AC 2010-1904: HOW TO DESIGN STRONGER AND LIGHTER PRODUCTS – A TERM PROJECT FOR A COMPOSITE MATERIALS COURSE

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Abstract

Composite materials are widely used due to their advantages such as high strength to weight ratios, high corrosion resistance, high fatigue life in cyclic loading, and greater feasibility for styling and design. This paper presents the development of a new course project focusing on the novel use of composite materials to promote enhanced performance and safety while reducing the mass and cost of various products. In order to stimulate the students' critical thinking and problem solving skills, the students are required to study the product specifications, analyze the design requirements, perform engineering analysis, and propose several design approaches. The goal of the project is to achieve the maximum mass reduction by the maximum usage of composite materials. With the aid of advanced simulation software, the students are able to optimize their design.

1. Background

Composite materials are widely used in diverse applications due to their advantages such as high strength to weight ratios, high corrosion resistance, high fatigue life in cyclic loading, and greater feasibility in styling and design. From aircraft, spacecraft, submarines, and surface ships to civil structures, automobiles, and sporting goods, advanced composite materials consisting of high strength fibers embedded in matrix materials are gaining increasing popularity. The course learning objectives (CLOs) of MECH-582[1], "**Mechanics, Process, and Design Simulation of Fiber-Reinforced Composite Materials"** at Kettering University are:

- Understand the fundamental properties of composite materials;
- Demonstrate proficiency in the application of the fundamental principles for mechanics of composite materials;
- Demonstrate proficiency with the application of modern theoretical analysis techniques to mechanical systems with composite materials;
- Demonstrate proficiency with the application of computational analysis techniques for mechanical systems with composite materials;
- Understand the manufacturing processes and cost analysis in composite materials;
- Demonstrate effective communication and teamwork skills through technical presentations and reports in term projects.

The Mechanical Engineering Department of Kettering University has an enrollment of 1300 students. The university offers one of the largest cooperative educational programs in the country, and strives to provide its students with top quality classroom instruction, state-of-the-art laboratory facilities and career oriented work-experience in industry. The *mission* of the Plastic Product Design Specialty (PPDS) is to prepare the student as an entry-level product or process engineer with the appropriate plastic specialty knowledge for the first five years of their careers. Students gain the *basic skills* to

- Be able to converse with chemists and material supplier product specialists;
- Understand the material's property changes with temperature and material selection;
- Understand linear visco-elastic constituent equations and their inherent differences with linear elastic constituent equations;
- Understand how mechanical engineering analysis and design changes with polymers;
- Understand the primary manufacturing processing variables and their effect on part characteristics;
- Understand how to interpret data from instrumented processes;
- Understand process capability issues using statistical techniques;
- Be able to compare process data to simulations in order to improve accuracy of simulation tools;
- Be able to make engineering and project management decisions, and perform project cost analysis.

The corporate sponsors of Kettering University co-op students include: U.S. Army, General Motors, Ford, Daimler-Chrysler, aircraft companies and their suppliers such as United Technology, Moog, Vickers-Airequip, the computer manufacturer IBM, the appliance manufacturer Whirlpool, and over 600 other companies. It is seen that the companies that sponsor Kettering University co-op students represent a diverse cross section of US industries. The changes that have been taking place in these industries, industry needs, and current challenges are immediately reflected in the classrooms since the students bring their valuable experience into class discussions after each alternating 12 week co-op term with their corporate sponsor.

One of the most reoccurring challenges that our students often face in their co-op jobs, senior thesis projects, and other capstone course projects is *how to design stronger and lighter products*. The driver behind this persistent question, obviously, is the never-ending demand of *higher fuel efficiency* in transportation industries, and *more mass and cost reduction* in all engineering fields. Often our students are asked by their industrial sponsors to investigate the use of alternative materials in current or emerging designs. Even though there is no straightforward answer to such a question, composite materials do offer unique solutions in developing stronger and lighter products in many engineering applications. This paper presents a term project developed for MECH-582 focusing on stronger and lighter products design.

2. Description of the Project

One of the most important and challenging tasks in an engineering course is the development of practical and application based projects since engineering students have a proclivity for constructionistic learning. Because this course focuses on application and design based on composite material's properties and mechanics, the course project needs to be practical, rigorous, and interesting. State-of-the-art engineering tools in industry are used in the project that is scoped appropriately for completion within the semester.

The objective of the course project is to design stronger and lighter products using fiber-reinforced composite materials. Through the pedagogical integration of the course project with theoretical concepts, the course learning objectives are attained. Following is a discussion using an example of a case study project involving an automotive windshield wiper system. This topic is ideal because, consistent with the concept of Project-based Learning (PjBL) [2], it is a familiar mechanism for most students, although they may not have previously thought about it in depth. This provides a framework upon which new knowledge can be constructed. Because students must work collaboratively in groups, the learning extends beyond the technical outcomes, to critical thinking and communication skills. Project-based learning has been shown to increase the student's retention of concepts [3] [4]. Since this is an upper level course, students are expected to move beyond the first levels of Bloom's taxonomy [5] of learning, knowledge and comprehension to reach proficiency in the application of composite design principles and analysis techniques, Bloom's level 3. Students are also expected to be able to trouble shoot current designs, Bloom's level 4: analysis and offer a proposed alternative solution to address deficiencies, Bloom's level 5: synthesis.

The course project is assigned in Week #5, and a project team can be set to consist of five members. Each team is given an existing wiper system used for a particular platform obtained from our industrial sponsors. In Phase I of the project, students collect the wiper systems data of the current design and familiarize themselves with the design and analysis process demonstrated in the following with the help of the instructor.

Automotive windshield wiper systems, in conjunction with washer systems, are used in vehicles to remove contaminants such as rain, sleet, snow, dirt and washer fluid from the windshield. Therefore, the student must consider both structural and chemical performance in their design which highlights both the advantages and challenges of using composite materials. As shown in Figure 1, a typical wiper system consists of an electric motor, a linkage mechanism to transform the rotational motion from the motor to oscillatory motion, and a pair of wiper arms and blades[6] [7]. The areas of the windshield that must be wiped by the wiper system are mandated by the federal motor vehicle safety standards FMVSS 104[8].

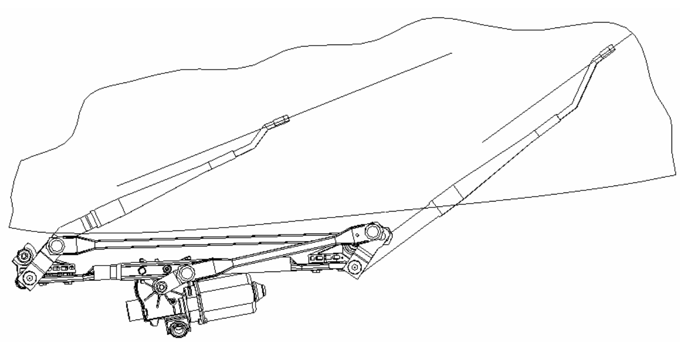

FIGURE 1 – A TYPICAL WIPER SYSTEM

The design of a typical wiper system starts with the technical specifications of the OEM car maker. Given a particular application platform, the geometry of the windshield glass is known. Based on the wiping pattern requirement (Figure 2) dictated by FMVSS 104, the lengths of the wiper blades and wiping angles can be determined. Then wiper arms and blades can be designed based on wiping speed and blade-glass frictional loads. The wiper mechanism can be designed based on the kinematics, structural strength, wiping angle, and system packaging requirements. The electric motor can be chosen according to the power required by the wiper system.

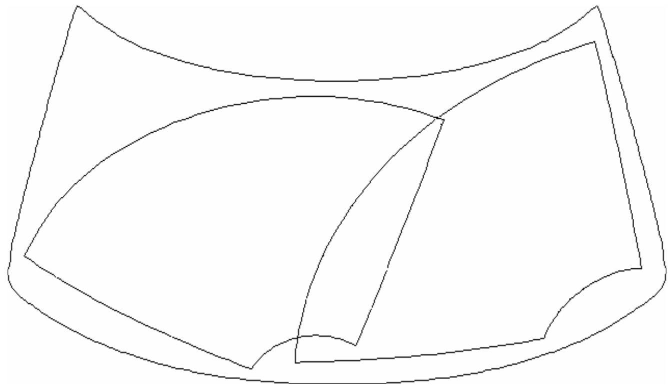

FIGURE 2 – WIPING PATTERN

A typical wiper arm and blade structure is shown in Figure 3, while a stress analysis of the wiper arm using finite element method (FEM) is depicted in Figure 4.

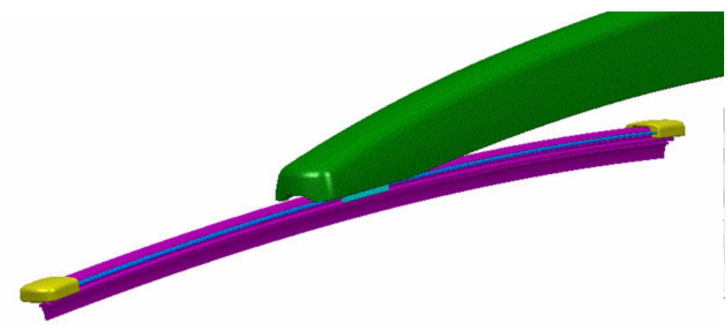

FIGURE 3 –ARM AND BLADE ASSEMBLY

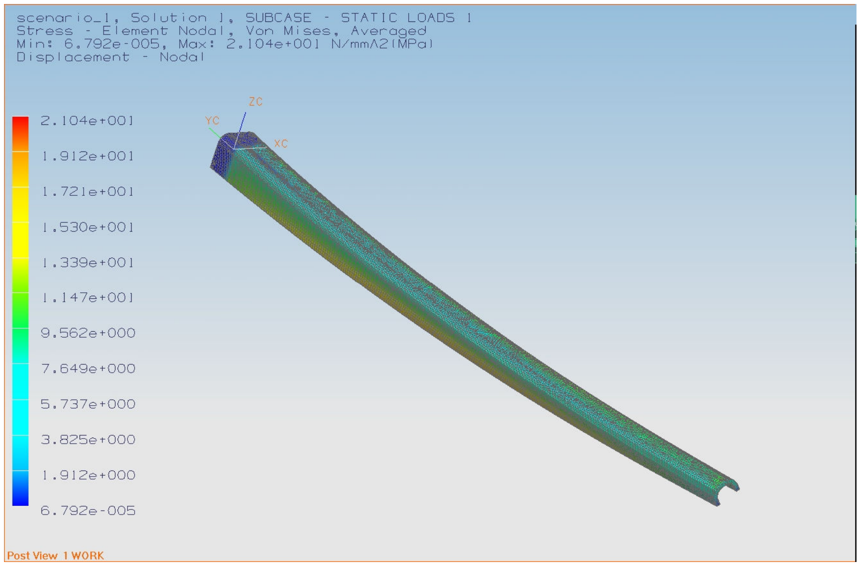

FIGURE 4 – ARM STRESS DISTRIBUTION BY FEA

The wiper arm and the lever are mounted on the pivot shaft that is located in the pivot housing assembly (Figure 5). The pivot housing assembly includes grommet, retainer, washer, O-ring, bearings, spring washers, pivot shaft, lever and ball stud.

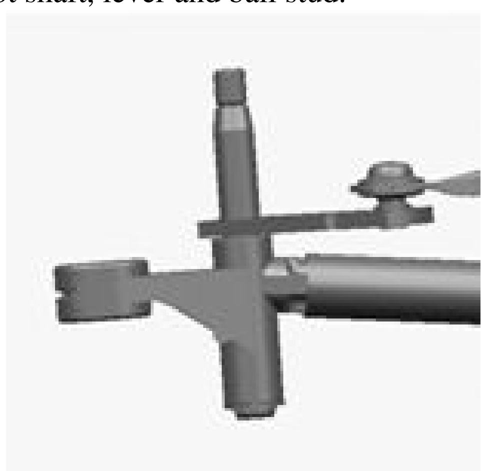

FIGURE 5 – FRAME AND PIVOT HOUSING ASSEMBLY

The pivot shaft is the most critical component in the pivot shaft assembly, because the wiper arm and blade assembly is mounted on the top and the lever is connected in the middle. If the pivot shaft fails, the whole wiper system will lose its performance, or worse, its function. Figure 6 shows the stress and displacement distributions. Given the same material properties as the wiper arm, it is seen that this design is safe.

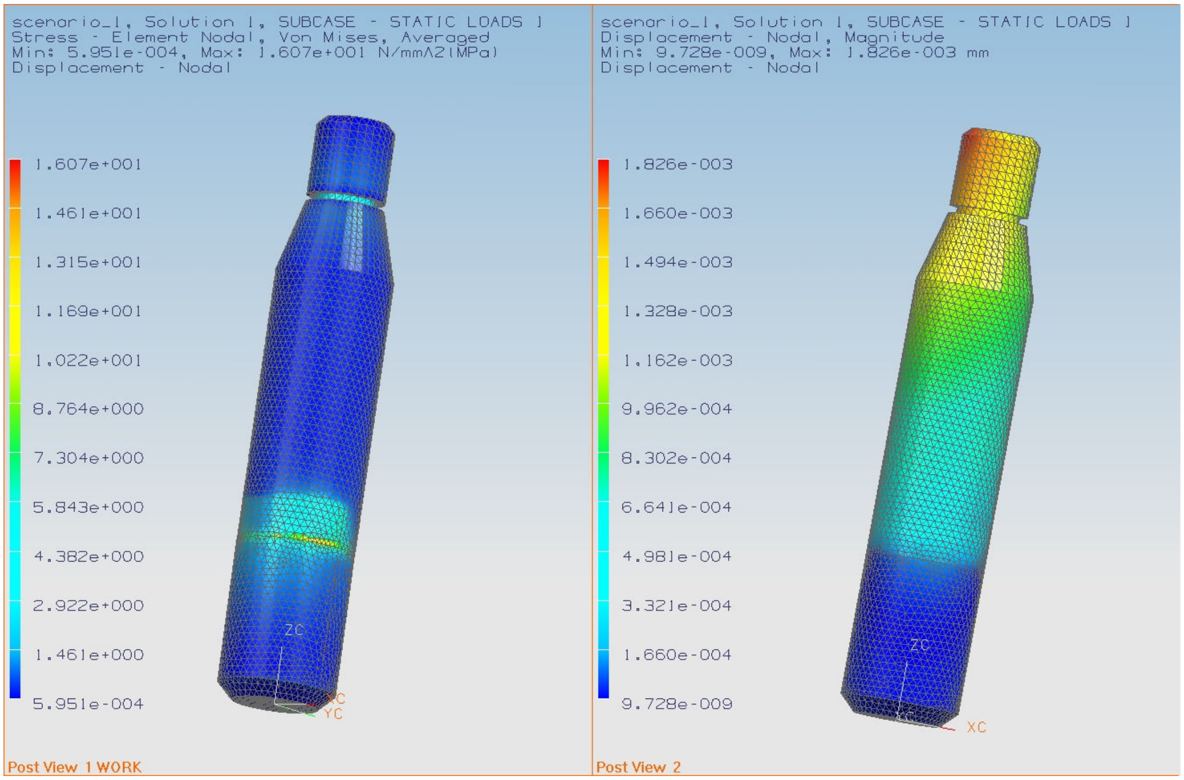

FIGURE 6 – PIVOT SHAFT STRESS AND DEFORMATION BY FEA

3. Stronger and Lighter Wiper Systems

Once the project teams complete their study on the existing wiper systems, they will move on to Phase II of their project: an alternative design to solve one of the major safety problems associated with automotive wiper systems – snow load damages.

3.1 Failure Mode due to Overload

Snow and ice often builds up on the windshield glass in the winter, as shown in Figure 7. The snow/ice stack can literally block the wiper arms/blades, and therefore the wiper system load will significantly increase. Such an excessive load, often referred to as snow load, will cause either fatigue or catastrophic system failure if all components in the wiper linkage mechanism are made of steel. Figure 7 shows a broken rocker arm.

FIGURE 7 – WINDSHIELD WIPERS UNDER SNOW LOAD THAT BREAKS A ROCKER ARM

3.2 Composite Coupler for Overload Protection

Figure 8 depicts a proposed solution. In this illustration the hatched area represents snow/ice pack above the cowl screen, which restricts the normal motion of the system. Once the arms have contacted the restriction, the loading in the system increases as the motor torque approaches its stall value. However, once this critical load is reached in the coupler, it will buckle, limiting any further increase in system loading and allowing the motor crank to rotate through the reversal position. In the illustration, the coupler is shown in the post-buckled configuration.

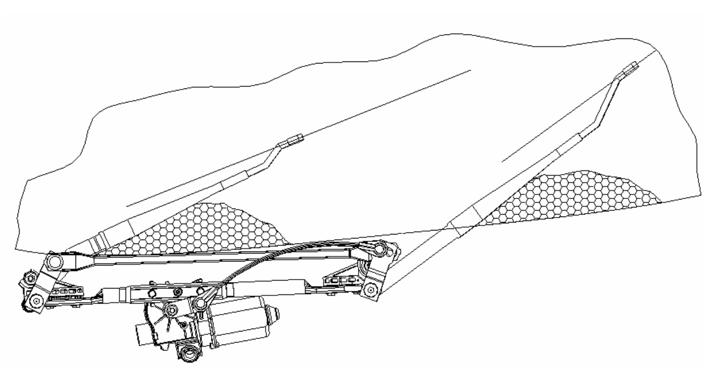

FIGURE 8 – WINDSHIELD WIPERS WITH A FLEXIBLE LINKAGE

3.3 Design of the Composite Coupler

The buckling load of the composite coupler should be determined such that it will be substantially higher than the maximum normal wiping load to avoid inadvertently buckling the coupler. On the other hand, the buckling load needs to be less than the minimum load that will stall the wiper motor. For the example application used in this work, a test on existing wiper systems was performed to obtain the following data to facilitate the composite coupler design:

- The maximum normal wiping load in the coupler is 560 N;
- The maximum load in the coupler under restricted wiping conditions is 2100 N.

A buckling load of 850 N was chosen for the composite coupler and was experimentally validated to meet the above requirements, as shown in Figure 9. Employing such a composite coupler reduced the load in the coupler from 2100 N to 560 N. Therefore, the system peak load due to restricted wiping conditions can be greatly reduced to prevent the wiper system failures demonstrated previously. Figure 9 also shows the enormous difference in stiffness of the composite coupler before and after buckling. The elastic-perfectly plastic behavior provides the most desirable functionality for the wiper system. Under normal wiping conditions, the composite coupler functions just like a traditional steel coupler. In case of restricted wiping conditions, the composite coupler buckles and keeps nearly constant post buckling load, which enables the wiper system to wipe at a reduced wiping pattern without collapsing. Such a safety device not only protects the wiper system from overload damage, but also provides vehicle operators with a functional wiper system under extreme weather conditions.

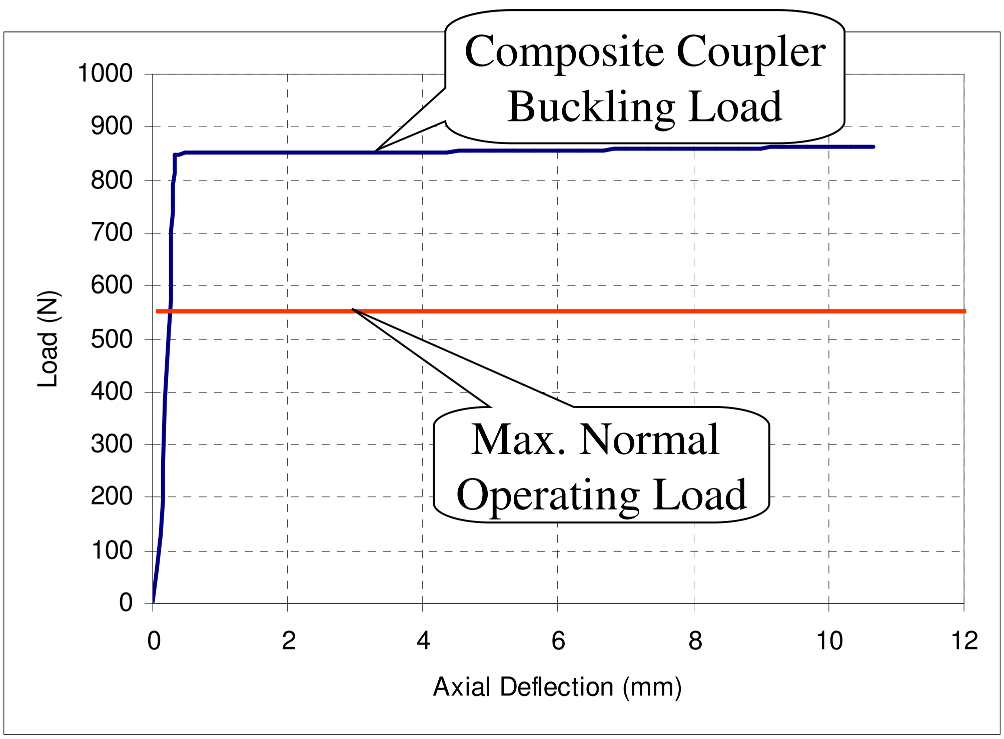

FIGURE 9 – LOAD VS. DEFLECTION CURVE OF THE COMPOSITE COUPLER

Figure 10 depicts the composite coupler of length L, cross sectional area A, and cross section moment of inertia I. The elastic modulus of the material is denoted as E. The ends of the coupler are free to rotate due to the socket-ball joints. External compressive load P is applied at the centroid of the cross section.

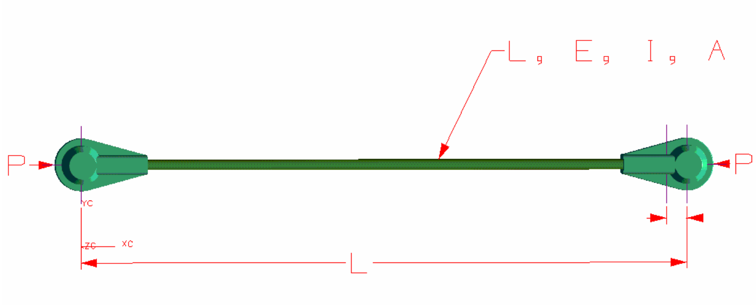

FIGURE 10 – A FLEXIBLE LINKAGE

As the load is increased and assuming that the elastic limit of the material is not reached, a critical point is encountered at which the rod deforms laterally. In this configuration the coupler supports the load via bending. The applied load at which this transition occurs is referred to as the critical load *Pcr*. The critical load can be determined for a given cross section, column length, and material from [9]

$$Fcr = \frac{\pi^2 EI}{L^2} \tag{1}$$

The formula for the cross sectional moment of inertia of a rectangular section is given by

$$I = \frac{1}{12}(b-2R)h^3 + \frac{1}{12}(2R)(h-2R)^3 + 2\left\{0.1098R^4 + \frac{\pi}{2}R^2\left[\frac{4R}{3\pi} + \frac{1}{2}(h-2R)\right]^2\right\} \tag{2}$$

Where *b* and *h* denote the width and height of the rectangular cross section, and *R* represents the radius of fillets. Note that the pultrusion process requires that the section have filleted corners. The engineering drawing of the composite coupler is depicted in Figure 11.

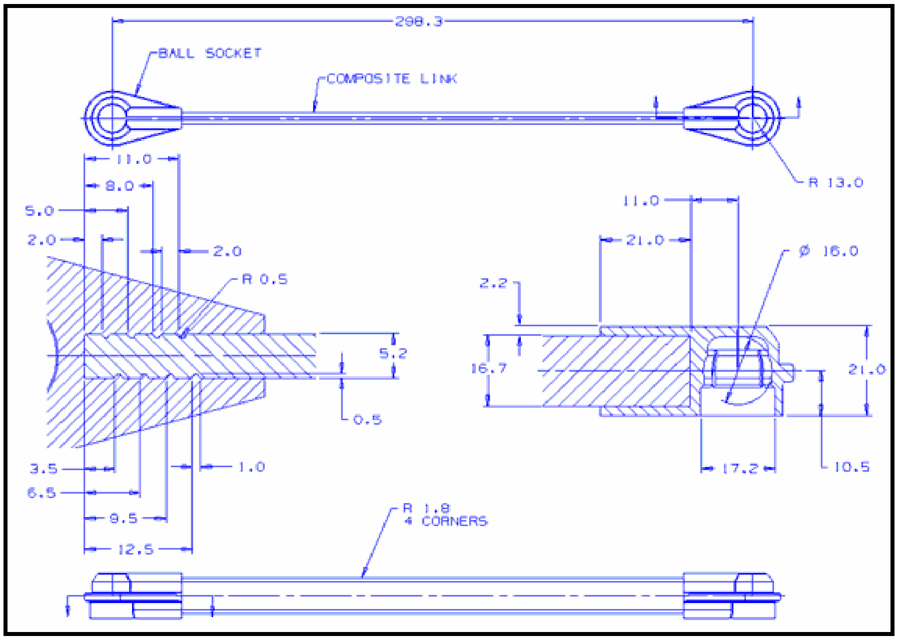

FIGURE 11 – DESIGN OF THE COMPOSITE COUPLER

The wiper linkage mechanism can therefore be designed with the flexible connecting rod. The spherical sockets at both ends of the linkage are over-molded plastic parts to provide for ball-socket joints [6] [7]. The composite material is selected per the following specifications:

Resin Specification: Thermoset Polyester (21% by weight)
Fiber Specification: 113 Yield E-glass Roving (75% by weight)
Filler content (4% by weight)

Monotonic mechanical properties of the materials are:

Elastic Modulus: 43 GPa (6.2 Mpsi)
Ultimate Strength: 1140 MPa (165 ksi)
Strain at Fracture: 2.6%
Specific Gravity: 1.92

The flexible coupler undergoes a maximum tensile load of 1000 N at motor stall. The stress and deformation are calculated by FEM as shown in Figure 12. From the stress contour plot it is seen that the maximum Von Mises stress in the coupler is 271.4 MPa. Therefore the safety factor is 1140/271.4 = 4.2, indicating a safe design for the chosen material.

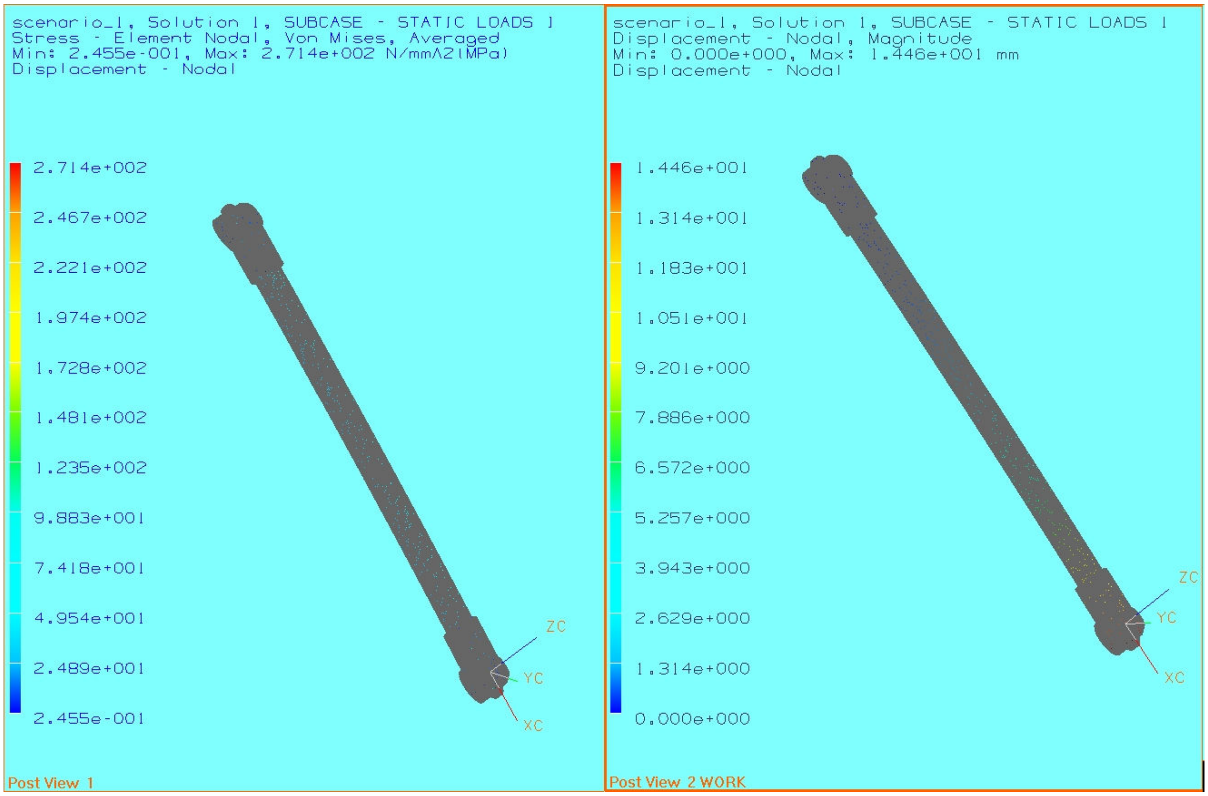

FIGURE 12 – LINKAGE STRESS AND DEFORMATION BY FEA

Conclusions

The purpose of the course project is for students to learn how to design stronger and lighter products using composite materials. By designing a "compliant" composite coupler, students are able to demonstrate how the peak loading in the wiper system under restricted wiping conditions can be reduced. For the sample application used in the assignment, with the protection of the composite coupler, the maximum load in the coupler is reduced from 2100 N to 850 N. Because the system is protected from loading extremes, durability of the wiper system is enhanced, and the application of alternative materials is made possible. Moreover, the students can understand that when the system is made extremely stiff it results in excellent pattern control without fear of the extreme loads that normally result from extreme stiffness. In this project, the students are given the insight that with the novel use of composite materials, it is possible to eliminate material in some components in the wiper systems, which holds the potential for additional mass reduction and cost saving. Also, coupling this potential with the fact that composite couplers are approximately 25% the mass of their steel counterparts, mass savings are inevitable. The Project-Based Learning pedagogy utilized in this course has been shown to increase critical thinking and retention of course content, as well as communication skills [4]. Through the case study in the project, it is concluded that it is indeed feasible to design stronger and lighter products with innovative application of knowledge learned in the classroom. Students can then be guided to transfer the specific insights from one assignment into the potential of benefits of composite materials in other engineering applications.

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