COMPOSITES AS A SUBSTITUTE FOR STEEL BOOM ARMS IN AGRICULTURE APPLICATIONS

Alessandro Rengan, Charles Chirume, Ayanna Russell

Central State University

1400 Brush Row Rd.

Wilberforce OH 45384

ABSTRACT

This work was conducted as a senior design project. The initial objective was to develop and characterize an advanced composite tube that can be used as an alternate to steel in agriculture applications, specifically to replace steel arms in sprayer booms. Carbon prepreg specimens and fiberglass prepreg specimens were prepared using an out-of-autoclave technique. Impact testing and flexural testing were performed on sample specimens. Impact testing on Carbon prepreg gave a median energy absorbed of 335 KJ/m^2. Flexural testing on Carbon prepreg gave a median flexural strength of 517 MPa. It was not possible to test the fiber glass prepreg samples due to the pandemic shutting down the university. Impact testing data and Flexural testing data fit the Weibull distribution, giving a Weibull parameter of 2.2 and 5.9 respectively. Survivability of 90 %, 75 % and 50 %were derived from the Weibull analysis. A composite tube was made as a laboratory demonstration. In conclusion it has been shown from previous work that polymer matrix composites could replace steel in terms of its specific impact absorption and specific flexural strength, and, in this work that Weibull analysis can predict failure properties.

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1. INTRODUCTION

Carbon fiber reinforced polymers (CFRP) are attractive engineering materials primarily because they have a high ratio of strength to weight. Their stiffness and strength properties with respect to weight (Specific stiffness and specific strength) are superior to metal [1].

There are various ways in which impact will affect the structural integrity of a composite. This will rely of various factors that include the materials (both fiber and matrix) making up the composite, the orientation and configuration of composite laminates environmental factors such as temperature and water [2, 3].

The Weibull distribution is a continuous distribution that is used as tool to assess failure time, analyze life data and to assess product reliability. The benefit of Weibull statistical analysis for reliability engineering is that it measures the probability of failure and makes accurate forecasts for engineering composites at the design and manufacturing stage [4]. Ray et al [5] prepared E glass fabric with epoxy resin and used a hand lay-up technique to prepare samples for tensile and compression testing using a two parameter Weibull distribution to analyze the data. Naresh et al [6] studied the tensile strengths of glass/epoxy and carbon/epoxy composites. They used compression molded composite specimens.

This paper is meant for those with a basic knowledge of mathematics and those interested in polymer matrix composites as a substitute for heavier structural material. The out-of-autoclave is a less expensive version to the autoclave.

2 EXPERIMENTATION

2.1 Experimental Set up

Pre-impregnated carbon – epoxy material was obtained from Fiber Glast Development Corporation (Brookville, OH). The high modulus fiber was rated with an elastic modulus of over 2.8 GPa, and a tensile strength of over 79 MPa, the thickness of the fabric was 0.3 mm (0.012 in). An out-of-autoclave, previously put together by one of the authors [1] was utilized. The vacuum pump was located outside the oven and the vacuum line was threaded into the oven by means of a port on the oven. The vacuum inside the bagging material was measured at ~700 mm Hg (~ 90 kPa). A temperature controller held the oven temperature at ~ 130 ^{o}C. The curing process was carried out for a minimum of 4 hours and testing was performed only on flat specimens. For demonstration purposes a tube was fabricated. The mold was 10 cm. diameter tube of aluminum.

2.2 Charpy Impact Testing

Generally impact testing is of two types 1) low velocity impact and 2) High velocity impact. Charpy impact testing and Drop Weight methods belong to low velocity type. Ballistics belong to high velocity impact testing [7].

In this study low velocity impact Charpy testing (Satec Systems Inc. 2 ft. lb. minimum) has been performed to measure the impact strength of Carbon fiber reinforced composites conforming to ASTM D6110-04 [8]. The drop height was 24 in., and the angle was 60^{o} from the horizontal.

Impact test specimens were rectangular of length 127 mm and width 12.7 mm. Notched specimens were utilized.

2.3 Three Point Flexural Testing

Flexural testing is a combination of shear, tensile and compressive loading. The top surface of the specimen is subject to compressive stresses and the bottom of the specimen is subject to tensile stresses. If the ratio of the span length, l, to the thickness of the specimen, d, is less than 5

: 1, the specimen is subject to interlaminar shearing. To achieve a tensile fracture of the specimen the L: d ratio should be greater than 16 : 1. For ratio's in between, that is 5<L:d<16, a mixed mode tensile and shear failure, prevails. However, for low loading rates, that is for loading rates lower than 10 $\left(\frac{mm}{min}\right)$, primarily tensile fracture occurs. At loading rates greater than 11 $\left(\frac{mm}{min}\right)$, pure shear fracture occurs [9].

Flexural characteristics of the composites were determined by using an Instron Model 5569 Universal Testing machine. The test method used was a 3 – point loading by a support span of length 76 mm. The radius of the loading tip was 5 mm and the cross head speed during flexural testing was 2.5 $\left(\frac{mm}{min}\right)$. The testing was conducted according to ASTM Standard 790 [10].

2.4 Theory of Weibull distribution

Weibull distribution is used to model extreme values such as failure probabilities. A popular form of this distribution is the two parameter Weibull distribution for cumulative probability density is given by [11]:

$$F_v = 1 - e^{-\left(\frac{v}{\alpha}\right)^{\beta}} \qquad (1)$$

Where F_v is the probability of failure (cumulative probability density function)

Therefore survival probability $S_v = 1 - F_v$

v denotes the variable of interest (impact energy)

α is the scale parameter or characteristic impact energy

β is the shape parameter or Weibull modulus

By taking natural logarithms of both sides, eq (1) can be written as:

$$\text{Ln}\left(Ln\left(\frac{1}{1-Fv}\right)\right) = \beta \text{ Ln } v - \beta \text{ Ln } \alpha \qquad (2)$$

This is a linear equation of the form: $Y = mX + C$ (3)

Where the LHS of eq (2) is the 'Y' axis, and on the RHS, Ln v is the 'X' axis

The slope of the curve 'm' gives the value of β or the Weibull modulus.

The scale parameter, α, can be obtained by solving the linear regression equation for 'C':

$$C = -\beta \, Ln \, \alpha \qquad (4)$$

Cumulative probability density is expressed in terms of Median Rank Formula which is given by:

$$F_v = \frac{j - 0.3}{N + 0.4} \qquad (5)$$

Where 'j' is the rank and 'N' is the total test number of samples respectively.

3 RESULTS

3.1 Impact Tests of prepreg Carbon Fiber Reinforced Polymer

The results for the impact testing are given in Table 1. A plot of the Ln(Impact Energy) vs. Ln $\left(Ln\left(\frac{1}{1-Fv}\right)\right)$ are shown in Figure 1.

Table 1 Summarized Weibull values for Impact Tests of Carbon Fiber Reinforced Polymer

Impact Energy	**Rank**	**Median Rank (Eq. 5)**	**Ln (Impact Energy)**	**Ln(Ln(1/(1-Fv))**	**α Scale Parameter**	**β Shape Parameter**
(KJ/m^2)	**j**	**Fv**	**(X – axis)**	**(Y – axis)**	**(KJ/m^2)**	**(Weibull Modulus)**
216	1	0.129	5.3753	-1.8994		
256	2	0.314	5.5452	-0.7928		
276	3	0.5	5.6204	-o.3665	394.650	2.2296
386	4	0.681	5.9558	0.1446		
605	5	0.870	6.4052	0.7131		

The values of Ln(Impact Energy) vs. Ln $\left(Ln\left(\frac{1}{1-Fv}\right)\right)$ are plotted and are shown in Figure 1.

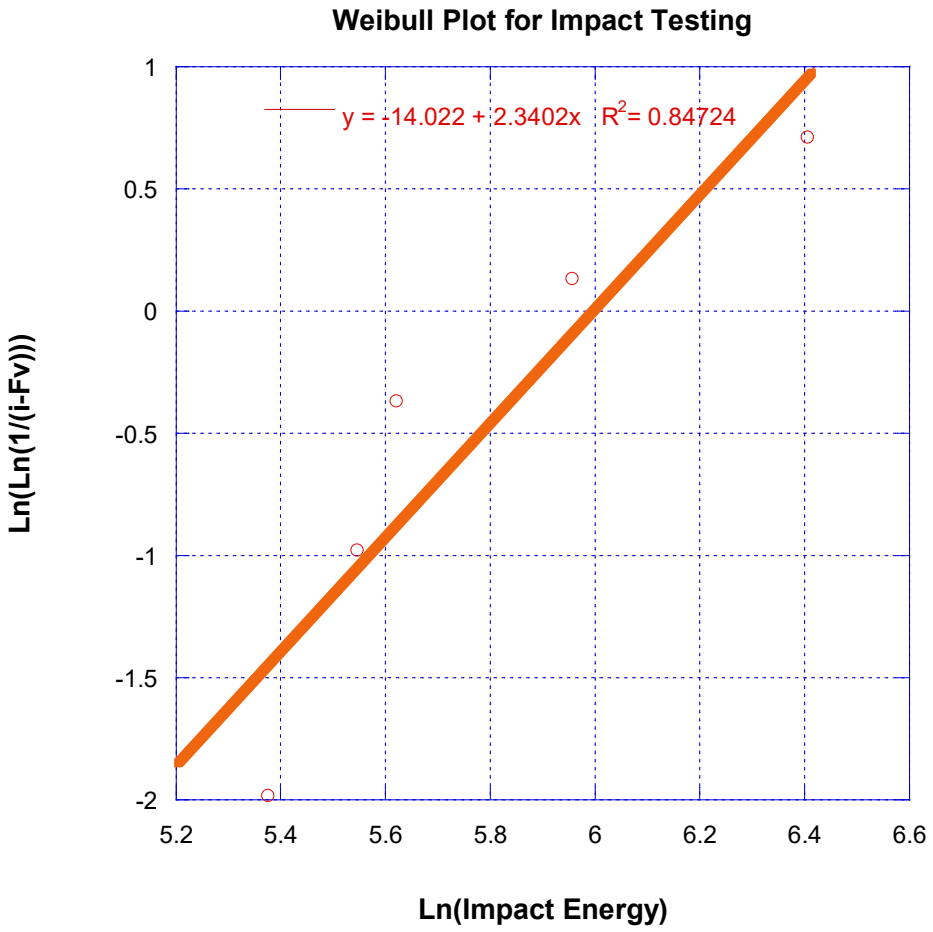


Figure 1 Weibull plot of specimens of impact Energy absorbed by CFRP.

The correlation coefficient (R^2) values as obtained from the curve corresponds to 0.84 which demonstrates a reasonably good fit between experimental values and the curve fit.

The median impact energy can be found by using F = 0.5 in the linear regression equation (2). E.g.

$$Ln(ln2) = 2.23\ ln(v) - 2.23\ ln394.7 \quad (6)$$

On simplifying the median energy is 334.62 KJ/m^2

Similarly estimating the 90 %, 75 % 50 % survival rate can be obtained by substituting these values into the linear regression data in eq. (2) noting that the survival probability $S_v = (1 - F_v)$ estimating the impact energy that 90%, 75%, 50% of the same CFRP can survive is given by the survival probability by substituting Eq. (7) into Eq. (2) :

$$S_v = (1 - F_v) \quad (7)$$

These results are summarized in Table 2.

Table 2 Impact Energy survivability probability of (CFRP)

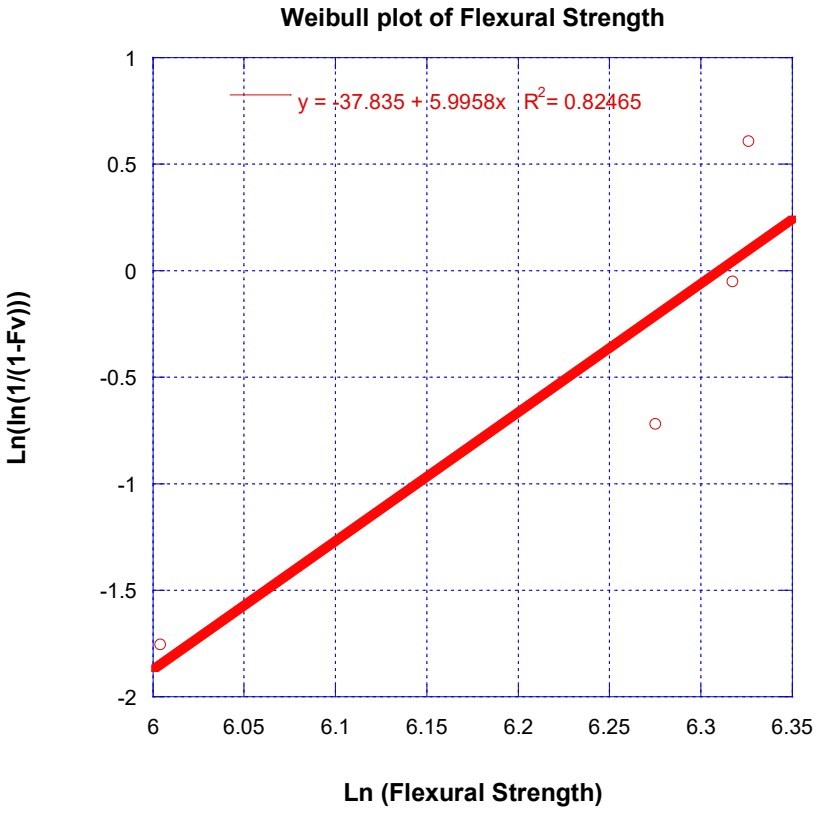
Survival Probability, S_v	**Ln(ln (1/1-F_v)**	**Impact Energy V**
$S_v = (1- F_v)$	**LHS of Eq. (2)**	**KJ/m^2**
90%	Ln(ln(1/0.9)	142.59
75%	Ln(ln(1/0.75)	225.58
50% (Median Impact energy)	Ln(ln(1/0.50)	334.62

3.2 Three Point Flexural Testing

The results of the three point flexural tests are shown in Table 3. A Weibull plot of Ln(Flexural Strength) vs. Ln $\left(Ln\left(\frac{1}{1-Fv}\right)\right)$ is shown in Figure 2

Table 3. Flexural test results for prepreg carbon fiber reinforced polymer samples.

Flexural Strength	Rank	Median Rank (Eq. 5)	Ln (Flexural Strength)	Ln(Ln(1/(1-Fv))	α Scale Parameter	β Shape Parameter
(MPa)	J	Fv	(X – axis)	(Y – axis)	(MPa)	(Weibull Modulus)
405	1	0.159	6.0039	-1.7535		
531	2	0.386	6.2748	-0.7179	550	5.996
554	3	0.614	6.3172	-0.0492		
559	4	0.841	6.3261	0.6091		



The correlation coefficient, R^2 , of 0.82 is an indicator of the reasonably good fit of the theoretical curve with the experimental data.

The shape parameter (Weibull Modulus) is obtained from the linear regression of the best fit curve by the slope, β. The scale parameter α, is obtained by substitution and solving Eq. (4)

The shape parameter (Weibull Modulus) is a function of the data in each of samples (Flexural tests and Impact tests). The higher values of shape parameter provide uniform distribution of the data. On the other hand the values are highly scattered when the β values are lower.

As in the Impact testing the survivability rate for 90 %, 75 % and 50 % of the flexural testing can be obtained by substituting for the survival probability as shown in Eq. (7). These results are summarized in Table 4.

Table 4. Summary for Survival probability for flexural strength.

Survival Probability, S_v	**LHS of Eq. (2)**	**Flexural Strength V**
$S_v = (1- F_v)$	**Ln(ln (1/1-F_v)**	**MPa**
90%	Ln(ln(1/0.9)	377
75%	Ln(ln(1/0.75)	447
50% (Median Flexural Strength)	Ln(ln(1/0.50)	517

The lower the expected probability of survival the higher the flexural strength.

4 CONCLUSIONS

It has been shown previously that prepreg carbon fiber reinforced polymer has higher specific impact energy and higher specific flexural strength to be able to replace steel [1]. An out-of-autoclave oven has been utilized to prepare specimens of prepreg CFRP specimens. Impact testing and flexural testing have been conducted. It is shown that impact energy data and

flexural strength data fit the two-parameter Weibull distribution. From the scale parameter, α, and the shape parameter, β, the survival probabilities for 90 %, 75 % and, median 50 % were obtained. A demonstration CFRP tube was fabricated in the laboratory. In the future testing can be performed on these tubes to determine impact stresses and Weibull analysis can be utilized to determine survival probabilities. However, for the purpose of boom arms in agriculture, impact absorption is not as critical as in if used as automobile impact absorbers.

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