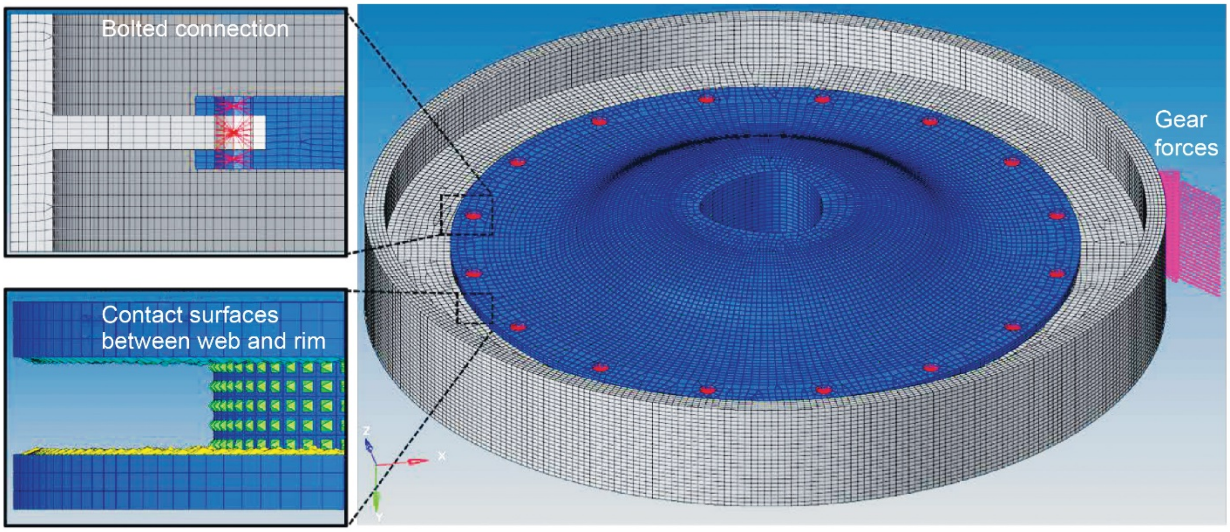

Figure 3.—Model of hybrid gear with all-composite web.

The model in Figure 3 shows the appropriate connections, contacts, and conditions to simulate the hybrid bull gear for a static representation of the load. However, the actual loading is dynamic where the line of nodal forces would be constantly moving around the circumference of the gear because of the rotating gear mesh. Since the bull gear is not axisymmetric, because of the geometry of the polygon attachment feature, three individual simulation cases were created by applying the gear forces at different locations around the gear rim to observe the effect on the response of the gear. The case presented by the model in Figure 3, also shown in Figure 4(a), is referred to as the “0° loading condition,” and the loading conditions in the two other cases were rotated with respect to the 0° orientation. These modeling cases, and the respective von Mises stress contours, are presented in Figure 4, where the maximum stress is approximately 90 percent higher in the hybrid gear web case loaded at a 60° orientation. Shape-change results (Figure 5) from subsequent optimization simulations of the 60° loading case demonstrate that changes could be made to optimize the design for this particular loading case. However, the combination of results from each optimization simulation case was considered, since an optimized gear will experience loading at each of these orientations. The end result from these shape optimizations was an optimized design that was used to create a solid model for subsequent simulations and to define the ply geometry.

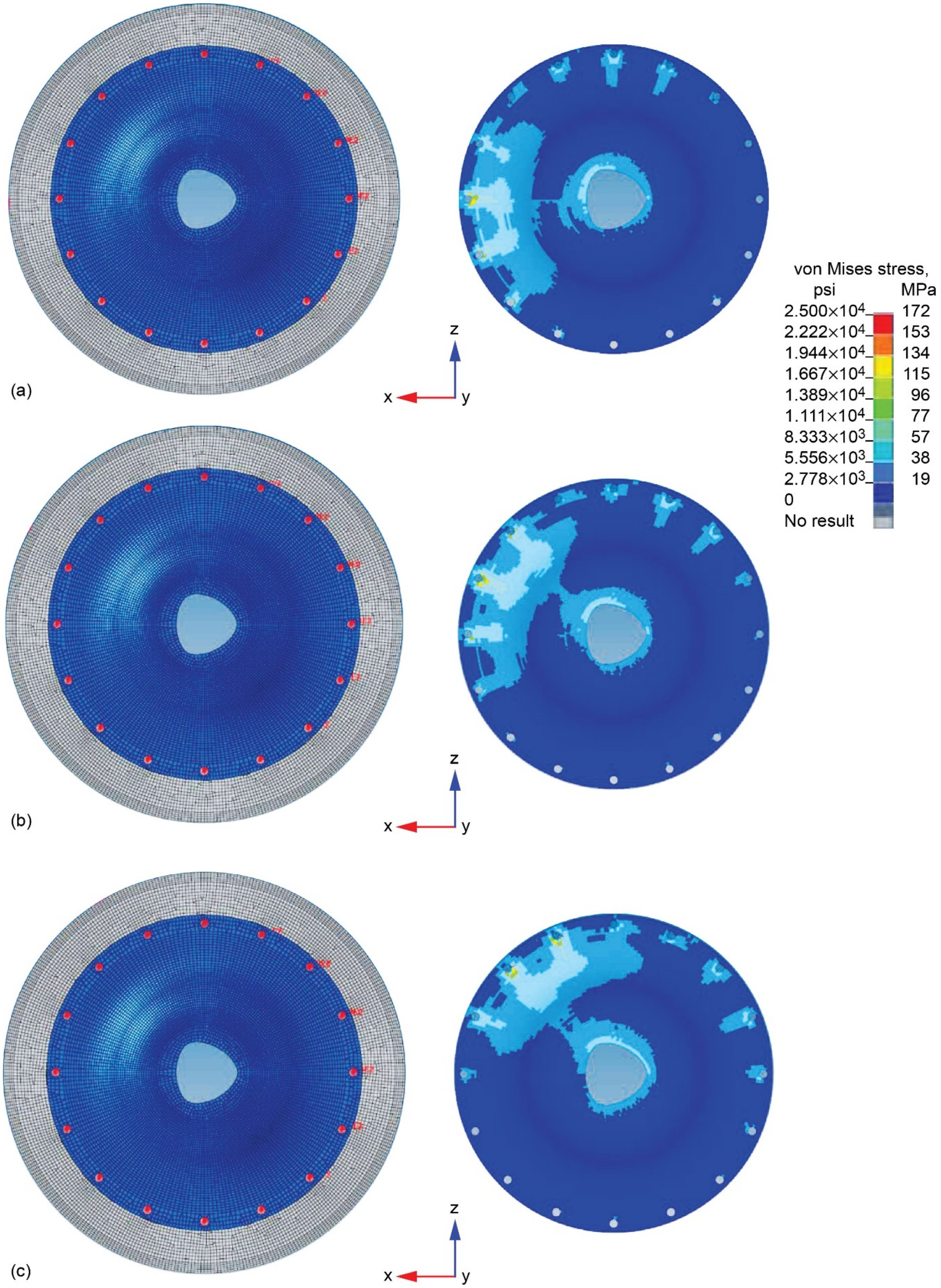

Figure 4.—Model of hybrid gear with all-composite web at various loading conditions, indicating location and orientation of each individual load state (left), and corresponding von Mises stress contour (right). (a) 0°. (b) 30°. (c) 60°.

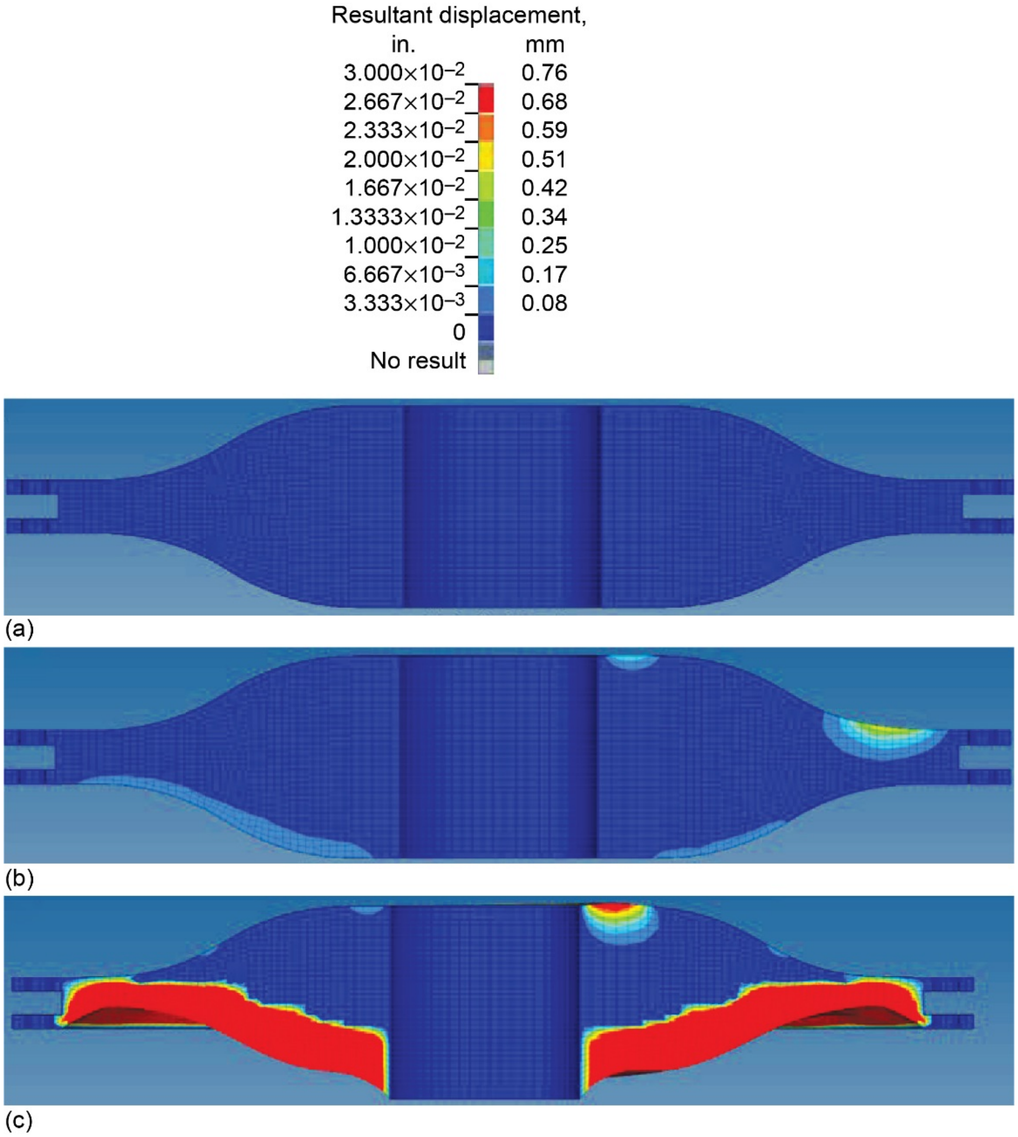

Figure 5.—Shape-change contours and optimized geometries of cross sections from simulation of hybrid gear with all-composite web. (a) Initial design. (b) 0° load condition. (c) 60° load condition.

Forming Trials

As previously mentioned, the forming of certain plies before the manufacture of the composite web is a key aspect in defining material and load continuity for high power transfer. Therefore, the formability of the composite prepreg is crucial to the production of these designs. Initial laboratory experiments were performed using T700/TC275 triaxial braid prepreg plies to determine the material's formability. Forming tools were fabricated by three-dimensional (3D) printing, using a high-performance polyphenylsulfone (PPSF) material. Solid models of the tools are shown in Figure 6. The tools were designed for forming the composite prepreg layers to the same diameter and thickness change as that of the aforementioned composite web design. Holes were added to the corners of each tool design for alignment of the two tools. A heat gun was used to apply temperature to the composite prepreg while it was hand pressed to the inner surface of one of the forming tools. The second forming tool was pressed with the prepreg layer and the first forming tool to obtain the resulting images in Figure 7. The results show that wrinkling and damage of the ply were avoided during forming.

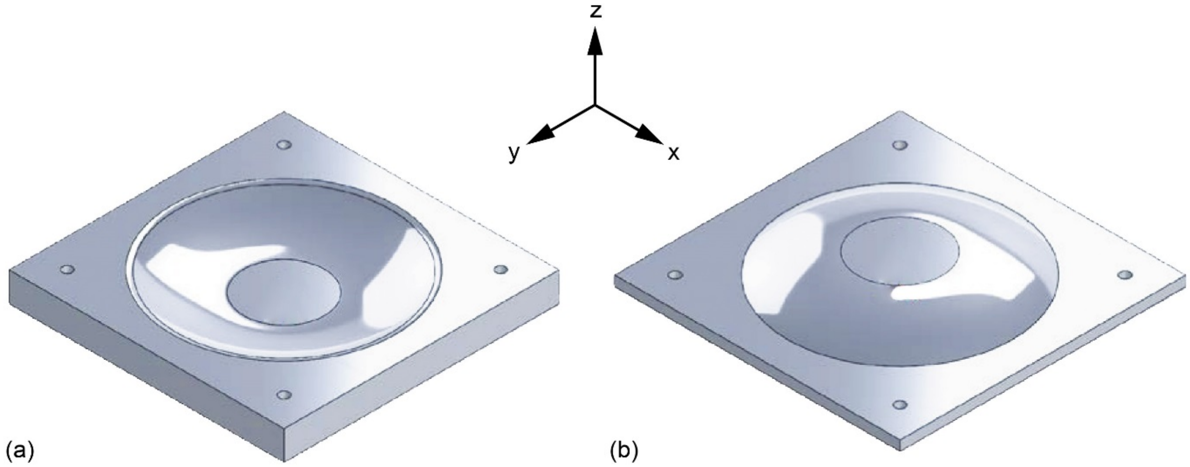

Figure 6.—Tool design for composite web formability trials. (a) Convex mold. (b) Concave mold.

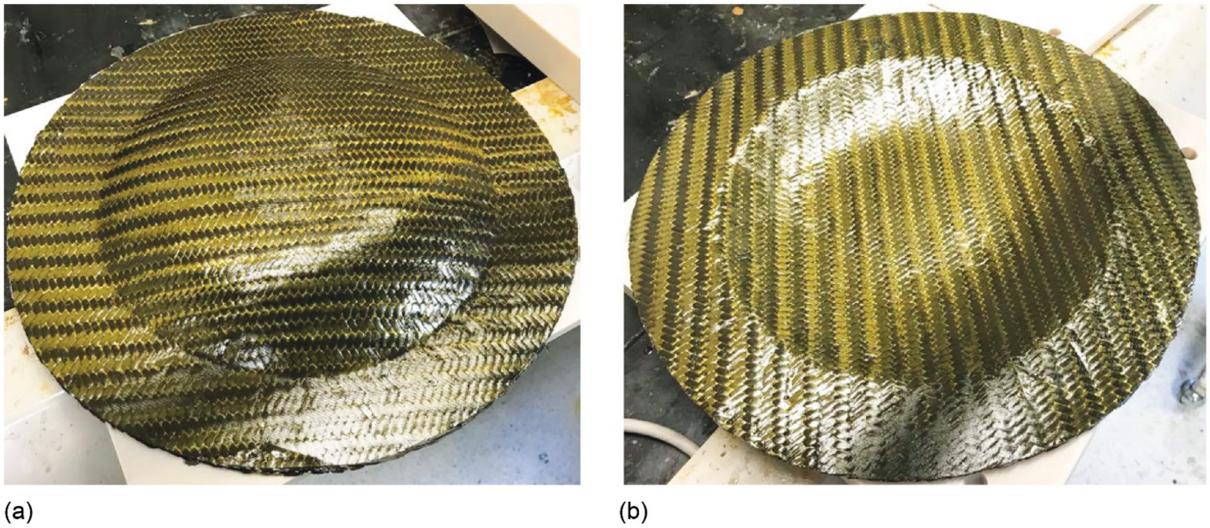
(a)
(b)

Figure 7.—Forming results of three circular T700/TC275 triaxial braid prepreg plies. (a) Convex surface. (b) Concave surface.

Design of Extended Composite Gear Structure

Another potential application for composite integration in gear structures is an extended axisymmetric structure that can be combined with the planar composite web described above. Figure 8 shows an example of this type of assembly where the composite web interfaces with the gear rim at the top of the figure and the extended composite section connecting to a bearing race at the bottom. The section view of this assembly in Figure 8(b) shows that the composite web and extended composite section in this design both connect using the same bolt holes. One approach to fabricating the extended composite section is to use a biaxial braid architecture that allows for variation of diameter and braid angle along the axial direction of the part. The extended composite part is similar to the planar composite web section in that there is fiber continuity from the top of the extended composite section to the bottom (Figure 9) without any internal fiber cuts. The example shown in Figure 8 provides one configuration for an extended gear structure, and many other gear and gear-shaft configurations could be designed.

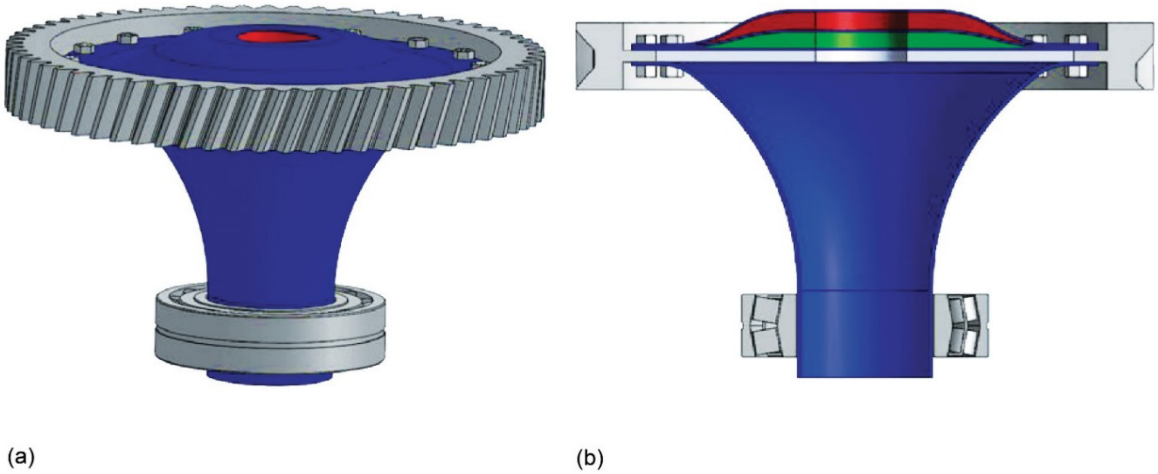

Figure 8.—Hybrid gear with extended composite section. (a) Structure overview. (b) Section view showing internal features.

Figure 9.—Load continuity of biaxial braid tow in extended composite section of hybrid gear.

A modeling methodology was developed to incorporate the variability in braid angle and wall thickness. As shown in Figure 10, these changes can be applied by discretizing the model into multiple ring sections. Each section has a different thickness as well as a distinct set of material properties, which are related to the braid angle in the section defined by the curve in Figure 11. The current model was made in LS-DYNA® (Livermore Software Technology Corporation) and is composed of 17 discrete ring sections; initial structural simulation of this model was performed under static torsional loading. The boundary and loading conditions for the simulation are presented in Figure 10. Several variants of the flared composite tube model geometry have been simulated and compared including models with constant thickness. Figure 12 shows the shear stress-strain plots from the different static torsion simulations where the simulation was run until an instability occurred, which is possibly due to geometric buckling or numerical instability of the analysis. The results demonstrate the effect that variable thickness and braid angle have on the response where changing the wall thickness of the model shifted the instability point along the curve. The introduction of thickness and braid-angle variability caused a decrease in the stiffness of the overall part. The shear stress pattern at the instability point is displayed in the contours of Figure 13 for a model with a constant thickness of 0.095 in. (0.241 cm).

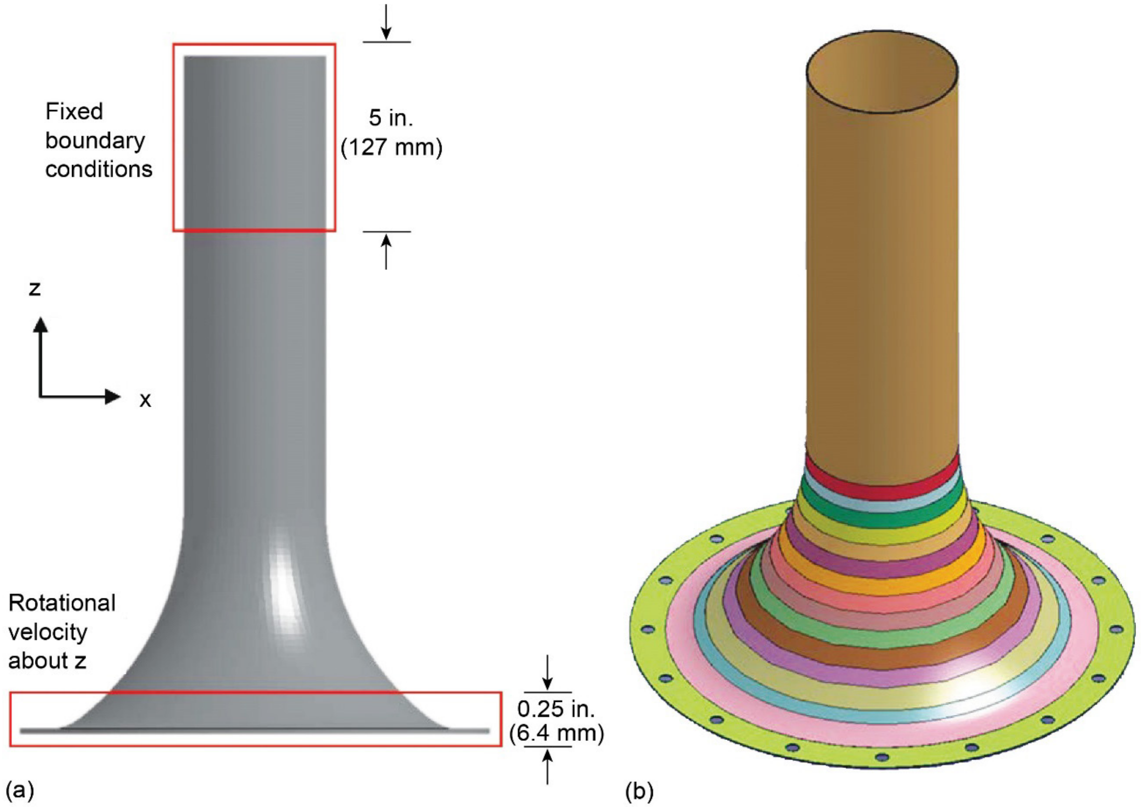

Figure 10.—Boundary and loading conditions for composite flared-tube model. (a) Conditions. (b) Discretized model.

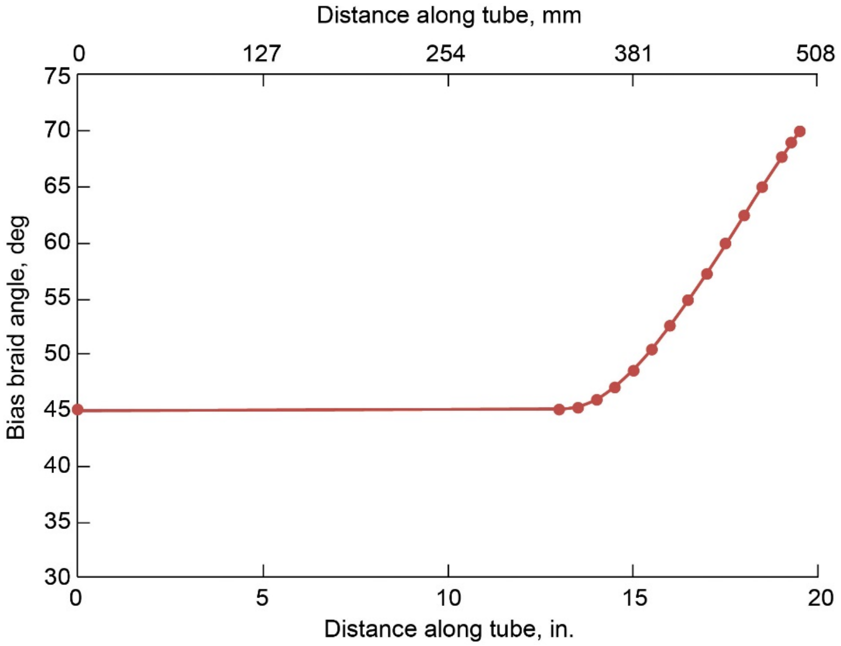

Figure 11.—Biaxial braid angle change for extended composite section of hybrid gear.

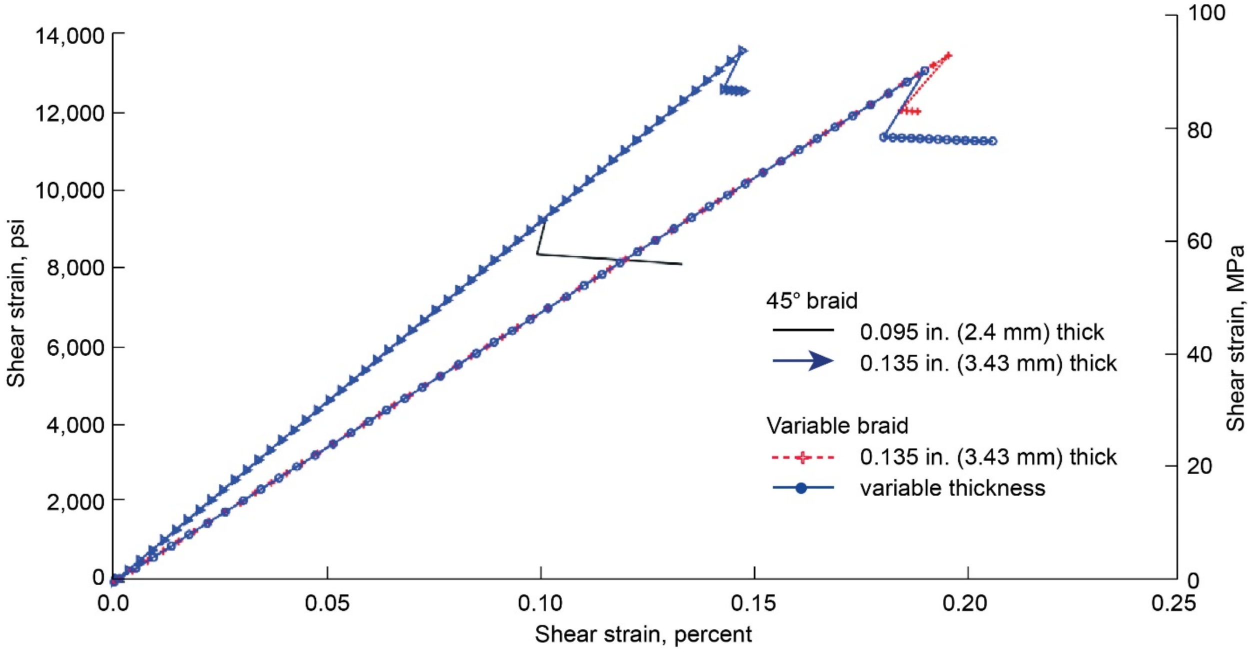

Figure 12.—Shear stress-strain plots from static torsion simulations of different extended composite section models.

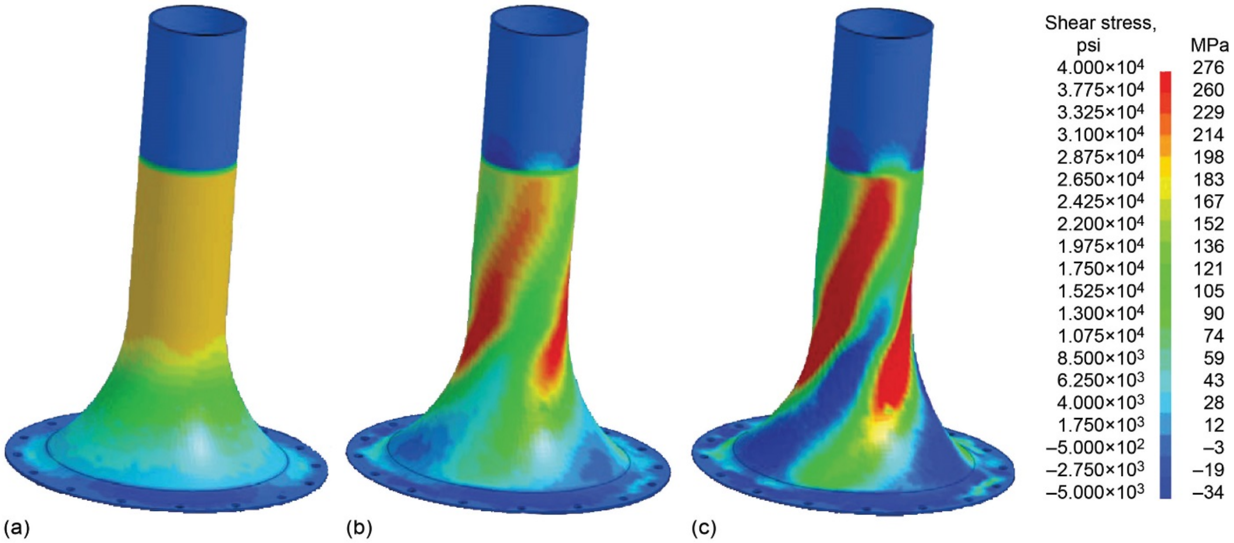

Figure 13.—Shear stress contours from extended composite section model with 0.095-in. wall thickness. (a) Extracted immediately before instability point. (b) Extracted immediately after instability point. (c) Prolonged time after instability point.

Proposed Optimization Methodology

An optimization methodology is proposed for designing gear structures with composite materials. The intent is to develop a generalized optimization methodology that is capable of designing composite gear structures for different applications, spanning from traditional rotorcraft systems to the emerging urban air mobility market. The challenge in developing the methodology for gear structures is that performing optimization simulations for a dynamic system can be difficult and computationally expensive. In order to overcome this complexity, the methodology reduces the dynamic problem into multiple static optimization problems that account for rotational asymmetry in the geometry, material, and loading conditions. Although the reduced set of simulations are not able to address dynamic fatigue loads directly, the goal of the static optimization is to minimize strain and stress variables to mitigate damage precursors associated with fatigue. Additional challenges in the methodology consist of changing material coordinate systems associated with composite ply forming and accounting for the composite architecture of weaves and braids.

The steps of the methodology is detailed in Figure 14, where the composite web design from the previous sections is used as an illustrative example, and it addresses the various challenges by performing different types of optimization at each step. The output for each step is multiple designs of the composite gear structure that can be used as input design for the subsequent step. The complexity of the model increases for each subsequent step to enable computational efficiency while improving reliability of the design. The breakdown of the methodology into steps allows the user to review the designs at each step to determine feasibility and insert composite knowledge that may not be taken into account. The free-shape optimization takes an initial, arbitrary design of the gear structure and applies orthotropic composite properties to a 3D element mesh of the hybrid gear structure. The hybrid gear structure is represented as a bulk volume model in this step (i.e., without explicit ply definition). The objective for this optimization is to minimize stress or strain in the part while constraining or preserving key geometric aspects of the design, such as the connecting shaft interface or the bolt-hole dimensions. In the section

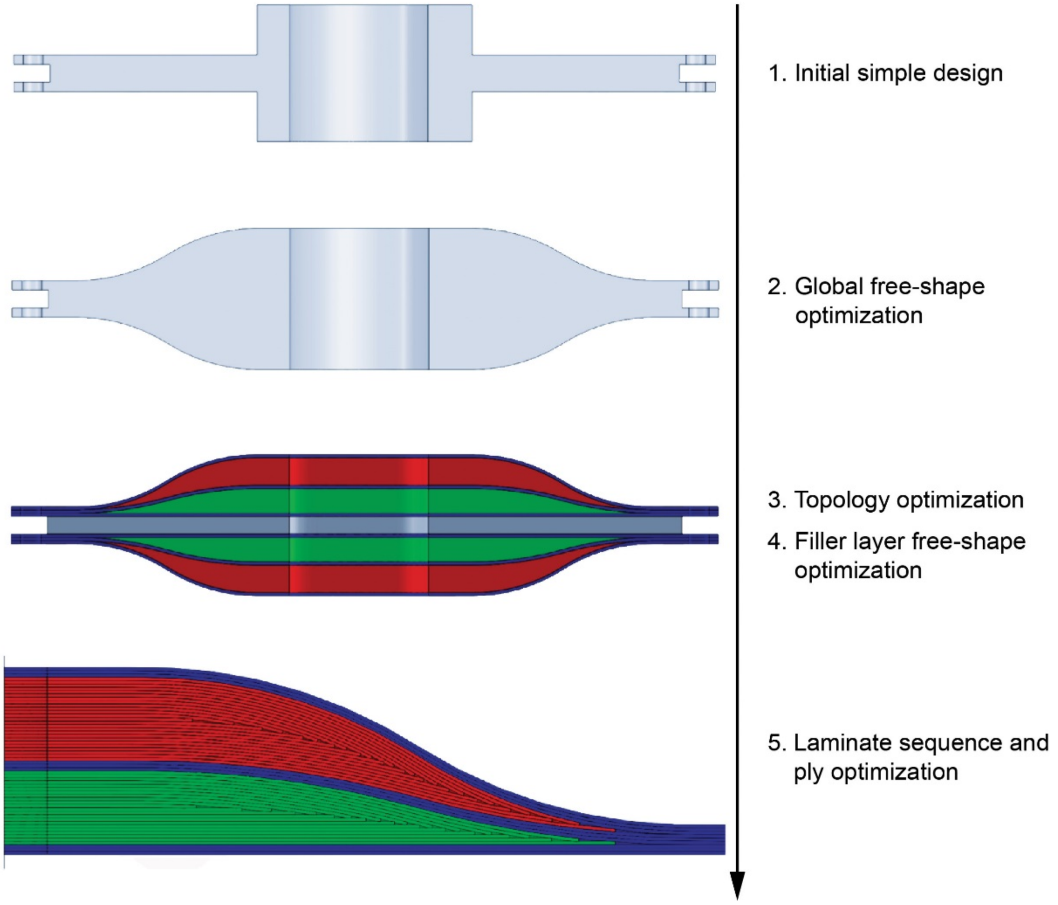

Figure 14.—Optimization methodology flowchart for composite gear structures.

“Design and Optimization of Composite Gear Web,” some initial optimization results were presented for the free-shape optimization of the bulk composite volume of the web. The following topology optimization step utilizes the geometry of the free-shape optimization results and minimizes the weight or volume of the hybrid gear structure. Constraints are placed on the stress to ensure that the minimization of stress from the previous optimization simulation is preserved. The results from this optimization provide a loading map of the gear structure cross section where the continuous-fiber layers of composite material are required. Additional or thicker layers can be added for greater strength and stiffness, and lower density filler layers can be added to volumetric regions where load-bearing material is not needed. If the filler layers are defined using different materials from the continuous-fiber composite layers, another free-shape optimization step is performed to minimize stress or strain in the filler regions. The last step is an optimization of the laminate sequence for the different layers, and the output is the final optimized design with ply shapes.

Concluding Remarks

Methods for modeling and optimization of a composite hub-web structure in a hybrid composite-steel gear were demonstrated. The composite hub-web structure is designed with continuous-fiber layers as the primary load path and filler materials between the continuous-fiber layers for thickness buildup. An optimization methodology was proposed that creates load continuity using continuous-fiber composite material layers and allows the user to integrate composite knowledge at various steps of the process. Initial free-shape optimization simulations of a planar composite gear web demonstrated that the rotational symmetry of the part is important and needs to be considered when designing gear structures with composites. The feasibility of forming triaxial braid composite prepreg to the complex shapes required for the continuous-fiber layers was demonstrated in forming experiments. The methods in this study provide a tool for designing and optimizing composite structures for gears and other high-power-density applications.

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