Failure Prediction Analysis of Hybrid Resin Composite Materials by Using Weibull Analysis

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Abstract:- Carbon fiber reinforced composite materials are extensively utilized as structural components in aerospace applications owing to their specifically customized characteristics. The assessment of the materials relies on their characteristics and how they perform when subjected to various types of loads. The objective of this study is to explore the optimal blend of various Bifunctional and Multifunctional epoxy resins in order to attain enhanced characteristics. Five variations of a blend are being considered, with varying percentages of two components 20:80, 40:60, 50:50, 60:40, and 80:20. Utilizing the Weibull distribution, a statistical analysis was conducted on experimental data obtained from NOL ring studies. This analysis resulted in the formulation of a mathematical model for predicting the failure of hybrid resin composite materials under hoop tensile loading conditions. Using tensile tests and constructing distribution curves, researchers identified the properties of failure stress within the Weibull distribution. A critical vulnerability has been identified in the 50:50 hybrid resin combination of the composite material, with predictions suggesting a high likelihood of failure.

Keywords*: Hybrid resin, Carbon fiber, NOL ring, Weibull distribution, Probability failure*.

1. Introduction

The combined overall characteristics result from the combined effects of the matrix and fiber properties along with their respective volume proportions. The fiber properties of the two components play a more significant role in determining the overall properties of the composite material. Even though resins are also important component of the composite material its role is limited to holding the reinforcements together and form a means for distributing the load.

Attempts have been made by many researchers to improve the overall property of the composite by using high strength resins. Also, few researchers explored the use of more than two resin systems i.e., hybrid resins to achieve improved properties of the composite. The present research endeavors to develop a composite resin that merges Bifunctional and Multifunctional epoxy resins, intending to enhance the mechanical properties of fiber-reinforced polymer composites. The blending of these two resins, Bifunctional and Multifunctional, is being explored in various weight proportions. Different methods like filament winding, tape winding, pultrusion, compression molding, vacuum bagging, liquid molding, and injection molding involving a matrix material can be employed to produce composite components. The characteristics of composite materials differ significantly from both their fibers and the matrix.

The primary approach worldwide for fitting and examining data, as well as forecasting material behavior, is through Weibull analysis. The Weibull distribution demonstrates its versatility through various real-world applications, such as assessing material strength. Additionally, it has been validated as an effective model when parts experience multiple failure modes, showcasing that the time until the initial failure is most accurately represented by the Weibull distribution. The Weibull method has demonstrated effectiveness in handling notably small sample sizes, sometimes as minimal as two or three failures, particularly in engineering analysis. This attribute holds significance, especially in aerospace, aiding the development of tests with limited samples. A primary merit of employing Weibull analysis lies in its capacity to furnish reasonably precise failure analysis and predictions. This allows for potential solutions at the earliest signs of an issue, circumventing the necessity for additional failures. Weibull testing concludes upon the initial failure within each set of components, whereas subjecting all components to testing for failure significantly escalates costs and time requirements. Another advantage of Weibull analysis pertains to its ability to generate straightforward and valuable graphical representations of failure data. The Weibull plot utilizes a horizontal scale to depict failure or ultimate strength, while the vertical scale denotes the cumulative percentage of failures. Employing the Weibull distribution curve, various graphs are derived from the experimental data of hoop tensile tests on NOL rings. The characteristics of this curve, aligning with the equation, allow for predictions about material failure before experimental testing occurs.

2. Weibull Analysis

The Weibull distribution is employed for representing extreme occurrences like failure durations and fracture resilience. Typically, equation (1) is used to describe the conventional probability density function (PDF) for this distribution with two parameters.

$$f(x) = \frac{\beta}{\alpha} \ x \ \left(\frac{x}{\alpha}\right)^{\beta-1} \ x \ e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \qquad (eq.1)$$

Where x ⩾ 0

Equation (1) is typically acknowledged as the two-parameter Weibull distribution when β, representing the shape or slope parameter and being greater than zero, and α, denoting the scale parameter within the distribution and also greater than zero, are both present. The importance of the slope, β, in the Weibull distribution cannot be emphasized enough since it determines how well the distribution matches or suits the provided failure data. β, the shape parameter within the Weibull distribution, functions as a signal of whether the rate of failure is increasing, remaining constant, or decreasing. A β value below 1 implies that a system or part experiences a decrease in failure rate. Conversely, a β value of 1 denotes a steady failure rate, while a β value above 1 indicates a rising rate of failures.

Integrating the probability density function (PDF) leads to obtaining the cumulative density function (CDF).

$$F_f(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \qquad (eq.2)$$

$$1 - F_f(x) = e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \qquad (eq.3)$$

$$F_s(x) = 1 - F_f(x) \qquad (eq.4)$$

$$R_x = 1 - P_x \qquad (eq.5)$$

In the above equations,

x represents a variable indicating the lifespan of the specimen.

β refers to the shape parameter or the slope of the Weibull distribution.

α represents the scale factor.

$F_f(x)$ represents the likelihood of x failing (P_x)

$F_s(x)$: Probability of survival or reliability (R_x)

The natural logarithm of both parts of equation (3)

$$ln\left(ln\left(\frac{1}{1-F_f(x)}\right)\right) = \beta\, ln(x) - \alpha\, ln(x) \qquad (eq.6)$$

Equation (6) altered to form a linear equation.

$$Y = ln\left(ln\left(\frac{1}{1-F_f(x)}\right)\right), X = ln(x), m = \beta \ and \ c = -\beta$$

$$Y = mX + C \qquad (eq.7)$$

$$\alpha = e^{-\left(\frac{c}{\beta}\right)} \qquad (eq.8)$$

As per equation (8), the characteristic lifespan represents the duration or cycle count when the population is anticipated to experience failure.

3. Experimentation

The current research involves altering the matrix by employing a hybrid resin system comprising varying weight proportions of two resins. Different ratios of the hybrid resin to hardener HT972 (80:20, 60:40, 50:50, 40:60, and 20:80) were utilized, maintaining a consistent ratio of 100 parts hybrid resin to 27 parts hardener by weight. Samples were fashioned using the filament winding technique, where carbon fiber strands were unwound and continuously passed through a resin tank. These resin-coated strands were then directed onto a rotating cylindrical mandrel, carefully wound in a specific fiber orientation and manner. Maintaining optimal fiber tension is crucial in filament winding, as the compression occurs via this tension. Ensuring the tension remains at an ideal level is essential, as excessive tension could lead to complete fiber breakage or surface fractures.

The NOL ring specimens mimic the cylindrical shape of composite overwrap pressure vessels (COPV). The samples were produced by combining carbon fiber with a hybrid resin system and utilizing the filament winding method on a specialized NOL ring mandrel, as depicted in figure 1. This particular mandrel was created with the intention of crafting NOL ring samples using a method similar to hoop winding to imitate filament winding. Figure 2 illustrates the schematic representation of this winding technique. After undergoing a specific curing cycle in an oven, the sample was machined using a lathe machine to remove surplus resin. Following ASTM 2290 standards, the NOL ring samples were subsequently detached from the winding. The specific dimensions of these samples can be found in figure 3

Fig.1 The NOL ring mandrel

Fig.2 Filament winding machine

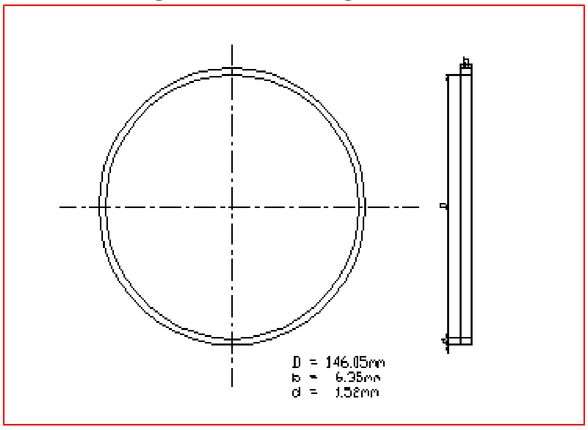

Fig.3 Dimensions of NOL ring specimen

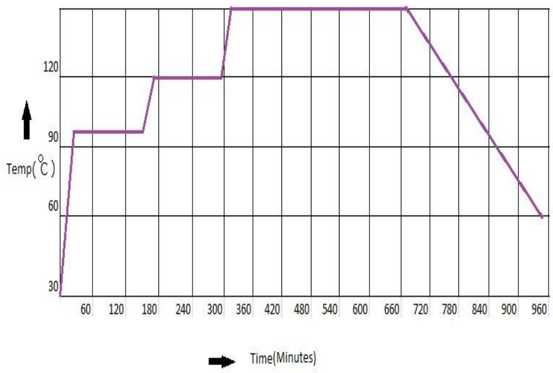

Fig.4 Cure Cycle for Carbon Fiber/hybrid resin

After finishing the filament winding process, the NOL ring mandrel containing the winding underwent curing in a precisely temperature-controlled oven. The subsequent curing procedure was implemented as follows.

- In half an hour, the oven quickly heated up from room temperature to a scorching 1000 degrees Celsius, staying at that intense heat for a solid two hours.
- Increase the temperature from 1000°C to 1200°C in 20 minutes after 2 hours, and sustain it at this degree for the following 2 hours.
- Increase the temperature from 1200°C to 1400°C in a span of 20 minutes, followed by sustaining the temperature at 1400°C for the subsequent 6 hours.
- Once the 6-hour curing process concludes, switch off the oven and allow the component to naturally reach room temperature within a period of 4 to 5 hours.
- Remove the processed mandrel from the oven by unlatching the oven door.

The specimens were subjected to NOL-ring examination at ambient temperature employing the INSTRON 4505 universal testing apparatus outfitted with a 100kN load sensor and a loading rate of 2mm per minute. A micrometer was used to measure the width and thickness of every NOL-ring sample. These specimens were then stretched until they ruptured using a test fixture conforming to ASTM D2290 specifications. The setup of the NOL-ring test fixture is depicted in Figure 5, the NOL ring in Figure 6, and the tested NOL ring specimen in Figure 7


Fig.5 NOL Ring before testing


Fig.6 NOL Ring


Fig.7 NOL Ring after testing

4. Results and Discussions

The NOL ring test replicates hoop-like circumstances and gauges the hoop stress experienced by the ring. It's important to highlight that the equation (9) can be used to calculate the tensile strength (σ).

$$\sigma = \frac{Fd}{2t} \qquad (eq.9)$$

According to the ASTM D2290 standard, Equation (9) specifies F as the maximum burst force measured in Newtons (N), where t stands for the thickness and d represents the diameter of the NOL ring specimen, both measured in millimeters (mm). Figures 9 through 13 display typical force-displacement diagrams at ambient temperature for various resin combinations, each figure showcasing a single sample. The tensile strength of the NOL rings was calculated using equation (9) for every experiment conducted. The corresponding tensile strength values for different resin experiments are depicted in figures 13 to 17. The displacement values obtained from the tensile tests of different resin ratios (50:50, 60:40, 80:20, 40:60, 20:80) range between 6.8 to 7.5 mm, 6.0 to 6.7 mm, 5.6 to 6.4 mm, 5.3 to 5.9 mm, and 5.2 to 5.8 mm.

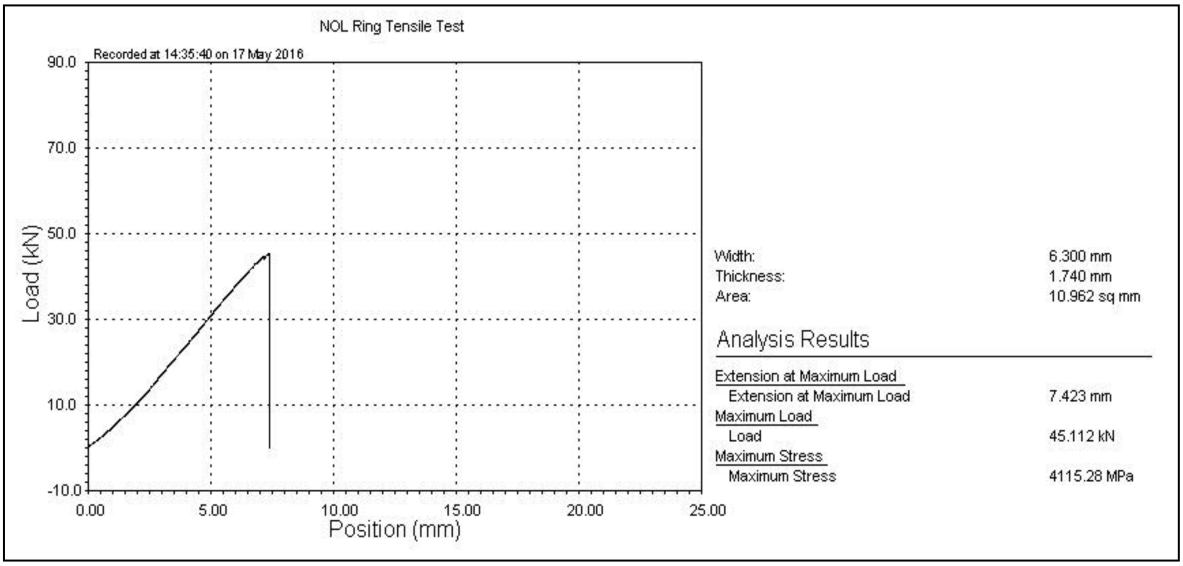

Fig.8 Hybrid resin 50:50 with Hardener

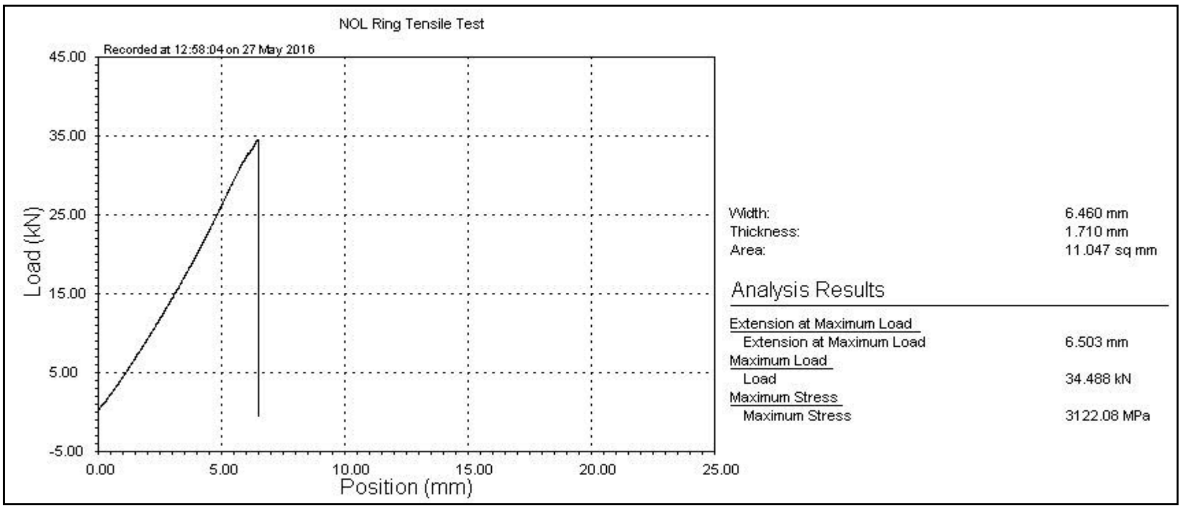

Fig.9 Hybrid resin 60:40 with Hardener

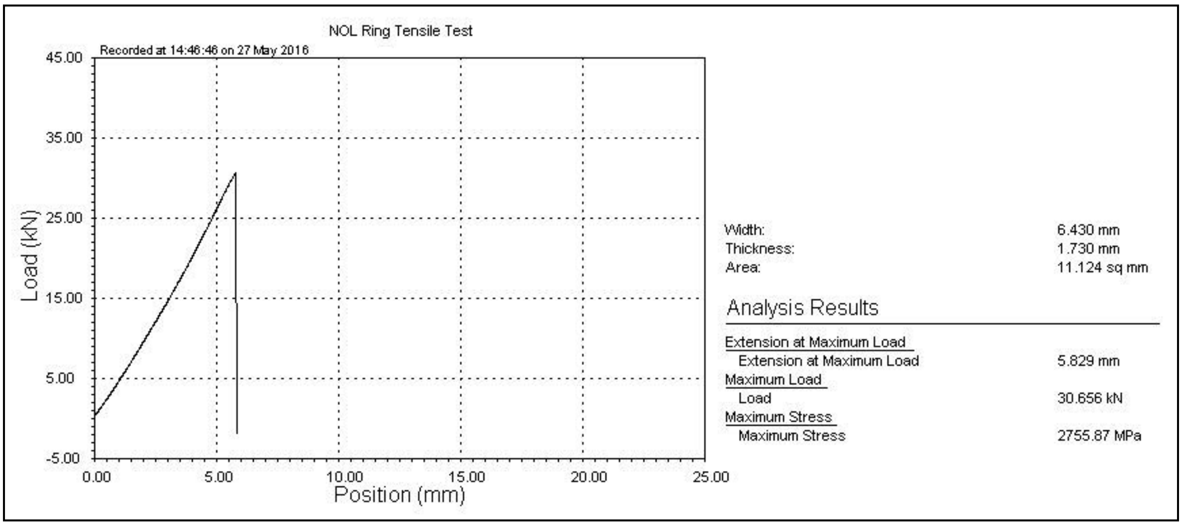

Fig.10 Hybrid resin 80:20 with Hardener

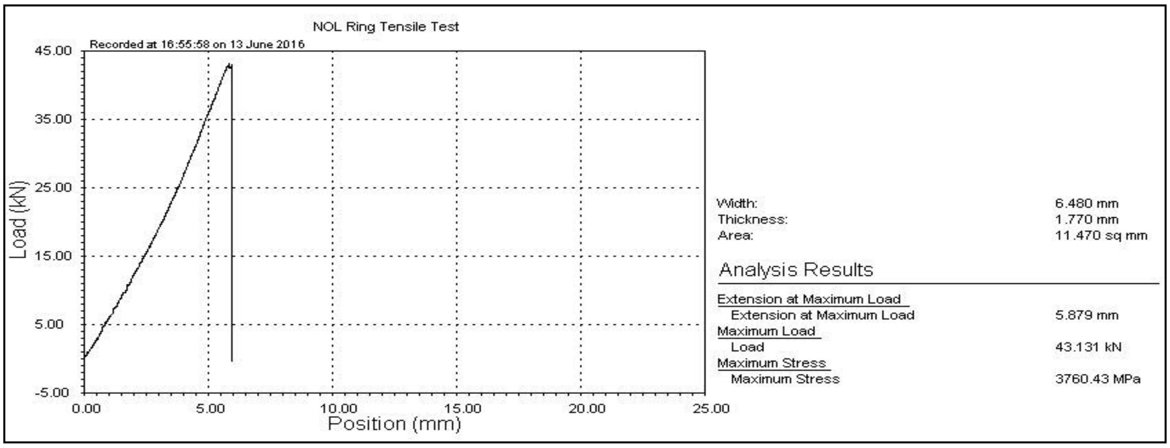

Fig.11 Hybrid resin 40:60 with Hardener

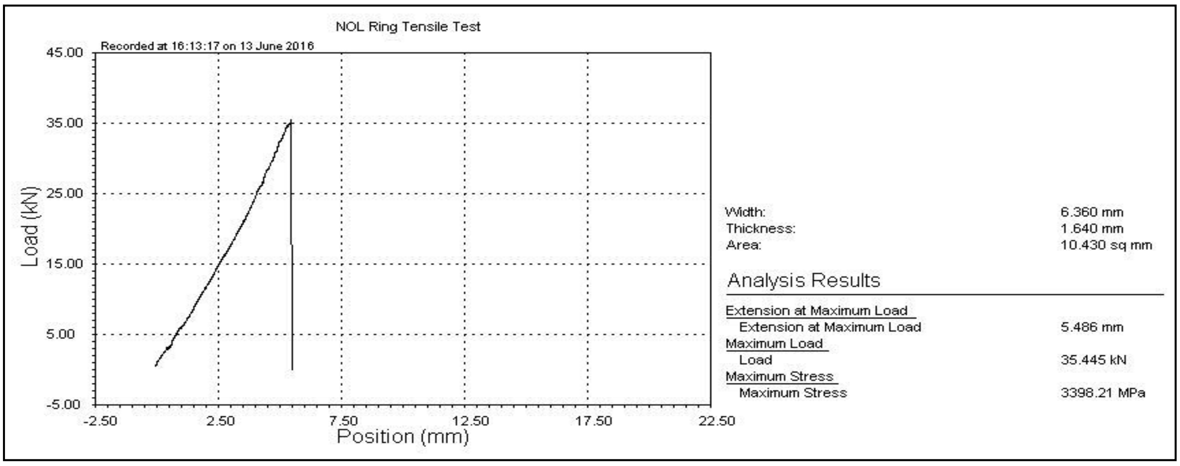

Fig.12 Hybrid resin 20:80 with Hardener

The histogram illustrates the fracture strength of five different resin combinations. Among these, the 50:50 resin combination histogram exhibits the highest occurrence frequency of failure stress between 1850 and 2000 MPa, surpassing the frequencies observed in other resin combinations depicted in figures 14 through 18. Utilizing the test data, a Weibull distribution was generated using equation (2) to calculate the probability of failure. This distribution curve was then constructed using software, with failure censored at 2200 MPa. Each hybrid resin combination underwent a total of 20 experiments. The probability plot for failure was created using the least square method, and the plots are depicted in figures 19, 20, 21, 22, and 23.

4.1 Cumulative Failure curves

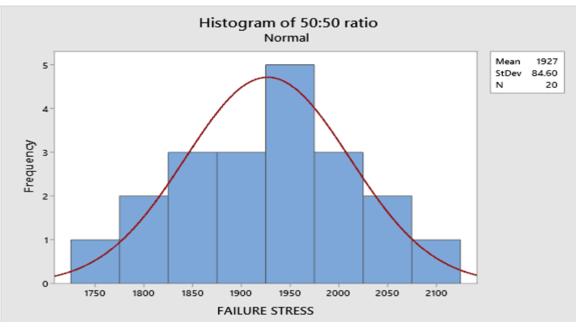

Fig.13 Histogram for fractured strength of 50:50

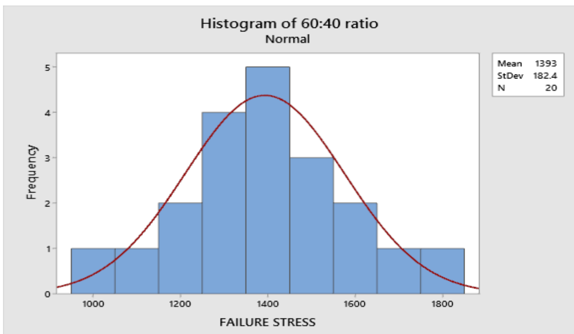

Fig.14 Histogram for fractured strength of 60:40

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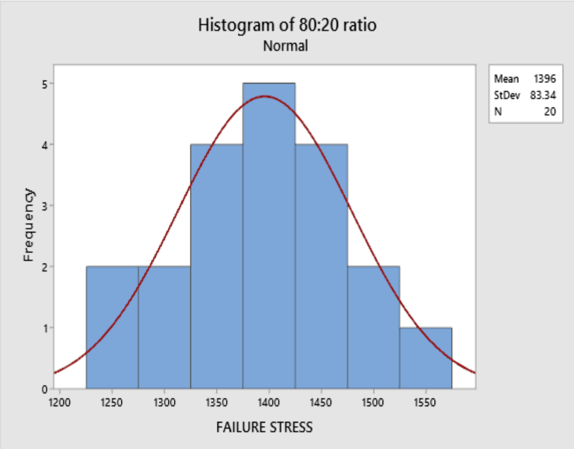

Fig.15 Histogram for fractured strength of 80:20

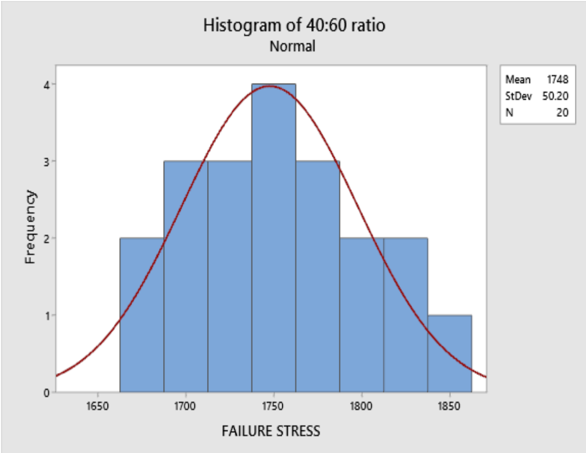

Fig.16 Histogram for fractured strength of 40:60

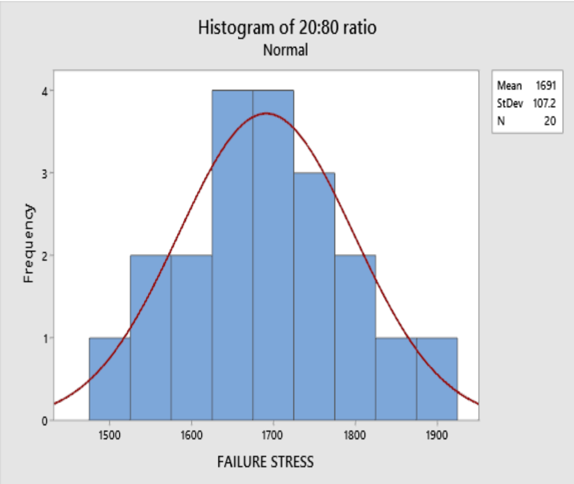

Fig.17 Histogram for fractured strength of 20:80

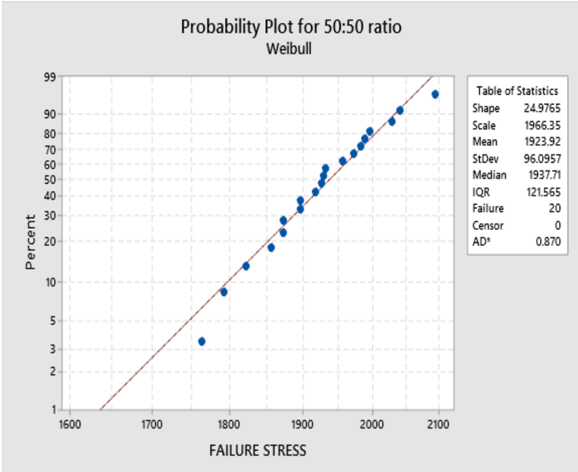

Fig.18 Weibull distribution curve of 50:50

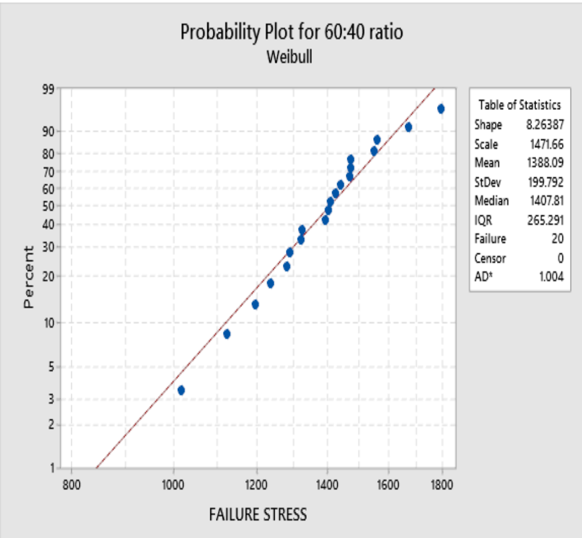

Fig.19 Weibull distribution curve of 60:40

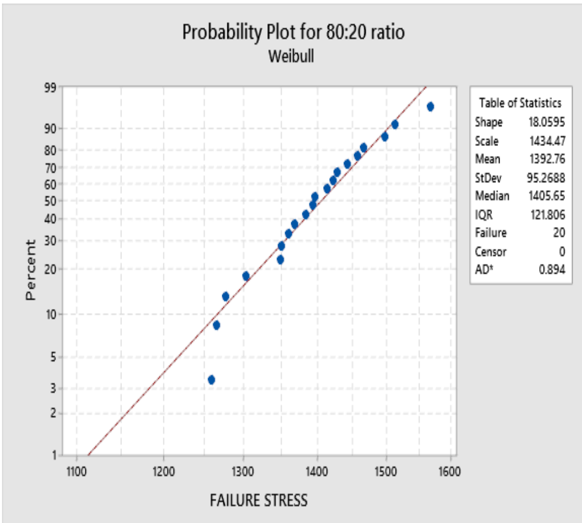

Fig.20 Weibull distribution curve of 80:20

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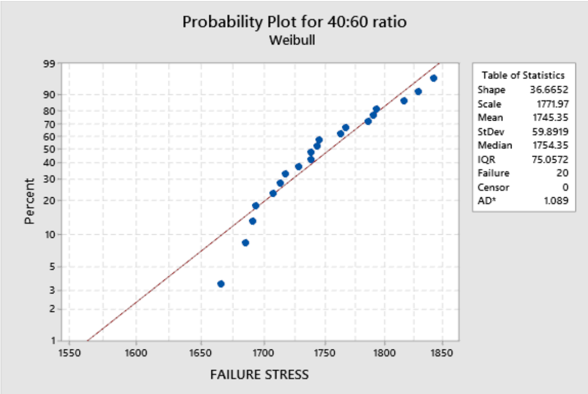

Fig.21 Weibull distribution curve of 40:60

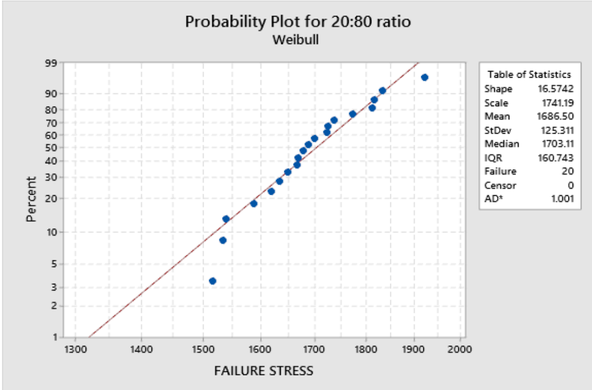

Fig.22 Weibull distribution curve of 20:80

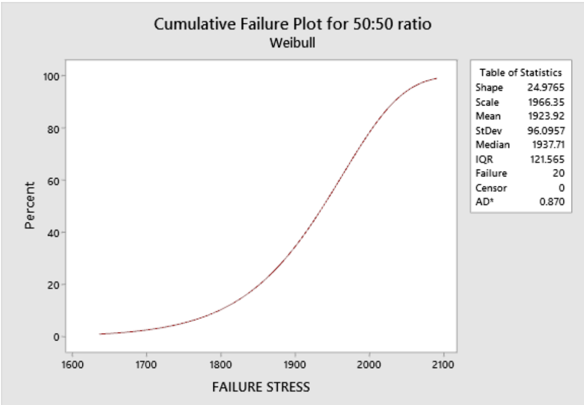

Fig.23 Cumulative Failure curve of 50:50

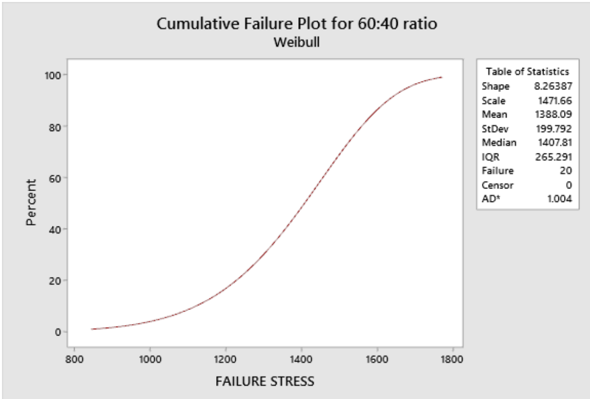

Fig.24 Cumulative Failure curve of 60:40

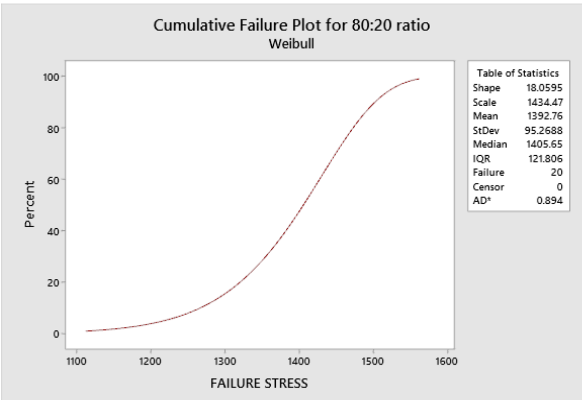

Fig.25 Cumulative Failure curve of 80:20

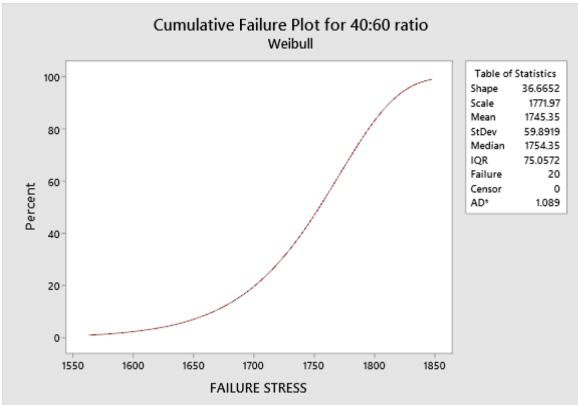

Fig.26 Cumulative Failure curve of 40:60

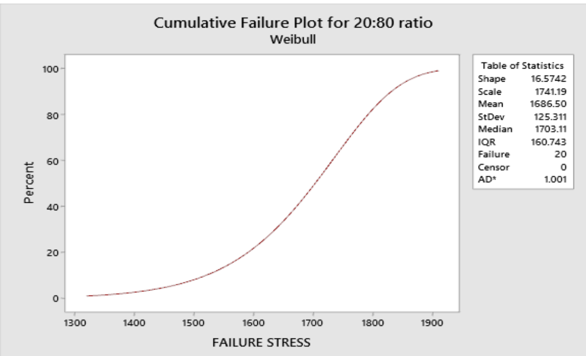

Fig.27 Cumulative Failure curve of 20:80

4.2 Probability of survival curves

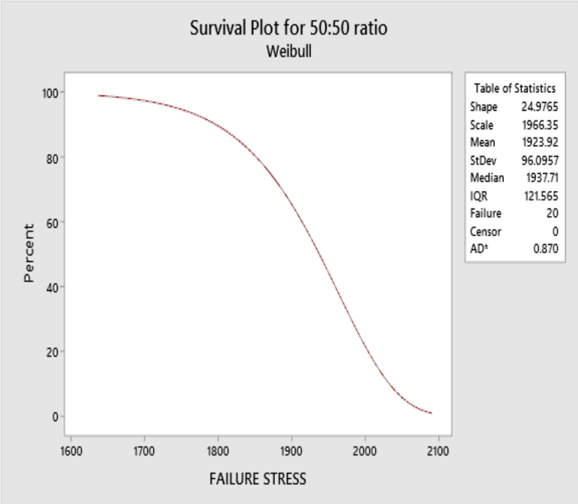

Fig.28 Probability of survival curve of 50:50

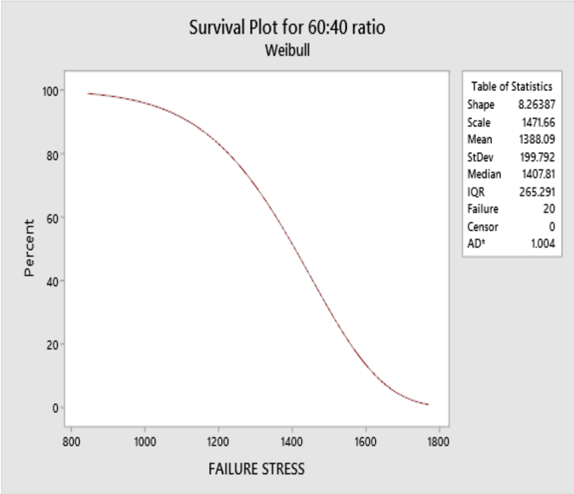

Fig.29 Probability of survival curve of 60:40

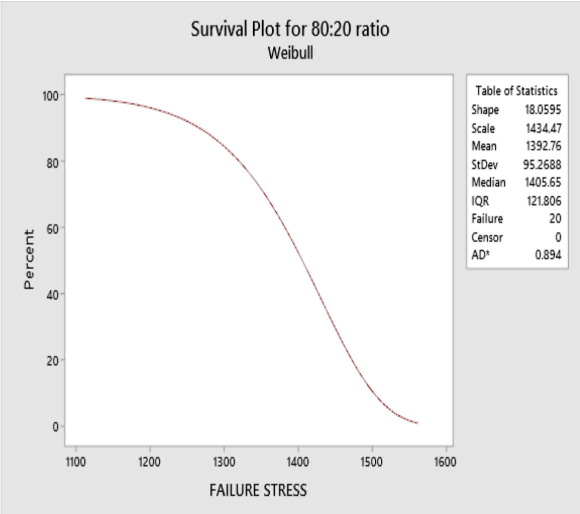

Fig.30 Probability of survival curve of 80:20

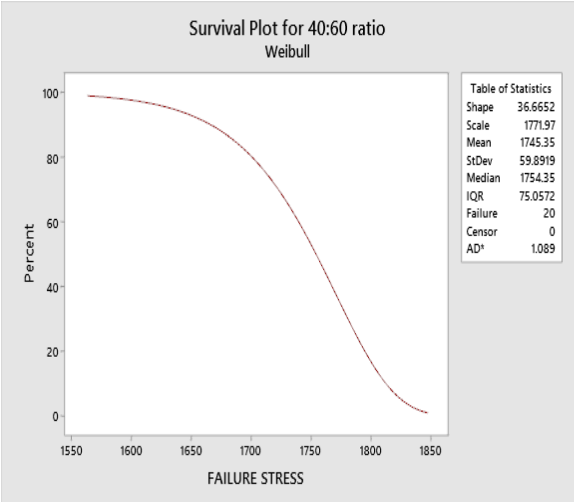

Fig.31 Probability of survival curve of 40:60

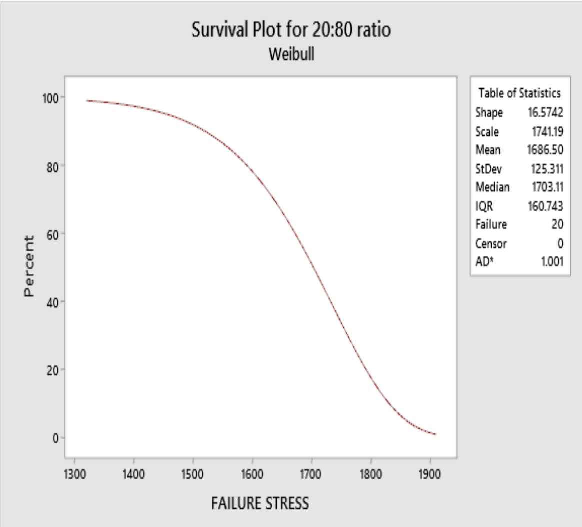

Fig.32 Probability of survival curve of 20:80

5. Conclusion

The information extracted from the experiments underwent parametric survival stress analysis to determine the survival probability (%) of various weight ratios of hybrid resin. It was discovered that a hybrid resin blend consisting of a 50:50 ratio could endure stress up to 1700MPa without deformation, exhibiting less than a 4% probability of failure compared to other resin blends. Weibull analysis can forecast failure stresses and the reliability of any material. The most frequent occurrence of failure stress lies within the range of 1900-1950MPa. Predictive data on reliability stress indicated that the composite's survival probability or reliability remains at 91.98% up to 1760MPa. However, if stresses exceed 2000MPa, the composite material's reliability diminishes to 22.74%. This observation holds significance in designing carbon fiber reinforced with a hybrid resin system for high-strength applications. Analysis of experimental test data reveals that the optimal tensile strength is achieved with a 50:50 hybrid resin composition due to its lower resin thickness and higher density, facilitating superior compaction of the composite laminate

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