Performance of through thickness, Stitched-Kevlar® Composites

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This study looks to add to the limited pool of stitched composite structural research by comparing unstitched resin-infused and stitched resin-infused Kevlar® configurations. This will be done by utilizing ASTM tension and compression standard tests as well as drop tower ballistic testing to compare the stitched and unstitched configurations. ASTM D3039 tensile testing as well as ASTM D6641 compression testing will be completed to obtain detailed results for comparison between stitched and unstitched Kevlar®. Drop tower testing will be completed on 6" by 3" test panels to test for the difference in delamination area between the stitched and unstitched subjects. X-ray imaging will be used to gain a thorough look at the delamination that will occur. The anticipation is that the forthcoming experiments will yield valuable insights into the performance of through-thickness stitched resin-infused Kevlar® composites as opposed to their unstitched counterparts and will lead to their wide acceptance as a viable solution within the aerospace industry.

I. Nomenclature

Tup = Drop tower impact head

II. Introduction

Composite materials entered the aerospace industry during World War II when alternate materials were needed for lightweight, high strength aircraft components. By the end of World War II, a small aerospace composites industry was taking off. In the 1970s, composite manufacturing had matured. During this time, DuPont created Kevlar® [1]. Kevlar® is a para-aramid heat-resistant fabric with many inter-chain bonds in its molecular structure that makes it extremely strong. Its uses span from aerospace composites, to personal protective equipment, to bulletproof vests. It has an extremely high strength-to-weight ratio that lends to its high tensile strength [2]. These properties make Kevlar® an excellent candidate for not only aerospace composites, but their stitched counterparts.

With composite materials becoming more widely used in the aerospace industry, the demand for increasingly durable and lightweight configurations rises. Advanced composites look to answer this demand, specifically through-thickness stitched composites. Unfortunately, due to the complexity in manufacturing these stitched composites, and the relatively new technology required to do so, there is little research and testing to support the following claims.The research done in this paper is to compare a nonstitched composite to a through-thickness, stitched composite of the same configuration. Experimentation with tension, compression, and impact is used to be able to reliably compare the two composites to each other.

Through-thickness stitching involves the insertion of reinforcing fibers perpendicular to the primary fiber orientation within the composite structure. This technique is believed to enhance interlaminar strength, mitigate delamination, and improve damage tolerance, thereby addressing critical challenges encountered in traditional composite materials. By effectively distributing loads and promoting load transfer between adjacent plies, through-thickness stitching enhances the overall structural integrity and performance of composite components, particularly in high-stress applications subjected to complex loading conditions.

Moreover, through-thickness stitching has garnered attention for its potential to enhance the ballistic resistance of composite materials. Ballistic impacts impose sudden and localized stresses on composite structures, often leading to catastrophic failure. Through-thickness stitching serves to arrest crack propagation and dissipate energy, thereby minimizing the extent of damage caused by ballistic threats. This property is of paramount importance in aerospace

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and defense applications, where the ability to withstand ballistic threats without compromising structural integrity is paramount. Stitched composites have been studied at Mississippi State University at the Marvin B. Dow Stitched Composites Lab, but more research is needed to understand the properties that occur as a result of stitching.

This investigation into through-thickness stitching in Kevlar® composites offers promising prospects for advancing aerospace and defense applications. By conducting rigorous experimentation and analysis, this research aims to bridge the gap between theoretical potential and practical implementation of stitched composites. Through a comprehensive understanding of their mechanical behavior and performance disparities compared to non-stitched counterparts, we seek to unlock the full potential of stitched composites in enhancing structural integrity and ballistic resistance. Ultimately, this endeavor strives to propel composite materials into a new era of innovation, reshaping the landscape of aerospace engineering and materials science.

III. Manufacturing Process

In order to manufacture the test coupons required to gather data, a rigorous manufacturing process is needed. The first steps for manufacturing test coupons is to start by acquiring the Kevlar® to be used. The Kevlar® used in this research project is, plain weave, DuPont Kevlar® 49. Once acquired the dry fabric Kevlar® is stored in an environmentally controlled area according to all commercial standards and requirements. When needed to manufacture the coupons, the first part in the process is to cut out the needed plies. In order to keep the plies uniform between the different tests a Gerber cutting machine is used. The Gerber cutting system employs an overhead gantry system to maneuver a cutting blade with precision. Initially, it reads AutoCAD files to understand the required shapes and dimensions of the composite materials. Then, utilizing its high-pressure blade mechanism, it cuts through a layer of composite material according to the specified design. This process ensures uniformity and accuracy in the plies needed for manufacturing. For this project, one stack of 15 plies of unstitched Kevlar, one stack of 15 plies of through-thickness stitched Kevlar, both stacks measuring 16”x16” and 0.165” thick, were prepared. Additionally, two other plates were made with stacks of 25 plies each, one with through- thickness stitching and one without, measuring 8”x14” and 0.275” thick. The stitching grid chosen for this research was a 1”x1” grid.

Once the plies that are needed are cut, preparation of the infusion plate, a thick steel or metal plate, needs to be done. This involves using an acidic compound and an abrasive sponge. In the case of this project the acid used was Acetone and the abrasive sponge used is a 3M Scotch-Brite™ Scour Pad. This allows for any residue and imperfections on the infusion plate to be cleared off preventing any FOD from occurring. After the initial cleaning is done a layer of Loctite® Frekote is applied to the surface. Frekote is an epoxy mold release agent that acts as a thin barrier between the plate and the part being manufactured, allowing for easier removal of the part from the plate after infusion. This prevents any form of damage that can occur by preventing the resin from infusing both the fabric and the plate together. Now that the plate is prepped each of the previously cut Kevlar® plies are laid one on top of the other until a desired thickness. A resin distribution medium is placed on top of the finished stack of Kevlar® plies, this allows for a better flow of the resin throughout the plate in order to assure an uniform distribution of resin into the plies. In order to force the resin into the Kevlar® a vacuum bag is placed around the plate and a vacuum is applied creating a uniform pressure around 27 psi forcing the resin throughout the system so the entire part is infused. The resin system used in this research is FIBREGLAST™ 4500 infusion epoxy resin with the FIBREGLAST™ 4570 70 minute epoxy cure. This allows for enough time to fully infuse the plate without the hardening of the resin. The plate is then allowed 24 hours to rest so that the epoxy is fully cured before the part can be cut into suitable test coupons and samples.

After manufacturing of the Kevlar® plates is finished, the plates need to be cut into the needed test coupons and samples. This action is achieved by using a waterjet cutting machine so that precise dimensions can be cut out of the plates. In order to achieve this an AutoCAD file was made for the two different sized plates that allowed for 10 ASTM D3039 and D6641 spec coupons to be made as well as for 4, 6”x3” drop tower specimens to be made.

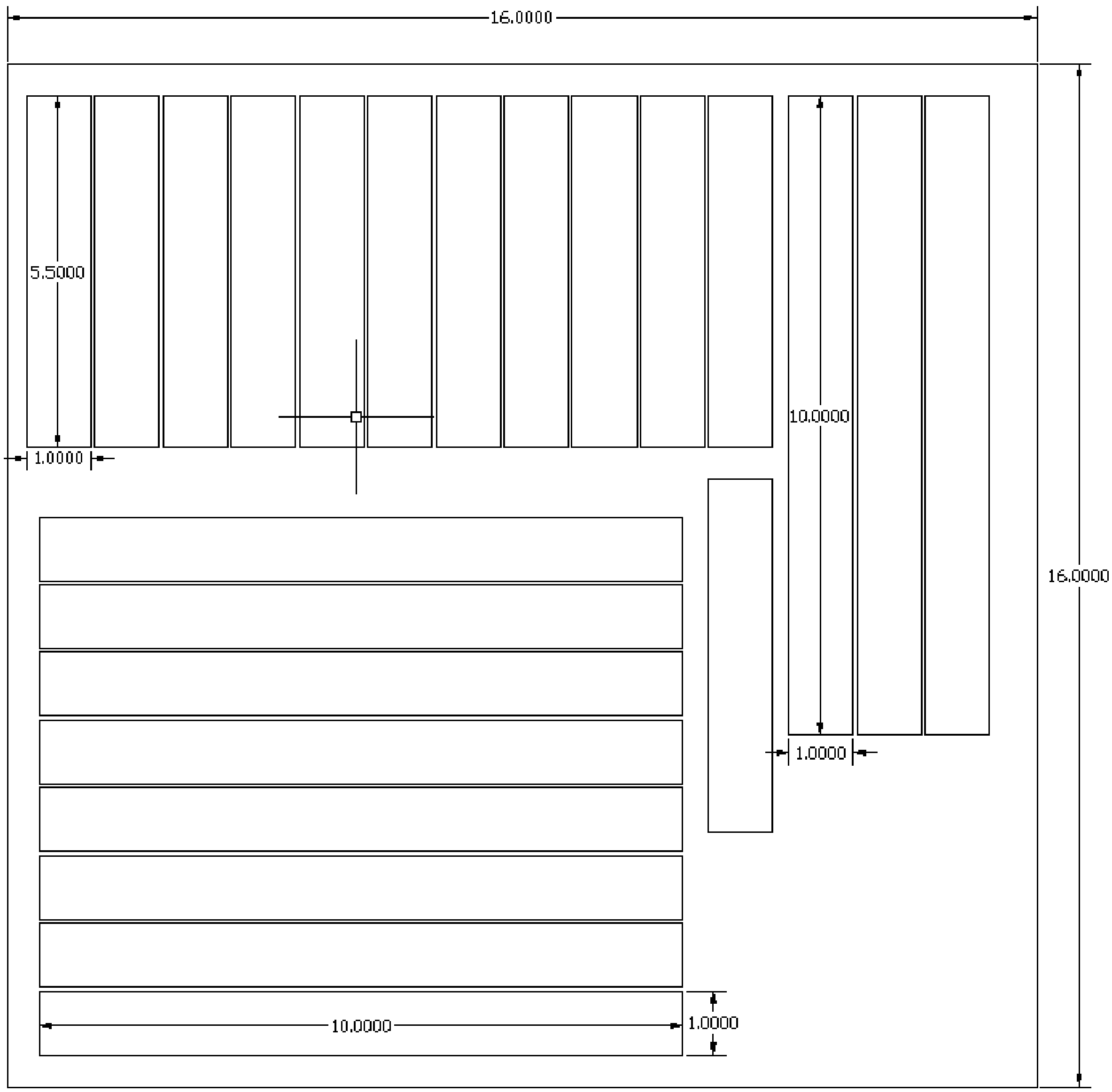

Fig. 1 AutoCAD drawing of the 16”x16” plate for waterjet cutting

AutoCAD sketch used to cut test coupons for tension and compression testing. Units are in Inches.

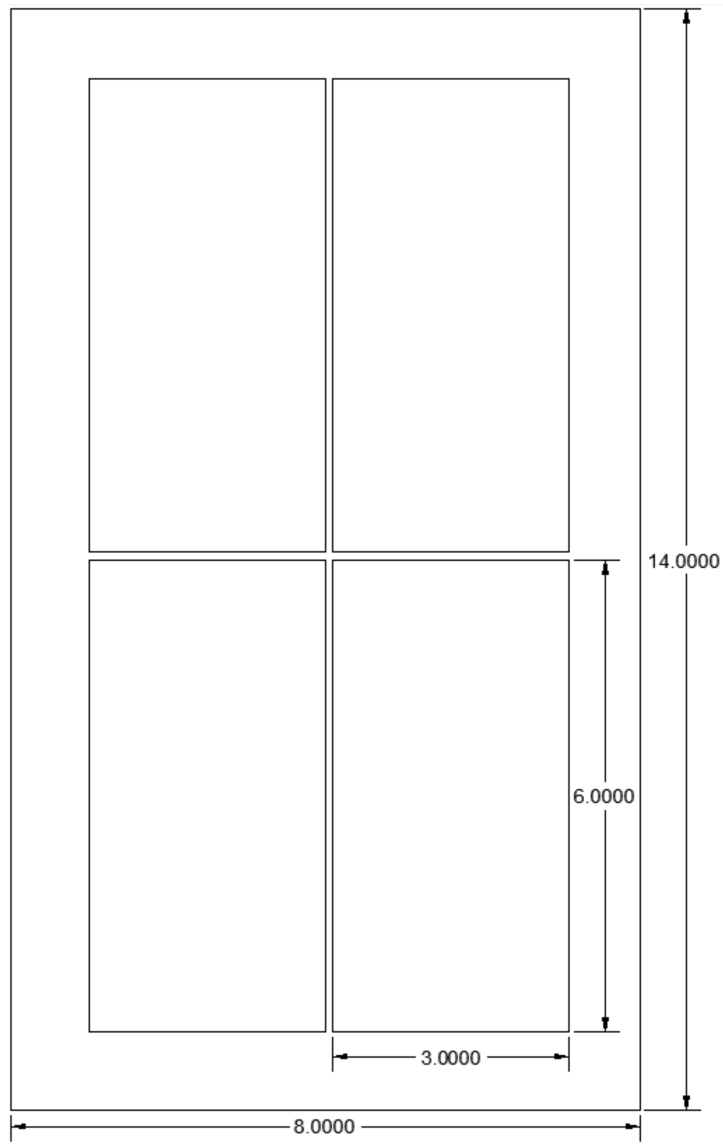

Fig. 2 AutoCAD drawing of the 8”x14” plate for waterjet cutting
AutoCAD sketch used to cut test coupons for drop tower testing. Units are in Inches.

As seen in Figure 1 above the ASTM D3039 tensile testing coupons were cut into 10”x1” rectangles according to the recommendation for a balanced and symmetric composite coupon [3]. The coupons for ASTM D6641 testing were cut to be 5.5”x1” as according to the recommendation for a balanced and symmetric coupon for compression testing [4]. As seen in Figure 2 above, the two 8”14” plates had 4 smaller, 6”x3” plates cut out in order to be used for drop tower testing.

IV. Experimentation

In order to collect a wide array of data to compare the characteristics of the examined composites a wide array of experimentation was used. ASTM standards D3039 and D6641 were carried out using the universal testing machine as part of the research conducted with the Advanced Composites Institute. In addition to this, drop tower testing was performed with a Instron® 9400 series drop tower out of Redstone Arsenal. However due to unforeseen complications with operating the drop tower and scheduling conflicts,, the experimentation has not been fully carried out. Therefore, the specifics regarding results and data will not be available until presentation as it needs further study and testing. However, there is some indication towards the results at this time which will be laid out in the rest of this research.

A. ASTM D3039, Tension Testing

ASTM D3039 is used to test the tensile properties of metallic and composite materials. The tensile properties to be measured are: tensile strength, ultimate tensile strain, tensile modulus, Poisson's Ratio, and failure mode. These properties are the maximum stress applied during testing, the strain at failure, how much the material can deform under stress, the ratio of the change in transverse to longitudinal strain between two points, and a three character code that corresponds to a test coupons failure type, area of the failure, and location of the failure on or in the coupon, respectively. This testing was performed on the universal testing machine at the Advanced Composites Institute.

B. ASTM D6641, Compression Testing

ASTM D6641 is used to test the compressive properties of composite materials. The compressive properties to be measured are: ultimate compressive strength, ultimate compressive strain, compressive modulus of elasticity, and Poission's ratio in compression. These properties are the compressive stress at failure, compressive strain at failure, how easily the test coupon bends under compression, and the ratio of the change is transverse to longitudinal strain between two points under compression. This test will be done on the universal testing machine at the Advanced Composites Institute.

C. Drop Tower Testing

Drop tower testing took place at the Redstone Testing Center on Redstone Arsenal in March. This test was carried out to study the delamination of different Kevlar® composite configurations.. The tower used is an Instron® 9400 series with a post impact compression test stand installed. Drop towers work by raising a sled to a specified known height then releasing the weight to create an impulse at impact. The sled can also be spring loaded and fired, which can create a maximum impact force of 500 lbf. The drop tower has its own specialized computer software to enter testing parameters and run the tests. These parameters include energy at ht that relates to a specific potential energy level so that when the "tup," or the impact head strikes the composite material, the exact amount of force at impact, mass of the impact head, length, width, and thickness of the test coupon. The test coupons were then x-rayed so that the delamination can be seen.

V. Results

The drop tower testing was conducted by utilizing the Instron® 9400 series drop tower at the Redstone Test Center aimed to evaluate the mechanical properties of the Kevlar® test coupons. However, the team's efforts were hindered by an unexpected limitation. The test coupons, measuring approximately 2.5 x 4.5 inches, were incompatible with the 3 x 5 inches cut-out on the testing plate that allows the impact head to pass through test samples. Consequently, data acquisition was not feasible under these conditions due to the coupons being too small to fit properly, creating only two points of contact on the test plate rather than four. The samples would then proceed to break and fall through the cut-out, not giving the tower's software enough resistance or time to collect data.

However, adjustments were made on the Instron® 9400 to lower the force of impact to 10 ft-lbf on the Kevlar® coupons in efforts to prevent them from being broken in half and falling through the cut-out and off the test stand. This modification provided semi-successful test results with these smaller sized Kevlar® coupons, allowing for observation of delamination phenomena. The reduced energy levels facilitated controlled impacts, resulting in visible delamination patterns within the coupons tested at this energy level. This delamination pattern can be seen in Figures 3 & 4.

Fig. 3 Unstitched Kevlar® coupon after drop tower impact at 10 ft-lbf

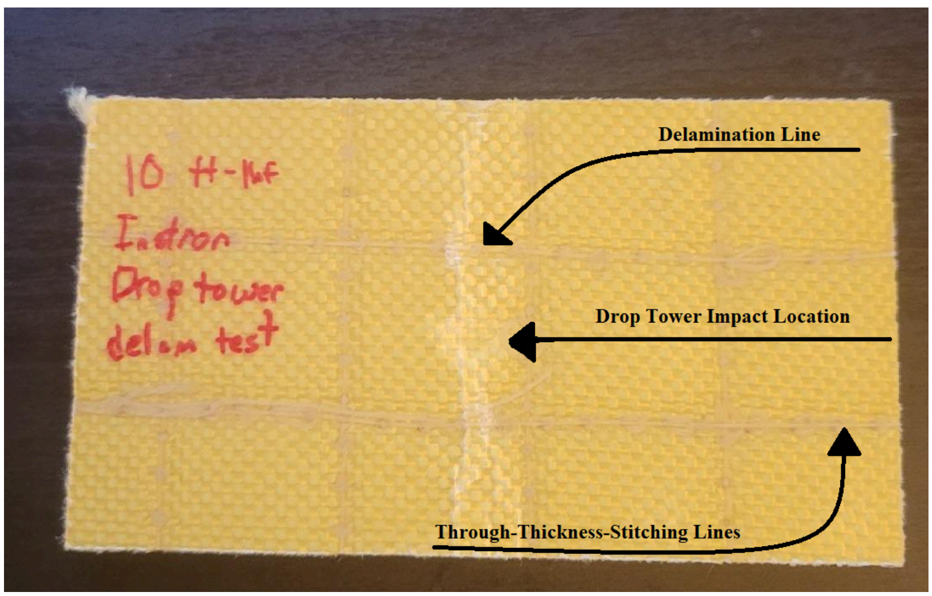

Fig. 4 Stitched Kevlar® coupon after drop tower impact at 10 ft-lbf

Examining the test coupons that were broken it was observed that frays of the Kevlar® fabric indicated that the resin had not fully spread throughout the fabric. This information will provide the team with insight on how to better the manufacturing process on further iterations of the test coupons.

Moreover, the delaminated samples offer a unique opportunity for material characterization and improvement. By studying the properties of the delaminated regions, such as stiffness, strength and interlaminar bond strength, the team can identify potential areas for material enhancement and optimization. This process of analysis and refinement holds promise moving forward for the next iteration of the team's next iteration of test coupons in order to collect crucial data.

VI. Conclusion

This study delves into the potential of through-thickness stitched composites, particularly focusing on Kevlar® configurations, to meet this increasing demand for durable and lightweight materials in the aerospace industry. The motivation behind this exploration is the belief that such stitched composites can enhance material strength, improve compression behaviors, and reduce the risk of total panel failure from ballistic impacts.

However, the complexity of manufacturing through-thickness stitched composites poses a challenge, and the relatively new technology involved has limited the available research and testing to meet industry standards. To address this gap, the study conducted an analysis of unstitched resin-infused and stitched resin-infused Kevlar® configurations. Although this study originally aimed to comprehensively examine the difference in stitched and unstitched Kevlar® configurations, due to the complexity of the research being performed, the need to outsource equipment use, and the limited timeframe to conduct the study, the scope has been restricted to allow the completion of work in time the AIAA Region II Student Conference where results will be presented.

While the experimentation results have not been fully presented here, the methodical approach to testing aims to contribute valuable insights into the behavior of stitched Kevlar® composites compared to their unstitched counterparts. It is anticipated that a deeper understanding of these materials will enhance their acceptance as a competitive solution within the aerospace industry.

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