MECHANICAL PROPERTIES OF HYBRID POLYMER FIBER-REINFORCED LAMINATES IN CRYOGENIC CONDITIONS

Michael D. Lambert, Eric A. Clark, Thomas H. Fronk
Department of Mechanical and Aerospace Engineering, Utah State University, Logan UT, 84321

Introduction

The strength of fiber-reinforced polymers after impact is of concern due to the brittle nature of carbon fibers and typical epoxies. At cryogenic temperatures the problem is more severe. In this paper the impact strength of hybrid composites at cryogenic temperatures is investigated using Naval Ordnance Laboratory (NOL) ring specimens that simulate the cylindrical geometry of a composite overwrap pressure vessel (COPV). Comparing three different thermosetting resins, NOL rings consisting of either carbon, Zylon®, or mixed carbon/Zylon® layups at cryogenic temperatures are damaged by impact then loaded in tension in a liquid nitrogen (LN_2) environment. This investigation supplements previous work accomplished by Swenson, who investigated the impact strength of tensile coupons made from different resin systems and carbon/Zylon® cross-ply layups at cryogenic temperature [1].

Experimentation

Materials

The carbon based fibers are desirable for a pressure vessel structure because of their high strength to weight ratio. For this experiment IM7 carbon fibers manufactured by HEXCEL® Corporation were used. However, due to the brittle nature of the carbon fibers a low tolerance to damage is expected when subjected to a transverse impact. In this case Zylon® an aramid fiber developed by Toyobo CO., LTD. was introduced to supplement the brittle carbon fibers under impact due to its superior toughness.

In search for an enhanced thermoset to reinforce the chosen fibers, three candidate resins were considered: HEI 535, a non-commercialized urethane, and Epon® 828. HEI 535, developed by HyPerComp Engineering Inc. (HEI) is an experimental epoxy designed for low temperature applications. The non-commercialized urethane is a resin developed to have increased flexibility and strength at cryogenic temperatures. The Epon® 828 developed by HEXION™ is a commercial grade epoxy resin commonly used for fiber-reinforced composite structures.

The NOL rings made of the chosen fibers and resins have a symmetric layup due to the property mismatch in order to avoid bend-extension coupling. The layup includes a total of 5 layers, where the hybrid rings alternate layers between carbon and aramid fibers. Fiber orientation is perpendicular to the tube axis so that when the ring was pulled in tension the fibers were oriented 0 to the applied load. The width of the NOL rings was determined so that the maximum capacity of the load cell on the Tinius Olsen tensile machine was not exceeded. Angled layers were not considered because of the boundary conditions; the fiber lengths would be cut short due to the dimensions of the ring and would thus not contribute to the rings strength.

Apparatus and Procedure

The NOL rings were cut from a filament wound tube made of the desired fibers, resin, and fiber layup using a pulse laser set at an optimal pulse frequency, pulse duration, power setting and tube revolution speed. A modified bench center as seen in Figure 1 was built in order to rotate the NOL tube with precision during the cutting process. There was no sign of delamination from the cut as has been seen with other abrasive cutting methods. This method has proven to be reliable and repeatable for both the stiff carbon and elastic aramid fiber-reinforced composites.

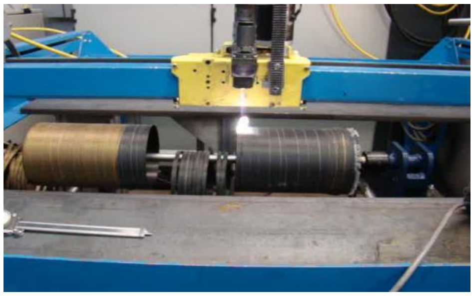

Figure 1 Laser cutting process of NOL tube.

Prior to impact, the cylindrical aluminum anvil designed to support the ring during impact and the NOL rings were submerged in LN_2 until thermal equilibrium was achieved. Following the cool down, the NOL ring was secured to the anvil in the LN_2 filled cryogen bath to be impacted as seen in Figure 2. Impact damage in the NOL rings was defined as either high (75% of impact breaking energy at cryogenic temperature) or low (25% of impact breaking energy at cryogenic temperature).

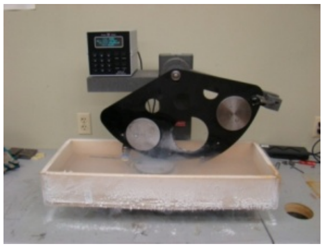

Figure 2 Test set up for NOL ring impact.

The tensile tests conducted on the damaged NOL rings were performed in accordance with ASTM D2290-04 with some modifications made for the rings to be tested in a cryogenic environment [2]. As seen in Figure 3, the two disk halves housing the NOL ring were submerged in LN_2 during the tensile test. Care was taken when loading the test sample to ensure that the ring was situated so that the point of impact was oriented in the plane of separation of the disc halves.

Figure 3 NOL ring tensile fixtures.

Results

Table 1 Average impact breaking energy for each fiber-resin system

Avg. NOL Ring Breaking Energy (in-lb) at LN_2 Temperature			
Layup	Resin		
	HEI 535	Urethane	Epon 828
5 C	3.98	2.08	2.72
3 C / 2 Z	37.04	32.84	25.82
2 C / 3 Z	42.01	41.85	30.23
*5 Z	44.57	44.07	45.33

From Table 1 it is seen that the NOL ring breaking energy increases with the number of Zylon® layers in the structure. It should be mentioned that the tough all Zylon® rings did not break but rather plastically deformed with the pendulum mass at its maximum potential energy and therefore did not have a true breaking energy.

The all carbon rings experienced a brittle laminate failure due to a tensile load if sufficient damage from impact was created. In comparison to the all carbon rings, the hybrid rings did not experience a brittle laminate failure at the impact zone. As expected the all Zylon rings underwent greater plastic deformation before failing in tension. It was seen with the urethane resin that the all Zylon® rings never experienced complete fiber failure while in tension at the impact zone as the other fiber-resin systems had.

Figure 2 Apparent NOL ring tensile strength comparisons between fiber-resin systems.

Conclusions

Introducing the high energy absorbing Zylon® fibers with the high strength carbon fibers significantly increases the strength of the NOL ring after impact in a cryogenic environment. Since the NOL rings used in this research did not have a stiff support behind the impact zone similar to what would be present in an aluminum liner composite COPV a suggested optimal fiber layup to be used as an impact strengthening technique for COPVs is not made at this time.

References

1. Swenson, D. C. (2007). *Cryogenic Impact and Tensile Testing of Graphite Composite Structures.* Logan: Utah State University.

2. ASTM D2290-04. *Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe by Split Disk Method.* 1996.