Michael Petralia
Harvard University – Division of Engineering and Applied Science
Fall 2006 ES – 240 Prof. Zhigang Suo
Fin Design by Kyla Grigg

Failure Analysis of a Fin Design for the Harvard MircoRobotics Laboratory's MicroMechanical Fish

Abstract: This paper documents the failure analysis of a fin design for a micromechanical fish using the finite element analysis program ABAQUS. Specifically the effectiveness of various fiber direction orientations for sheets of S glass fiber polymer matrix composite laminas are investigated.

Keywords: Glass fiber polymer matrix composite lamina, ultimate stress / strain, fish fin design, failure analysis, microrobotics, ABAQUS

Introduction

Kyla Grigg of the Harvard MicroRobotics Laboratory is currently designing a fin mechanism for a micromechanical fish. Her prototype makes use of square elements, but after the mechanism is designed, the elements will be constructed to mimic the shape of a fish fin (Figure 1).

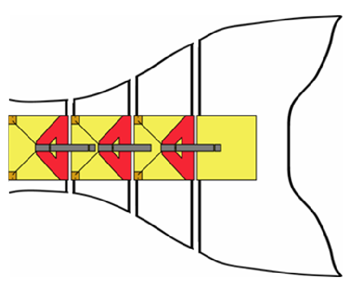

Figure 1: A schematic of the fin mechanisms and final fin shape.

The design (Figure 2) makes use of a shape-memory alloy (SMA) stretched from its original position by a piece of silicone rubber. When a current is applied to the SMA, it attempts to return to its original position, and causes the rubber to stretch. A composite tendon connects the rubber to the adjoining fin and causes an out of plane deflection when the rubber is stretched. The fin is constructed from 0.09*mm* thick sheets of S glass fiber polymer matrix composite lamina. Currently the design calls for two 7.5 x 7.5*mm* lamina with perpendicular fiber directions bonded together for each side of the fin. One of the mechanisms shown in Figure 2 will be attached to each side of the fin. The SMA is secured to the lamina via two 1 x 1*mm* brass plates. Because the rubber does not bond well with the composite lamina, it will be looped through the fin (please note that this is not shown in Figure 2).

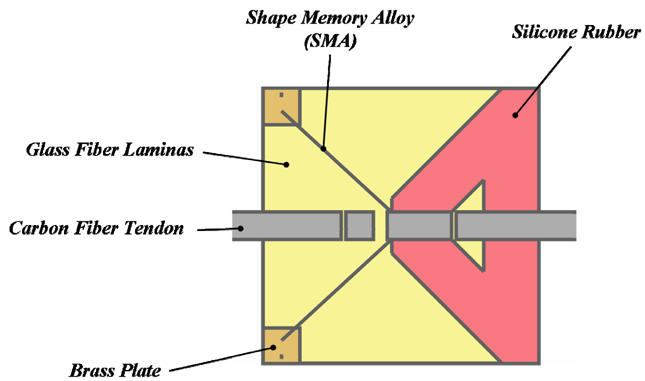

Figure 2: Schematic of Kyla Grigg's fin mechanism design.

Methods

The finite element analysis program ABAQUS was used to test various fiber direction configurations for the fin. Horizontal, vertical, and crisscrossed (perpendicular) fiber directions were investigated for the case of two bonded lamina. Additionally, systems employing a single lamina were also investigated for the horizontal and vertical situations.

The maximum force in the SMA was provided by the manufacturer (1.47 *N*). The rubber was assumed to deflect a maximum of 1*mm*. The force from the SMAs and the tendon were modeled in ABAQUS as concentrated loads at the center of the brass plate and the center of the fin, respectively. The force from the rubber was modeled as a distributed load along the right edge of the fin. It was applied 0.5*mm* from the top and bottom edges. Figure 3 shows the free body diagram of the fin.

Two situations were considered for each of the five fiber direction configurations: maximum force and maximum deflection. For the maximum force, it was assumed that the rubber had no deflection and that the maximum angle of the SMA off of the vertical axis would be 22^{o}. Based on maximum force provided by the SMA, the horizontal force from the SMAs is 1.10 *N* and the force distributed by the rubber is 0.874 N/mm^2 for the two lamina case and 1.75 N/mm^2 for the single lamina. For the case of maximum deflection, the SMA has an angle of 6.5°. The horizontal force from the SMA is 0.166 *N*. The force distributed by the rubber is 0.264 N/mm^2 for the two lamina case and 0.528 N/mm^2. In both the maximum force and maximum deflection cases, the force in the tendon was set at 1.10 *N*. The forces were all applied statically.

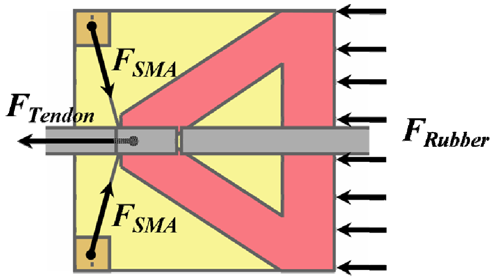

Figure 3: Free body diagram of the forces on the fin from the fin mechanism.

According to [1], unidirectional lamina can be treated as a homogeneous, orthotropic continuum. Additionally, for circular cross-section fibers randomly distributed in the unidirectional lamina, the lamina can be considered transversely isotropic. The result is that there are only five independent material constants, which were provided by the manufacturer and are listed in Table 1. Figure 4 shows the orientation of the axis with respect to the fiber direction. In ABAQUS, the fins were modeled as 3D shell elements with the material type lamina.

Table 1: Elastic properties of S-glass fiber/polymer as provided by the manufacturer+

E_{11} (GPa)	E_{22} (GPa)	v_{12}	G_{12} (GPa)	v_{23}+
50	7	0.33	5	0.33

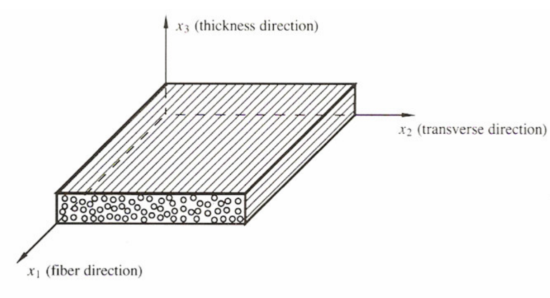

Figure 4: Orientation of the axis with respect to the fiber direction [1].

+ This value was not provided by the manufacturer, but it was required by ABAQUS. Different values for v_{23} were tested without much variation in the final results.

Results

The maximum tensile and compressive stresses and strains both along the fiber direction and perpendicular to it were compared with the ultimate stresses and strains provided by the manufacturer. For the case of the crisscrossed fibers, the stresses and strains in each of the lamina were different and were considered separately. Figures 5 – 14 provide the comparison.

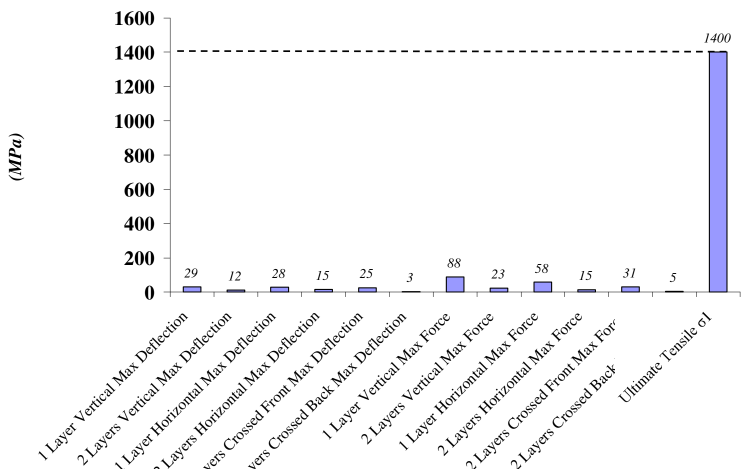

Figure 5: Maximum tensile stress in the fiber direction.

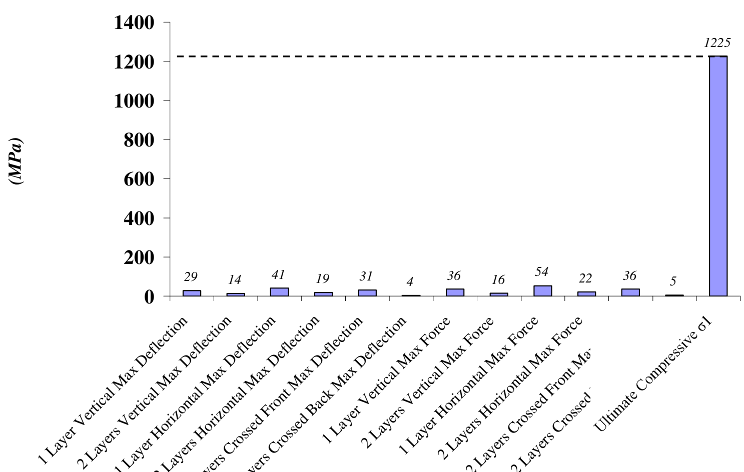

Figure 6: Maximum compressive stress in the fiber direction.

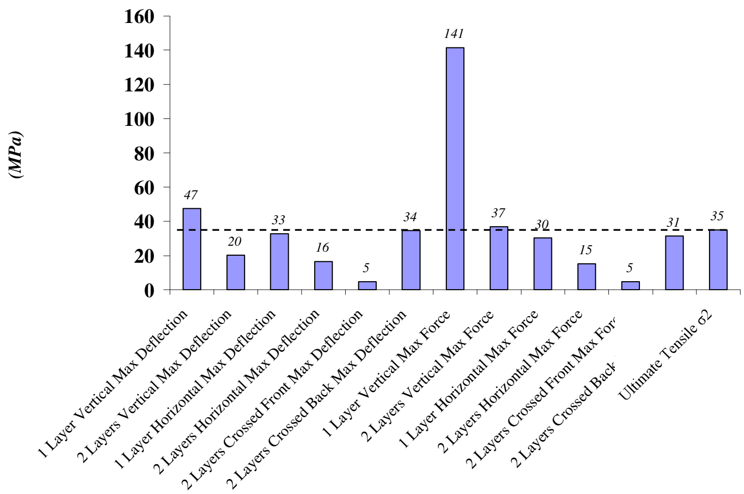

Figure 7: Maximum tensile stress perpendicular to the fiber direction.

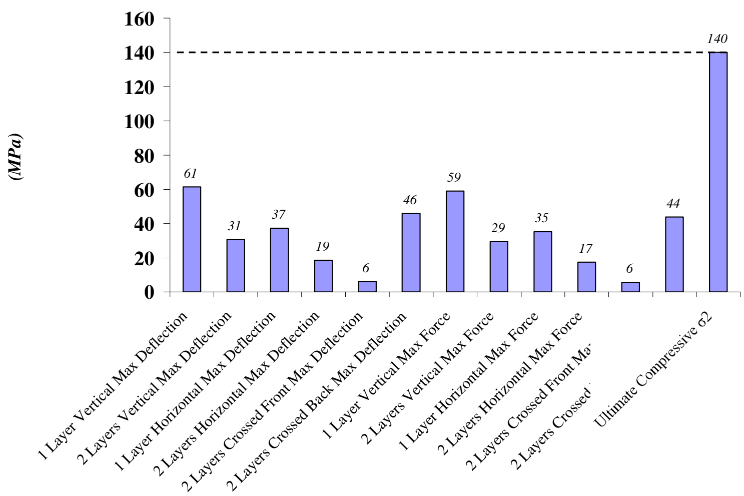

Figure 8: Maximum compressive stress perpendicular to the fiber direction.

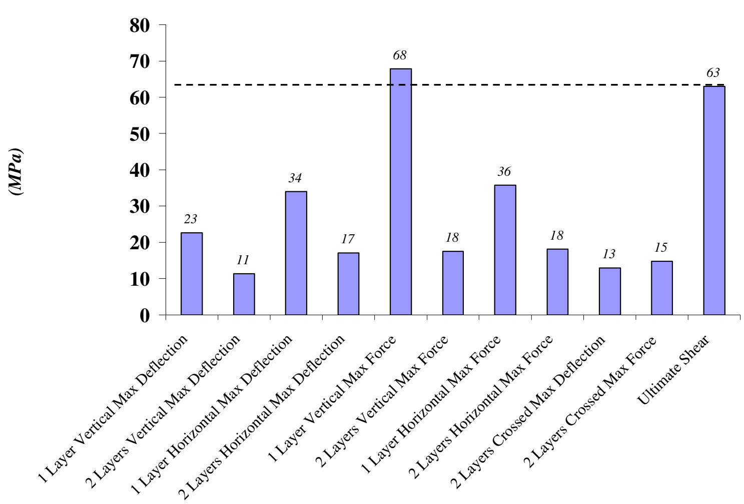

Figure 9: Maximum shear stress.

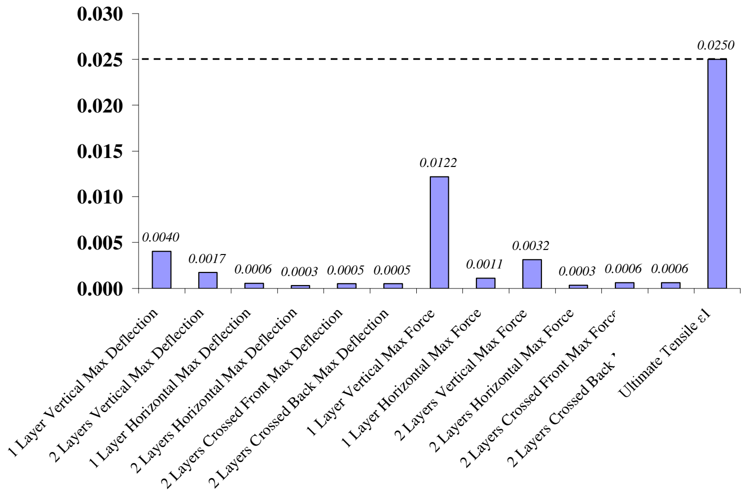

Figure 10: Maximum tensile strain in the fiber direction.

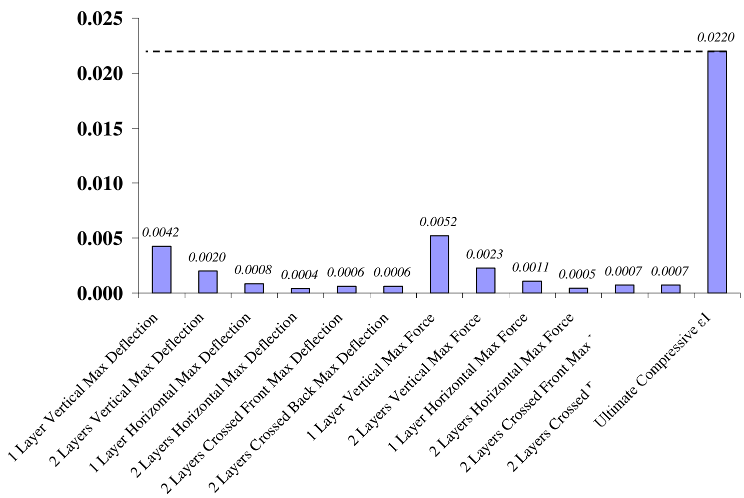

Figure 11: Maximum compressive strain in the fiber direction.

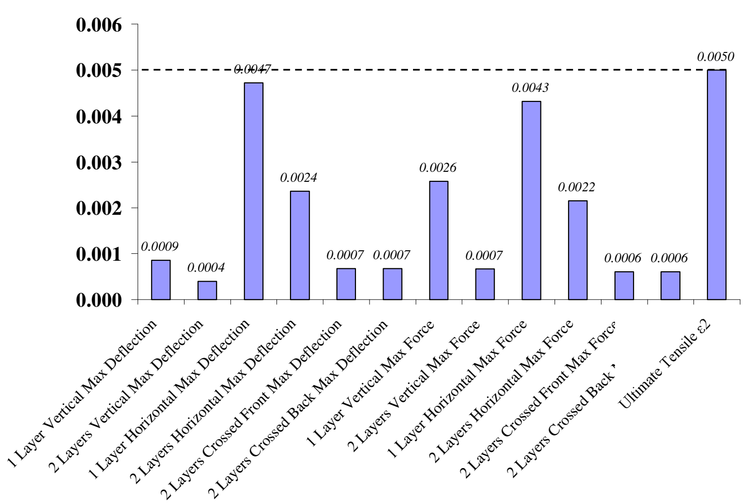

Figure 12: Maximum tensile strain perpendicular to the fiber direction.

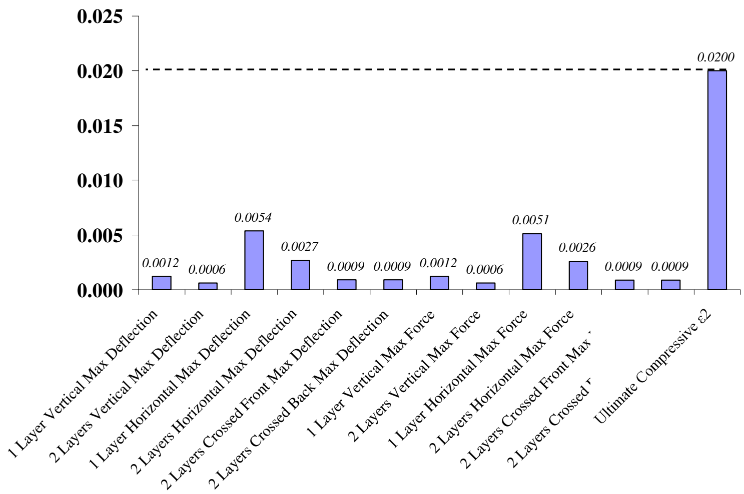

Figure 13: Maximum compressive strain perpendicular to the fiber direction.

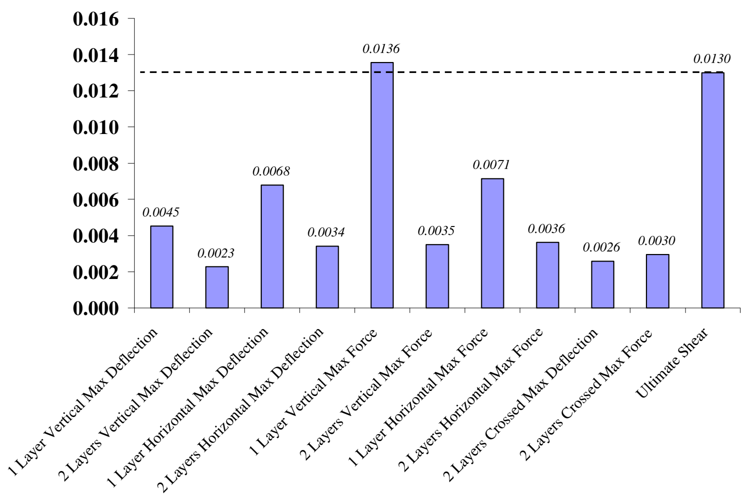

Figure 14: Maximum shear strain.

Discussion

From Figure 7 it can be noted that the vertical lamina in the crisscrossed fiber configuration will approach the limit of the material for tensile stress perpendicular to the fiber direction in both the case of maximum force and the case of maximum deflection.

Other configurations where failure is probable are the single layer vertical and horizontal lamina. Figures 7, 9, and 14 show that the single vertical lamina would fail with respect to the tensile stress perpendicular to the fiber direction and the shear stress and strain. Figure 12 shows that the single horizontal lamina approaches limit of the material in tensile shear strain.

Conclusions

Due to the fact that the two lamina horizontal configuration never experiences stresses or strains within 50% of the limit of the material, it is recommended that two lamina horizontal configuration be used in place of the crisscrossed configuration for the fin mechanism.

References

[1] Chou, Tsu-Wei. (1992). *Microstructural Design of Fiber Composites*. Cambridge, NY: Cambridge University Press.