ADVANCED TECHNOLOGIES FOR DESIGN AND FABRICATION OF COMPOSITE AUTOMOTIVE COMPONENTS

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Abstract

Structural composites are available in various forms and functionality, providing the designer a tremendous amount of flexibility to develop innovative composite design solutions. But these advantages often cannot be realized without novel manufacturing methods that can accommodate heterogeneous parts of complex shape. Today, new manufacturing methods allow the designer to satisfy specific local strength criteria by judicious selection and placement of materials. At the same time, the freedom of complex component geometry provides the added benefits of combining multiple components/operations into a one-piece compression molded component.

These new material combinations and manufacturing techniques provide a vast and comprehensive set of new opportunities for novel design solutions that exceed previous performance, overcome previous limitations and stretch the limits of previous engineering design intuition. In order to take full advantage of these new materials and manufacturing techniques, advanced automated design optimization technologies can be used to discover creative solutions. These methods dramatically improve the relevance and speed of complex manual design processes, truncating them from months to days or even hours. They concurrently explore hundreds of design parameters and their relationships in product and process design scenarios, and intelligently seek optimal values for parameters that affect performance and cost. These design tools have been used in the development of several FRP structural programs solely focused on replacing traditional materials like steel, aluminum, and cast iron.

In this paper, a new composite manufacturing method and a new design optimization technique are discussed briefly. Several example applications to real automotive composite components are described to illustrate the benefits of combining advanced manufacturing and design methods to realize novel composite solutions at a fraction of the weight of equivalent metallic parts.

Manufacturing Concept Overview

Composite materials have long been utilized in various industries including automotive, heavy truck, aerospace, civil infrastructure, marine and durable goods. Many applications are centered on time tested manufacturing techniques such as: Pultrusion, RIM, SMC, VARTM, Compression molding, etc. The products originating from these production processes are being used in everyday life, yet the technology behind fiber-reinforced polymer (FRP) composites is just beginning to blossom into its full potential. Consolidation of parts, mass reduction, and local placement of materials to increase strength and stiffness are but a few of the possible benefits.

A new manufacturing approach has been developed that allows one to achieve specific strength criteria via local material placement and hybridization. This approach also accommodates complex component geometry, which provides customers with the added benefits of combining multiple components/operations into, in some cases, a one-piece molded component. While all component geometries may not be feasible as a one-piece design, this technology does offer a simplistic approach to combining otherwise multiple operations stemming from the steel or casting industries.

Design Overview

The design of modern vehicle structures is driven by many competing criteria, such as improved safety and fuel efficiency, lower cost, enhanced performance, and increased style flexibility. In addition, the introduction of new manufacturing processes and materials significantly increases the available design space, or the set of all possible designs for a problem. This is especially notable in the design of composite structures because, in addition to the many forms of composites, the fiber orientation of each ply within a laminate can vary independently throughout a 180 degree range. In order to explore this large design space more effectively while trying to reduce design cycle times, engineers can now take advantage of automated design optimization and simulation software tools. These tools can greatly decrease the time required to identify a set of feasible, or even near-optimal, designs prior to building and testing the first prototype. Moreover, these tools also overcome the limitations of human intuition and allow the designers freedom to seek creative solutions that are not obvious to even the most experienced engineer. This is true in general but particularly true with shape optimization problems, which can involve potentially hundreds of design variables.

HEEDS (Hierarchical Evolutionary Engineering Design System) is the design automation software that was used to find optimal designs for each of the composite automotive parts detailed below. This software combines local and global optimization techniques in order to more efficiently search the design space. It can dramatically improve the speed, quality, efficiency and relevance of complex manual design searches, truncating them from months to days or even hours. This is partly accomplished by quickly identifying design attributes with superior potential and using them to improve and accelerate the search for an optimum solution. It concurrently explores hundreds of design parameters and intelligently seeks optimal values for parameters that affect performance and cost. In addition, for problems that contain many design variables and criteria, it allows the user to decompose the overall problem into a set of smaller, more tractable problems. This design automation is able to use the power and availability of cheap computing resources to obtain improved results. It also can be integrated within existing design processes. Therefore, it is possible to use any combination of commercial and in-house proprietary and legacy analysis codes to complete the product design.

Roll Restrictor Bracket Example

The roll restrictor bracket shown in Figure 1 was designed to meet the functionality of an existing steel part. The bracket attaches to the transmission and engine, and supports a roll restrictor between the two roll restrictor attachment points labeled in Figure 1.

Design Requirements and Challenges

The major performance requirement of this bracket was that it have a natural frequency greater than 500 hz. Constraints were also placed on the stresses within the structure under multiple loading scenarios. The objective of the analysis was to minimize mass. Geometrical constraints fixed the transmission, engine, and roll restrictor attachments points. Additionally, a large access hole, shown in Figure 1, was necessary yet was not part of the original steel part.

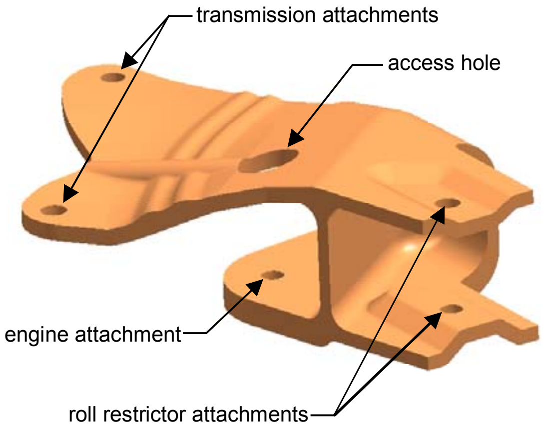

Figure 1. Final Design of Roll Restrictor.

E-glass fabric has about one-eighth to one-tenth the stiffness of steel. Therefore, in order for the composite part to meet the specified vibration constraint, special attention was given to the thickness and shape of the bracket. Inclusion of plies of uniaxial fibers was considered as well.

The original steel part did not have the web which connects the top and bottom plates shown in Figure 1, but did have a plate welded along the front face in Figure 1 that significantly added to the overall stiffness. One of the goals for the design of the composite roll restrictor was that it be one piece and not require any assembly. In order to accomplish this goal, the bracket had to be designed such that a mold could slide out after the composite set. This prevented the use of any structural stiffener like that on the original steel piece.

A common way of accomplishing this design task is to make an initial guess concerning which regions should be thicker or have a different shape, and virtually test these assumptions using finite element modeling or some other analytical scheme. If the targets are not satisfied, then the model can be changed and retested. This manual process might need to be repeated numerous times, a very cumbersome and time-consuming approach that often results in a design that is at best sub-optimal. Automated design optimization leads to a much more efficient and effective search for an optimal solution, and often leads to a much better design by simultaneously considering a much larger number of design variables than could be achieved manually.

Analysis

Initially, a simple finite element model was built based on the shape and thickness of the original steel part. It was fixed at the transmission and engine attachments, and a cylindrical tube was placed between the roll restrictor attachment points to ensure that the points would move together, as they will when the actual roll restrictor is in place. The model was analyzed using E-glass fabric throughout. As expected, the preliminary results showed that the part was much too flexible relative to the 500 hz. constraint. (A simple replacement of steel with composite material is seldom successful.) The main mode of vibration was torsion, so the web was added to help control the twisting and, although the web helped, the frequency of the natural vibration was still not high enough. The first mode shape indicated that the region between the access hole and the transmission attachments was too flexible. At this point, the automated design optimization software was used to determine the best shape at the end near the transmission, the required thickness of different regions of the part, at what orientation unidirectional fibers should be aligned, and whether or not unidirectional fibers should be used at all. The final shape is shown in Figure 1. Note the ripples in the top plate, which were based on the shape optimization results. The composite component is 40% lighter than its steel counterpart. In the end, it was found that unidirectional fibers were not a good choice of material because the part did involve a fair amount of torsion and fabric was a better choice

Control Rod Example

The control rod shown in Figure 2 was designed to replace an equivalent steel part. Bushings fit in both ends through which the rod is attached to the chassis on one end and an axle on the other.

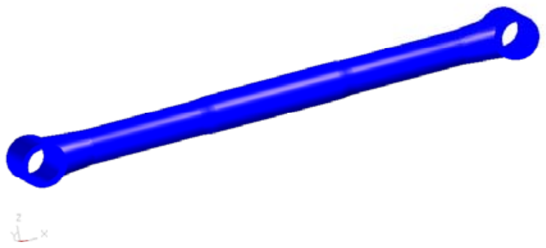

Figure 2. Final Control Rod Design.

Design Requirements and Challenges

This rod was designed for a set of five inertial load cases simulating vehicle movements such as braking and going over a curb. These loads were determined using the multi-body dynamics analysis code ADAMS. As with many composite applications, the challenge in designing this part was in the connections, specifically, connecting the cylindrical rod portion to the ends and ensuring a smooth transition throughout. The geometrical constraints were at the ends: the inner diameter of the ends was fixed so that bushings could be mounted, and the outer dimension had to be small enough in order to fit within a bracket designed for the original steel rod.

Analysis

Design automation software was used in tandem with a finite element solver to iterate on the design and find an ideal solution. Because composites do not fail according to the von Mises criterion, the rod was designed by limiting the principal strain values. Stiffness requirements were not definitively known prior to the analysis of the rod, so two extra load cases were included in the design to test the design under pure axial and pure bending loads. The optimization parameters consisted of a constraint on the maximum principal strain and an objective of minimizing the deflections of the two static load cases (axial and bending) in order to maximize the stiffness of the part. A cylindrical cross-section for the rod was selected due to the presence of torsional loads. The design automation tool was used to determine the thickness of material along the rod, whether the material should be fabric or unidirectional fibers, and the orientation of any unidirectional fibers that are needed. Although the steel rod was solid throughout, it was determined that the composite part could be hollow. The software determined the ply layup and the total mass savings over the original steel part was 50%.

Upper Control Arm Example

The upper control arm shown in Figure 3 was designed to replace an equivalent aluminum part and is a component of an independent front suspension system. Two bushings fit in either end of the cylinder and a ball joint bearing attaches to the hole at the top.

Design Requirements and Challenges

As in the control rod example, the control arm was designed for a set of five load cases based on vehicle movements such as braking and going over a curb. The inner diameters where the bushings and ball joint are inserted are fixed. Additionally, another component of the suspension system moves through the middle of the part, thus necessitating the large hole in the center.

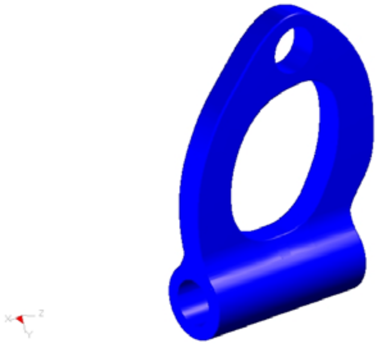

Figure 3. Final Design of Upper Control Arm.

Analysis

Design automation software was used in tandem with a finite element solver to determine a good design while incorporating geometrical and performance constraints and objectives. The constraint placed upon the model was one that kept the maximum principal strains below a minimum value. The objective was to minimize mass. The arms of the part that connect the cylinder to the ball joint are hollow, and the design automation software was used to determine the material thickness necessary for these arms. The total mass savings of this composite upper control arm over the equivalent aluminum part was 25%.

Torque Arm Example

Design automation software used in tandem with ABAQUS/CAE and its associated implicit solver was called to improve upon the design of the torque arm shown in Figure 4. This part is similar to one published by Botkin, et al[1].

Design Requirements and Challenges

The parameters shown in Figure 5 are the only factors affecting shape which could be modified. The goal of this analysis was to minimize the weight of the part, while constraining the maximum Von Mises stress to a specified value.

Analysis

This parameter driven optimization was accomplished using design automation software that worked together with a preprocessor and finite element solver. The preprocessor was used so that the shape of the torque arm could be parameterized and remeshed for each evaluation. Without remeshing, only minimal changes in shape could occur so as not to distort elements. The preprocessor can be called through a python script, and this enabled the design automation tool to use the preprocessor to create and mesh a design based on specified values for the four shape parameters.

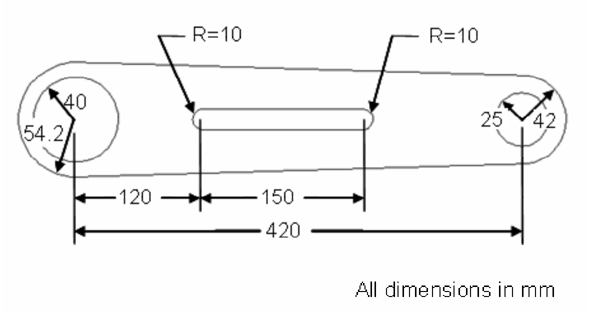

Figure 4. Geometry of Torque Arm.

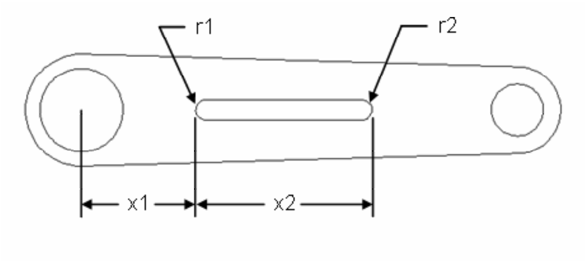

Figure 5. Design Parameters of the Torque Arm.

The final shape of the torque arm is shown below in Figure 6. Figure 7 illustrates the convergence of the mass objective, while Figure 8 shows the stress convergence. Through the integration of design automation software with a finite element code's preprocessor and solver, a solution 20% lighter than the original design was achieved. It should be noted that attempts to solve this problem using purely local search resulted in sub-optimal solutions (local optima) being found (Botkin, et al., 2002[1]).

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[1] Botkin, et al., "Shape Optimization of Two-Dimensional Automotive Components Using a Meshfree Method," 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, Georgia, 2002.

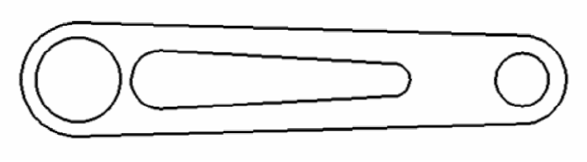

Figure 6. Geometry of Final Design.

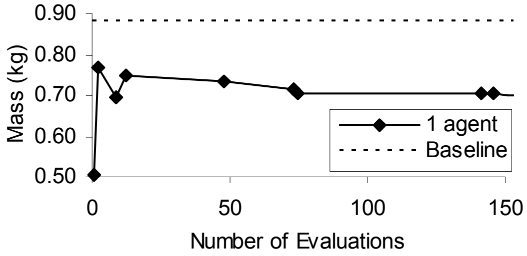

Figure 7. Trajectory of Mass.

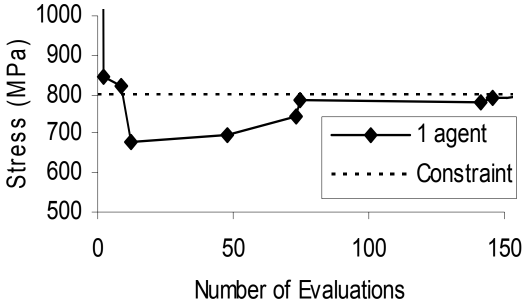

Figure 8. Trajectory of Stress.

Conclusions

Although the base geometries of each component discussed in this paper are different, they were all manufactured utilizing the same innovative manufacturing approach. The unique ability of this method to combine multiple operations into a one-piece molded component, localize fiber alignment relative to specific load bearing characteristics, combine multiple manufactured ‘glass’ types, and offer the ability to vary material thickness through a component’s cross-section allow unparalleled design flexibility when challenged with today’s vehicle weight targets.

Through the combined use of design automation software and new advances in the manufacturing of advanced composite materials, large savings in weight have been found for automobile components. A roll restrictor bracket, control rod, and upper control arm were designed to be manufactured from E-glass using a compression mold, resulting in mass savings of 25-50% over the equivalent steel components.