Strength Characterization of Thermally Cycled 3D Stitched Composites Using Response Surface Methodology

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This paper studies the strength characterization of 3D stitched composites that undergo extreme temperature cycles by using response surface methodology to observe the relationship between the response and three independent variables. The three independent variables chosen were linear thread density, stitch density, and number of thermal cycles. A Central Composite Design, a response surface method, was used to reduce the number of specimens while still gaining valuable data. Using ASTM standard C297, a flatwise tension test, specimen sizes were obtained. As of writing this paper, the specimens have been stitched and infused, completing the manufacturing process. The next steps are to thermal cycle the composites to extreme low and high temperatures. After thermal cycling, the specimens will then be tested according to ASTM standard C297, a flatwise tension test. When all the data from testing is gathered, contours will be made to examine the effects the combination of independent variables has on the response.

Nomenclature

p = Spacing (mm)
$X1$ = Linear Thread Density (Denier)
$X2$ = Stitch Density (stitches/mm^2)
$X3$ = Thermal Cycles

I. Introduction

Spacecraft launches and missions have been at an all-time high in the past decade, increasing from less than 100 launches per year to almost 200 launches per year. Now more than ever is the topic of reusable spacecraft structures worth researching and investing in. Many companies and agencies have prioritized reusable payloads and launch systems for their space missions. Thermal protective systems are the main field of research for reusable spacecraft as they are the main factor of protection against external forces on the vehicle. These forces can be from radiation, friction from reentering the atmosphere, and temperature cycles ranging from the cold of space to the high heat of reentering Earth's atmosphere.

Many parts of the spacecraft's structure are exposed to the temperature cycles experienced during space travel. Thermal stress and high delta values of temperature change deeply impact the structure due to the material properties of the base structure. Carbon fiber composites are the most utilized material to manufacture spacecraft. These materials are notorious for their poor thermal performance, hence why heatshields and thermal protective systems are so important.

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Carbon fiber composites have many manufacturing methods that can be used to alter their structural strength characteristics and properties. One such method being researched by NASA and other prominent institutions is stitched composites. Carbon fiber by itself has great in plane strength, but poor interlaminar strength due to the natrure of the composite material being stacked only within a single plane. Since carbon fiber has poor interlaminar properties, problems such as delamination between layers can occur due to interlaminar stresses and part assembly or repair [1]. Stitching carbon fiber composites improves their strength characteristics by a highly effective amount. The through-thickness strength of the materials is drastically increased whenever stitches are applied to the weaved material before resin application. There are various stitch parameters that can be observed, but for this paper, stitch density and linear thread density will be studied on their impact on carbon fiber. This research study serves to measure the out-of-plane strength of stitched composites when they are subjected to various thermal cycles like what would be experienced during repetitive space travel.

II. Discussion

To simulate modern day spacecraft under extreme temperatures, test specimens made of similar materials were manufactured and tested. There are many ways to manufacture and test these specimens, leading to many variables. Testing different values of each variable against every other would lead to many specimens and experiments to undertake. To identify the specimens and cases to be tested, a design of experiments, DOE, was used. This helped with the organization of the different specimens. To truly study how certain variables affect the strength characterization, a response surface methodology, RSM, a type of DOE, was used. For this paper, three variables were chosen to see how the strength characterizations would be affected by each one. With the response surface methodology, a high, plotted as 1, a medium, plotted as 0, and a low, plotted as -1, value was chosen for each variable. The three variables that were to be tested are linear thread density, X1, stitch density, X2, and number of temperature cycles, X3. The high, medium, and low values can be seen in Table 1 below.

Table 1. Values for Each Variable

	X1 (Denier)	X2 (stitch/mm^2)	X3 (cycles)
High (1)	1200	0.08	200
Medium (0)	800	0.04125	150
Low (-1)	400	0.0025	100

Raising the number of variables to the power of the number of values for each variable gives us three raised to the third, giving 27 experiments. This number can be reduced even further by using a type of RSM called central composite design. An example of a central composite design can be seen below in Fig. 1.

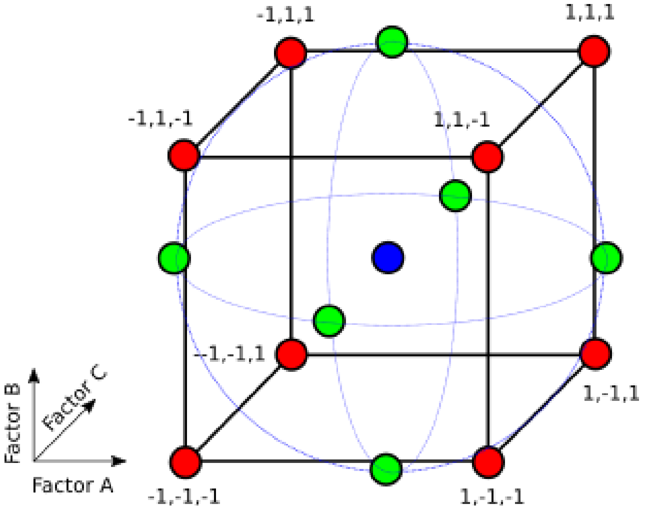

Figure 1. Central composite design example [2]

A central composite design can be used to reduce the number of experiments while still gaining data that can be used to study the response that is being affected by leveled variables. In the figure, you can see the exact data points that will be used. The data points used are the corner, midpoints of each face, and the center. This reduces the number of experiments from 27 down to 15. To better understand which levels of which variables are being tested for this paper, Table 2 shows each specimen that will be tested.

Table 2. Specimens To Be Tested

Specimen #	X1	X2	X3
SP1	1	-1	1
SP2	1	-1	-1
SP3	1	0	0
SP4	1	1	1
SP5	1	1	-1
SP6	0	-1	0
SP7	0	0	1
SP8	0	0	0
SP9	0	0	-1
SP10	0	1	0
SP11	-1	-1	1
SP12	-1	-1	-1
SP13	-1	0	0
SP14	-1	1	1
SP15	-1	1	-1

The table above shows the different specimens, each with different variable levels, that were selected according to the central composite design. Knowing the different specimens required, manufacturing became simpler and could then be undertaken.

A. Manufacturing

To begin manufacturing, the size for each specimen must first be known. The size of each test specimen is 2 inches by 2 inches, or 50.8 mm by 50.8 mm. This size was chosen from ASTM (American Society of Testing and Materials) standard C297 [3] which is the standard used for testing flatwise tension of sandwiched composites. The material used for this paper was Seartex hts40 ncf, a dry fabric. For ease of manufacturing, the test specimens were first cut from the carbon fiber in 1 foot by 1-foot squares. The specimens were cut in larger sizes so that they could be manufactured with more ease and then be able to be cut into the smaller sections to be tested.

To cut out these specimens, a Gerber fabric cutting table was used. The Gerber table software reads CAD files to know what to cut. The file to cut for this paper was created in AutoCAD. Since the material that was being cut is oriented at 45 degrees, the squares to be cut were also oriented at 45 degrees so that the test specimens could be manufactured with a fiber orientation of either 0 or 90 degrees. The AutoCAD file that was created and used can be seen in Fig.2.

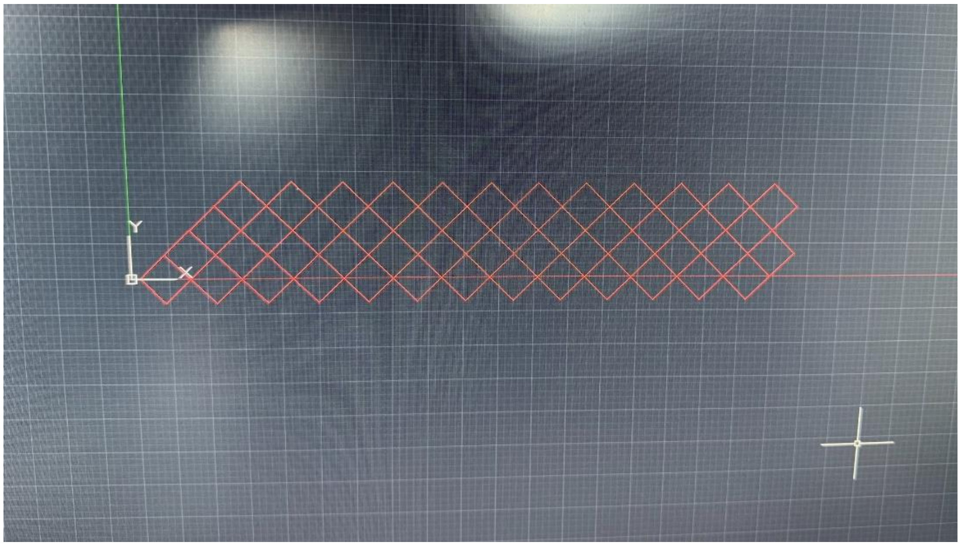

Figure 2. AutoCAD Toolpath File for the Test Specimens

The fabric to be cut was then laid on the table where the Gerber table then cut the material into the desired sizes. A clear plastic was placed over the fabric to make clean cuts. There were 50 twelve by twelve-inch squares cut during each run, and there were 4 runs, making 200 total squares. The Gerber table cutting the test specimens can be seen in Fig.3 below. These are then assembled into 40 ply stacks of dry carbon fiber fabric. Each layer has 2 plys.

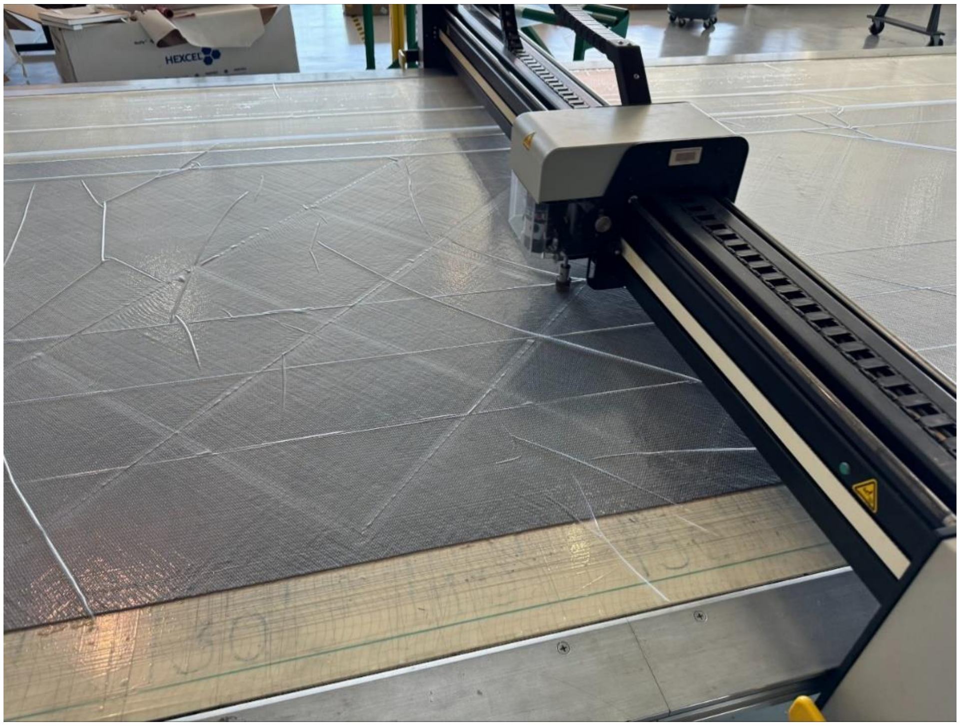

Figure 3. Gerber Table Actively Cutting the Test Specimens

The next step in manufacturing is to then implement the different variables as mentioned earlier. Although there are three different variables, only two will be implemented during the manufacturing process. These two variables are stitch density and linear thread density. Stitch density is the number of stitches per area in millimeters. To calculate the spacing between each variable, Eq.1 seen below was used with p being the spacing between each stitch both vertically and horizontally.

$$p = \frac{1}{\sqrt{X2}} \tag{1}$$

The second manufacturing variable is linear thread density. Linear thread density is the amount of mass in grams per kilometer of yarn. These two variables were implemented when manufacturing these specimens. After these variables were applied by way of stitching the material according to the specifications for each specimen, each panel was infused with 4500 Infusion Epoxy resin. This resin cures at room temperature in 3 to 6 days with a 4570 Part B hardening agent. Although this resin system is not aerospace grade, the results will still show some insight as to how any resin system used can be expected to perform under the same conditions. A simple ramp up of data can be used in order to get an estimated idea on how an aerospace grade resin system would actually perform. Since the panels are 12” x 12” and 40 plies thick, four out of the seven panels are infused at a time to avoid errors in resin travel during the infusion process. The remaining panels were infused after this batch using an identical setup, with one of the carbon fiber panels being a placeholder for process replication. Below in Fig. 4 is a picture of a completed panel after infusion.

Figure 4. Completed specimen panel

Seen in the figure above is a manufactured panel containing specimens 4 and 5 with a row of extras. On the left side of the panel it can be seen that there are dry spots where the resin did not reach. While this is not desired, it is accepted for this panel because the specimens themselves have been successfully infused with the resin. The reason that there are dry spots can be accounted for the resin system that was used. The 4500 resin system is more viscous than that of aerospace grade resin systems, so it was more difficult for the 4500 resin system to flow and infuse into the thick specimens. To prevent this for the second infusion, more pleats were included in the vacuum bag when infusing in order to control the flow so that the part gets more resin evenly throughout the entire part. After manufacturing was completed, the specimens were then ready to test.

B. Testing

Before any testing will be performed, the specimens will first undergo extreme temperature cycles in order to simulate the temperature cycles that spacecraft experience. The temperature cycles utilized in this study will range from the temperature of liquid nitrogen (-195.79 °C) to 300 °C. This is the maximum and minimum range of temperature for the cylces. While these not the exact temperatures that are experienced by spacecraft, that being a low of around -270°C [4] and a varying high, these are the most extreme temperatures that will be available for this paper. To perform out-of-plane strength analyses of our specimens, the plan will be to conduct flat-wise tension testing per ASTM C297 testing standards. This involves a rectangular specimen of a given thickness to be bonded to two metal tabs that are pinned into the testing machine. The machine then pulls the specimen apart in one direction to collect a maximum allowable force for scenarios where out-of-plane forces are being experienced. This is typically done on sandwich structures but can also be done on regular-thickness structures [5]. The schematic for the test configuration can be seen below in Fig. 5.

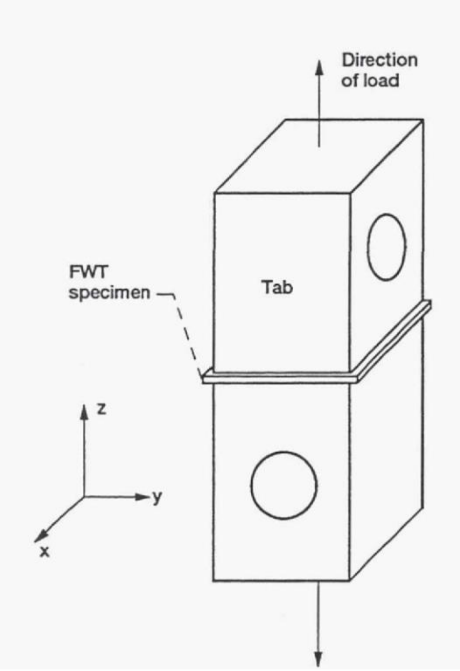

Figure 5. Schematic of typical flatwise tension test configuration

C. Results

When the experimentation is completed, it is expected that the specimens under a higher number of thermal cycles will fail sooner due to the structure weaking from increased cracking within the resin. Higher stitch densities and linear thread densities are hypothesized to strengthen the out-of-plane properties of the specimens as opposed to smaller stitch densities and linear thread densities as seen from empirical data [6]. The values between stitch densities are relayed in an exponential relationship, while the thermal cycles and linear thread densities follow a linear pattern relationship between the values. The conclusion can be drawn that the high-value stitching parameters will cause results linearly increased from any base values. Thermal cycles on low-value stitching parameters will cause results linearly decreased from base values. In order to show these results, graphs and countours will be displayed for simplistic viewing. An example of this can be seen below in Fig. 6.

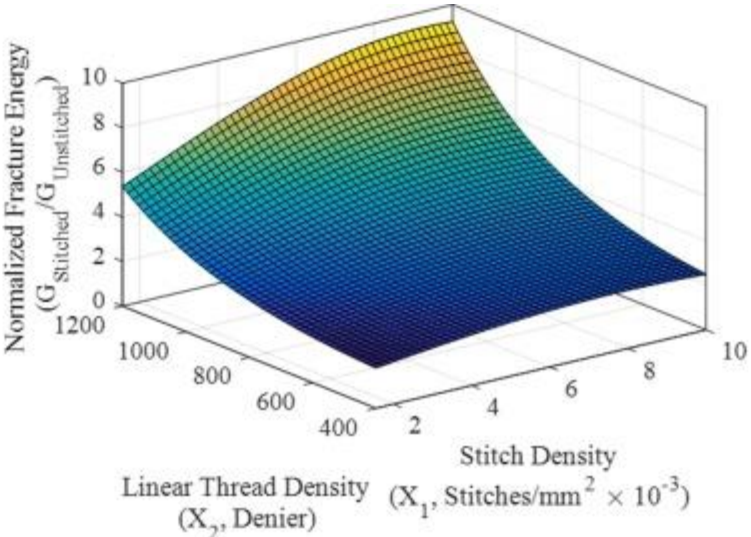

Figure 6. Example of a contour using stitched composites [6]

The figure above is the kind of results that can be expected when this research is completed. As stated, it is expected that the interlaminar strength of the carbon fiber specimens will increase at higher linear thread and stitch densities.

III. Conclusion

With the demand and capabilities of spacecraft structures increasing exponentially, it is important to test the limits of these structures while also trying to improve them. Stitching carbon fiber composites has been shown to improve the materials interlaminar strength. While it is difficult to directly improve the thermal properties of the carbon fiber itself, it is more plausible to improve the allowable forces and stresses that can be experienced during mechanical and thermal fatigue on the structure. The results of testing will show which combination of stitch density and linear thread density proves to be the most optimal throughout various temperature cycles. Information gained from this experiment may be used to modify or optimize a design for specific applications.

Specifically pertaining to the manufacturing process, it was learned just how important it is to research different design of experiment methods in order to lower the work load while still having applicable data. Another lesson learned was how difficult it can be to both stitch and resin infuse. There are a lot of steps that are involved in the infusion process, so a future study on stitched composites could be looking into ways to stitch into material that already has a resin system infused within in, such as prepreg material.

Following the study of this experiment, avenues for further research emerge. The long term durability of the material can be measured by documenting the materials performance over an extended period of time. Effects on properties such as strength and fatigue resistance could also be measured over the composite's lifecycle. The study could also expand to include exposure to different environmental conditions such as humidity and radiation. Implementation of better testing methods such as using ultrasound or thermal imaging could be used to provide feedback on potential defects without damaging the structure. Another future study could be looking at different stitching techniques such as cross stitching or even implementing different types of stitching such as zigzag stitching. By addressing these areas in follow up studies, reseachers can improve the understanding of stitched composite behaviour under thermal cycling to create stronger and more reliable materials for a vast range of applications.

References

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