# COMPRESSION AFTER IMPACT BEHAVIOR OF ELECTROSPUN NANOFIBER EMBEDDED FIBER GLASS COMPOSITE LAMINATES

E. Kimbro, A. Kelkar*, R. Mohan

*Joint School of Nanoscience and Nanoengineering, 2907East Lee Street, Greensboro NC 27401, USA*
**kelkar@ncat.edu*

**Keywords:** Electrospinning, Compression-After-Impact, Composite, Delaminations

## Abstract

*This paper investigates the reduction in compressive residual strength of electrospun nanofiber embedded fiberglass reinforced composite laminates subjected to low velocity impact loading. The fiberglass laminates were fabricated using Tetra Ethyl Orthosilicate (TEOS) chemically engineered glass nanofibers. Impacted specimens were examined using C-scan analysis to estimate impact damage area. Compression-After-Impact (CAI) coupons were obtained from impact tested specimen. Specimens were tested to determine the compressive residual strength. The test data from residual compression strength were compared for the impacted laminates with and without electrospun nanofibers added to lamina interfaces.*

## 1 Introduction

The use of composite panels has been steadily increasing in many applications especially the aviation field over the past 30 years. It is well known fact that composites have high strength to weight ratios, outstanding fatigue resistance and superior corrosion resistance. It is equally well known that composite components do not hold up well in impact related conditions and their compression strength, post-impact, suffers greatly. The intolerance of composites to impact damage has become a focal point of recent research. Methods such as stitching, z-pinning and 3-D interleaving offer increased interlaminar shear strength but comes at the cost of in-plane properties [1]. Recent developments in nanotechnology have a potential to help increase the energy absorption in composite materials under external impact. This is critical as until composite materials are developed into a highly evolved impact-resistant material system, their use for external impact loading service conditions will still be limited.

Impact damage can be categorized into 3 main failure criteria. 1) Matrix cracking, 2) Delamination, 3) Fiber breakage. The largest loss of transverse stiffness occurs during the delamination phase of impact damage [2]. Recent developments in electrospinning techniques have allowed new methods for producing high quality non-woven material systems to be incorporated into conventional composite systems. Compression after impact (CAI) measure the laminates ability to resist in-plane loading after known impact damage exist. Residual strength can be determined and correlated to undamaged laminates.

## 2 Materials and Testing Methods

Tetraethylorthosilicate chemically engineered glass was electrospun into nano fiber non-woven fabric sheets. Electrospinning is a process that does not use physical contact between a spinneret and a collection plate known as the collector. An electrostatic force is applied between the two in order to draw a sol-gel solution from the spinneret to the collector. Under hydrostatic surface tension, electro static forces cause a droplet to extend out of the spinneret. The droplet further extends into a thick fiber where bending instability causes a whipping action resulting in elongation of the solution. The whipping of the newly formed fiber continues to elongate as the surface area to volume increases dramatically. This increase of surface area to volume ratio accelerates the evaporation of solvents in the solution. This is necessary to minimize the fiber diameters. Formation of glass nanofibers was achieved using a solution that was mixed and aged properly for electrospining.

The main ingredients for the mixture were TEOS, ethanol, hydrochloric acid and deionized water [3]. In order to create a ‘sheet’ of nonwoven electrospun glass nanofibers the collector plate was attached to a computer numerically controlled screw slide. Two slides were used in conjunction with one another to give 2 degrees of freedom motion. The height of the collector plate could be adjusted as well as the lateral position. The two linear slides were fastened to one another and the collector plate is fastened as well. The linear slides are connected to a programmable controller to regulate the motion of the collector plate. Electrospun glass fiber mats were then formed using these computer controlled collector plates in conjunction with a high voltage power supply and syringe injection pump.

Thirty six nanofabric sheets were electrospun with dimensions of 36 cm x 36 cm. The glass nanofabric was post cured in a high temperature oven at 600$^{o}$C for 6 hours. Post curing the nanofabric increases strength and decreases fiber diameters [4]. Pre-impregnated composite VTM264/7775 fabric was supplied by Advanced Composites Group. Four composite laminates measuring 36 cm x 36 cm were manufactured with electrospun nanofabric applied at the interfacial layer. The electrospun glass nanofabric was applied with great care at interface and de-bulked using a de-bulker for 15 minutes at every interface. Figure 1 shows application of electrospun glass fiber mat at a single interface.

**Figure 1**. Image of electrospun glass nanofabric applied to pre-impregnated fabric

The final uncured laminate was debulked as a whole for 30 additional minutes prior to curing. The electrospun glass nanofabric added approximately 1.5% by weight to the neat system. The large laminates were then machined to obtain 15 cm x 15 cm specimens. In order to study the onset of progressive damage, the impact damage testing comprised of multiple increasing drop heights. The specimens were placed into a low velocity drop tower impact tester with the edges of the laminate specimen clamped along the boundaries. Drop test heights were divided into 5 discrete values. Empirically derived incipient damage determined the lowest drop height, while empirically derived protrusion determined the maximum drop height. Tests were conducted at five different drop heights of 5in., 11in., 17in., 23in., and 29in. Drop tests were conducted in accordance to ASTM D7136 standard. The standard dictates the use of a drop weight tower that has a crosshead affixed to guides with proper instrumentation. Although a drop test generally can take between 500-3000 milliseconds to perform, data acquisition is only recorded for approximately 20 milliseconds. This is the time period in which contact is made by the 1 inch hemispherical instrumented striker "tup" on the specimen.

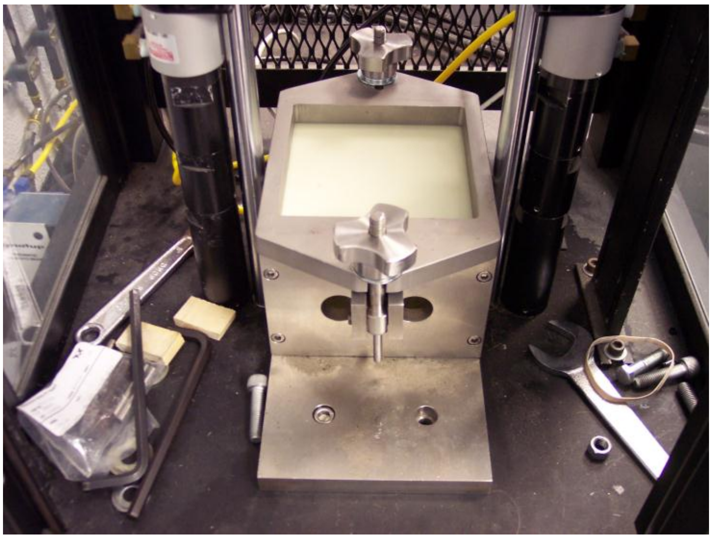

**Figure 2**. Image of impact specimen prior to drop test, clamp-clamp condition

Compression after impact tests were performed on each specimen for residual strength comparisons. Impacted test specimens were cut and tabs applied in accordance with ASTM D7137 test standard. A test fixture that would not allow out of plane bending was used. The test fixture holds the specimen such that out of plane bending will not occur. Guides are used in the test fixture that allow the specimen to slide but do not clamp the edges. Tabs were installed to prevent failure in non critical areas of the specimen. Figure 3 shows an example of s specimen in the test fixture during a test. The test fixture was loaded into an Instron 30 kip load frame. Blue Hill software was used for application and data acquisition of the test. Data was collected at a rate of 50 hertz.


**Figure 3**. Compression After Impact fixture

Failure appeared to be due to buckling occurring at the midpoint of the panel. The impact areas on the specimens without electrospinning appeared visually larger and this was confirmed by C-SCAN non-destructive testing. The compression test was displacement controlled. Crosshead velocity of 0.030 inch/second was utilized to yield the proper failure time criteria. Each test lasted approximately 3 minutes with failure occurring when compressive loading dropped by more than 40%. Test limits of 0.150 inch or 12000 lbf were implemented. Table 1 indicates the test data for maximum residual load carrying capabilities of each specimen.

| **Drop Height** | **Residual Strength Without** | **Residual Strength With** |
|---|---|---|
| (in.) | (ksi) | (ksi) |
| 5 | 20.3 | 20.3 |
| 5 | 17.9 | 20.5 |
| 5 | 18.8 | 21.6 |
| 11 | 20.1 | 7.4 |
| 11 | 21.6 | 10.2 |
| 11 | 21.6 | 12.9 |
| 17 | 22.8 | 17.3 |
| 17 | 22.6 | 16.6 |
| 17 | 20 | 15.5 |
| 23 | 18.1 | 18.1 |
| 23 | 17.8 | 17.3 |
| 23 | 17.8 | 14.6 |
| 29 | 15.8 | 8 |
| 29 | 18.9 | 10.4 |
| 29 | 17.6 | 7.8 |

**Table 1**. Compressive residual strength (maximum) of specimens with and without electrospun nanofabric

It is clear that adding electrospun nanofibers in between each lamina allows more damage to occur during the impact event. This damage weakens the specimen at the mid plane and allows micro-buckling to occur. Once the micro-buckling becomes unstable destructive damage occurs and the specimen no long carries the load. The 5 inch drop height does show much deviation between the two variants. Immediate evidence is shown with the 11 inch drop height specimens that have electrospun nanofabric between the lamina. An almost 50% reduction in compressive residual strength is observed in the composite panels with electrospun nanofibers compared to the specimens without the nanofiber layers. It is clear that the specimens with the nanofabric applied have a lower residual strength as compared to without. Figure 4 shows the crack tip morphology and the separation at the interlaminar region.

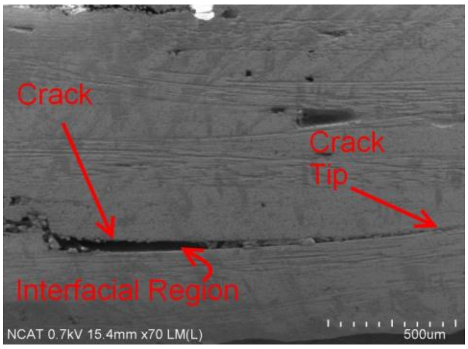


**Figure 4**. SEM image of crack morphology

## 3 Conclusions

Adding 1.5% wt electrospun glass nanofibers to the interfacial layer of pre-preg glass laminates appears to facilitate increased damage caused by low velocity impact. Clearly the nanofibers between the layers act as sacrificial layer [5]. The interlaminar region is of critical importance in this behavior. As viewed in Figure 4, crack propagation occurs in this region. Electrospun nanofabric was applied in attempts to slow or mitigate propagation. Instead, it seems propagation was facilitated with an increase in crack propagation in the composite specimens with the electrospun interlaminar nano fiber layers. After a threshold of approximately 11 inch drop height, compressive residual strength fell by approximately 29% in the specimens with electrospun glass nanofabric compared to those without the nanofibers. Future studies should include the interaction of the glass nanofabric with the 7775 polymer matrix. Perhaps functionalizing the nanofabric or preparation of specimens with various weight percentages may improve impact performance. The concept of embedding nanofibers interfacial might be attractive from the stand point that the laminates with embedded nanofibers will be able to absorb significantly higher impact energy as compared to the laminates without any presence of nanofibers.

## References

[1] Grassi, M., X. Zhang, and M. Meo, *Prediction of stiffness and stresses in z-fibre reinforced composite laminates.* Composites Part A: Applied Science and Manufacturing, 2002. 33(12): p. 1653-1664

[2] Jih, C.J., and C.T. Sun, *Prediction of Delamination in Composite Laminates Subjected to Low Velocity Impact.* Journal of Composite Materials, 1993. 27(7): p. 684-701.

[3] Choi, Sung-Seen, Seung Goo Lee, Seung Soon Im, Seong Hun Kim, Yong L. Joo, *Silica Nanofibers from electrospinning/sol-gel process*. Journal of Materials Scient Letters, 2003. 22: p. 891-893

[4] Shendokar, S., A. Kelkar, R. Mohan, R. Bolick, and G. Chandekar, *Effect of Sintering Temperature on Mechanical Properties of Electrospun Silica Nanofibers.* Proceedings of IMECE2008 ASME International Engineering Congress and Exposition, 2008

[5] Kimbro, Evan and Kelkar, Ajit, *Development of Energy Absorbing Laminated Fiberglass Composites Using Electrospun Glass Nanofibers*. Paper number IMECE2011-64746, Proceedings of ASME 2011 International Mechanical Engineering Congress and Exposition, Denver, Colorado, 2011