Improvements in determination of carbon fibre strength distribution using automation and statistical data analysis

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1. INTRODUCTION

Carbon fibres are widely used in composite materials to make light-weight and high-strength products. For failure modelling and to simulate the effective properties of the products, detailed information about tensile strength distribution and its parameters are required. Many studies have acknowledged difficulties in obtaining fibre strength data which can accurately represent the entire fibre population in a given application. These mainly include premature specimen failure during handling, improper alignment between the fibre and the loading direction, time and labour requirement, etc. An automated single fibre testing process (referred to as the LDS/LEX) has been developed at Dia-Stron Ltd. and described here, which could assist in overcoming most problems. It increases the efficiency of the process and enhances quality of the data generated. The errors occurring due to manual handling of fibres are eliminated and human effort is reduced notably.

2. CHARACTERIZING CARBON FIBRES

It is known that strength of fibre composites is primarily dependent on fibre properties. So, fibre strength is a very critical input parameter for computer modelling of composite materials for different applications such as composite Pressure vessels and automotive components. Failure in fibre composites usually originate inside fibres and using tow data may not be very useful. Also, for recycled carbon fibres, SFT is the best method for quantitative analysis and quality control.

2.1. Issues in testing carbon fibres

Carbon Fibres are usually tested manually which is associated with many issues, which if unaddressed, can be the reason behind huge variations in reported results.

Some of these issues include:

1. Fibre cross-section may vary between individual fibres and also along the length, hence accurate measurement of fibre diameter is critical for accurate determination of fibre strength.
2. The gauge length used for testing would affect the measured strengths, but there has been no general agreement on an optimum gauge length in the results that have been reported.
3. The confidence on the reported results would depend on the number of fibres that are tested. Since manual single fibre testing is a very time-consuming process, most authors have reported results only for a small number of fibres.
4. It is difficult to avoid fibre misalignment in manual single fibre testing, which may lead to inaccurate results.

2.2. Manual method for Single Fibre Testing

Manual SFT required separate instruments for measuring fibre diameter and applying tensile load. Card frames are used for mounting the fibres as shown in Figure 1(a). Sample preparation starts by extracting a single fibre from a bundle in placing it on the paper tab. The ends of the fibre are then fixed using epoxy or wax. This is followed by diameter measurement after which the specimen is transferred to the universal testing machine. The sides of the paper tab are then cut and the tensile load is applied. Cutting the paper often leads to fibre failure before the test commences.

One of the major problems with this process is avoiding fibre misalignment and ensuring an accurate gauge length as shown in Figure 1(b). It depends very strongly on the position of the epoxy which is very difficult to control manually, especially when the gauge length becomes very small. In addition to being very time consuming, a significant number of specimens break during the preparation process.

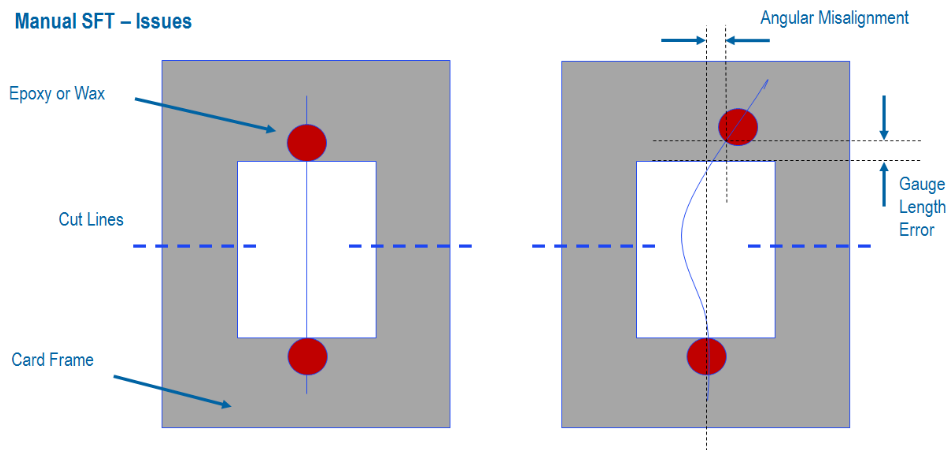

Figure 1: (a) Scheme of a single fibre mounted on Card frames (b) Major issues with sample preparation

2.3. Automated single fibre testing

To overcome the problems faced by the conventional method, Dia-Stron has developed an automated testing method which includes a dedicated sample preparation technique. Card frames are replaced by plastic tabs (Fig 2a). Each end of a fibre is held by a plastic tab. The tabs are arranged on a cassette in sets of 20 (Fig 2b). Each tab has v-shaped slots which help in proper alignment of fibres. UV Curing adhesives are dropped inside the wells at the end of the tab which locks the fibre in place, and defines the fibre bonding point very accurately (Fig 2c). UV curing of adhesive is done by flood illumination which takes between 3-10 secs (Fig 2d).

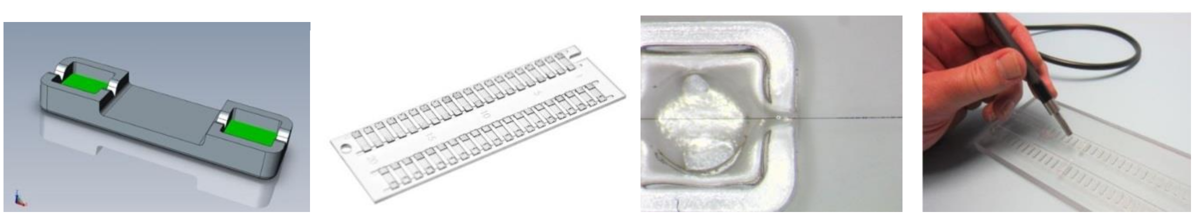

Figure 2: (a) Plastic tab for holding a fibre (b) 20 sample cassette (c) Wells in tabs for accurate gauge lengths (d) UV curing of adhesives

Dia-Stron automated testing setup is a combination of a tensile tester and a laser diffraction system for measurement, together known as the LEX/LDS system (Figure 3a). The automated pick-up system transfers the specimens from the cassette to the test location, where the fibre is straightened, diameter is measured and the tensile load is applied. After test completion, the system automatically transfers the plastic tabs back to the cassette and proceeds to the next test. The advantages of this system include reduction in testing time due to automation, improved alignment due to the presence of grooves in tabs, gauge length correction due to straightening of fibres before testing, reduced specimen failure due to elimination of operator handling, among others. The system allows the testing of fibres at several different gauge lengths.

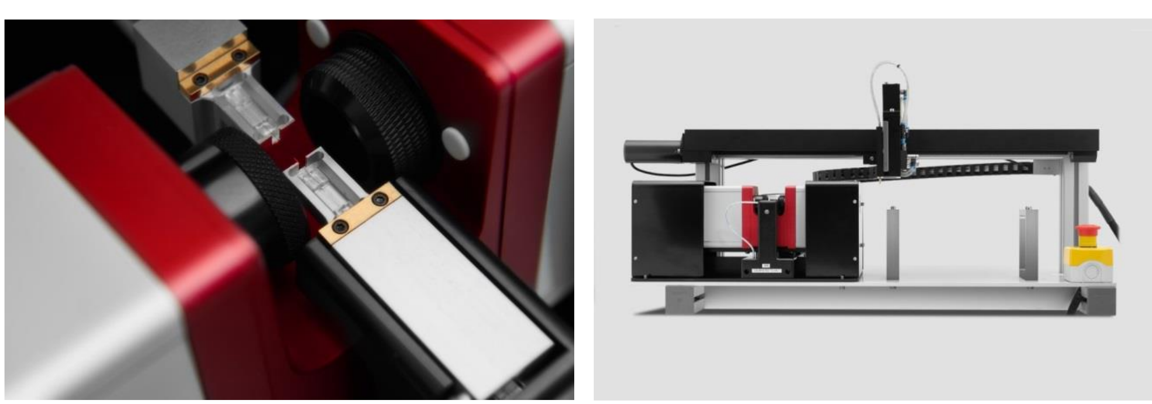

Figure 3: (a) Combined Linear Extensometer and Laser Diffraction system (b) Complete automated testing setup

3. STATISTICAL ANALYSIS

According to the weakest link theory each fibre is a chain composed of multiple small links connected to each other. Strength of the weakest link determines the strength of the fibre. The statistical function that best describes the weakest link theory is the Weibull distribution (Eq. 1). It is characterized by the scale (σ_0) and shape (m) parameters. One of the advantages of using the Weibull distribution is that it gives us a very useful 2D representation of the observation. The experimental data generated for carbon fibre strength was used to fit to a Weibull distribution (Fig 4a). The dots represent the experimental data and the straight line represents the best fit Weibull model. The vertical axis represents unreliability (or failure probability), which is the percentage of population that is expected to fail and the horizontal axis represents the corresponding strength. B50 life, or the median failure strength can be read directly from the graph and is 4.01GPa. This means that 50% of the fibre population is expected to have strength of less than 4.01GPa.

$$P(\sigma_f) = 1\text{- } exp\left\{-\left(\frac{L}{L_0}\right)\left(\frac{\sigma_f}{\sigma_0}\right)^m\right\} \quad (1)$$

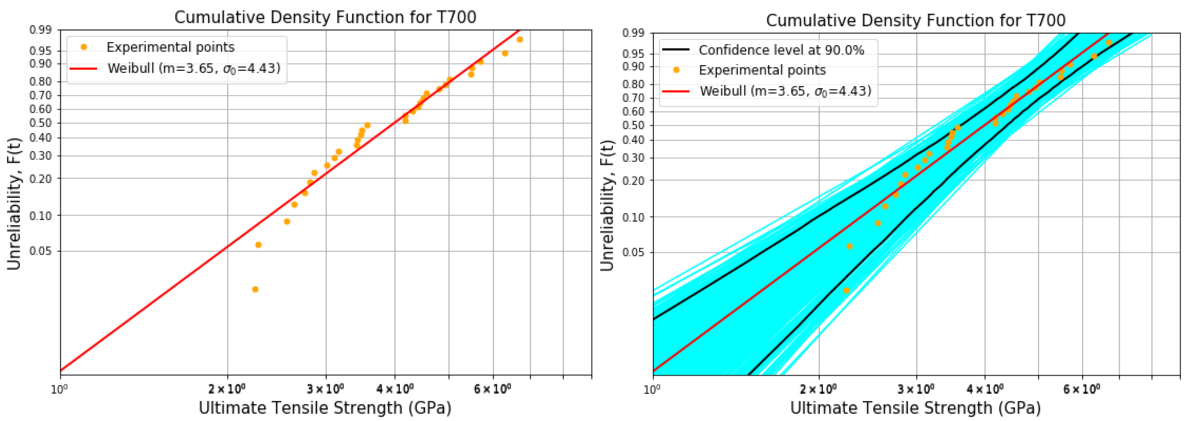

Figure 4: (a) Best fit Weibull plot for experimentally generated carbon fibre strength (b) Simulated Weibull distributions and Confidence Region

To get an indication of the confidence that can be associated with the results, a confidence interval has been calculated. Monte Carlo simulations of the Weibull distributions were generated, as shown in blue in Fig. 4(b). Using these distributions, the confidence region was obtained which is the area between the 2 black curves. Using this, the Confidence interval can be calculated. The B50 life (or the median strength) can be seen to fall between 3.65-4.37GPa. It would be more appropriate and useful to report this Confidence Interval along with every point prediction.

However, this Confidence Interval is very large and needs to be narrowed down for more accuracy in reported results. More experimental data points are required for that purpose. Thanks to the automated test setup, it was possible to generate a large number of fibre strength data and for different gauge lengths, as shown in Table I. The experimental data set was fitted with the two-parameter Weibull distribution using the method of truncation. This was required because the experimental data set does not contain the strength of weak fibres, as they were too weak to survive the testing process. So, to represent this data set, we used the method of truncation to predict the actual Weibull distribution. Monte Carlo simulations were made and the Confidence Interval was calculated. The width of the 90% Confidence Intervals reduce to less than half the original size. For example, the new Confidence Interval for the B50 life (or the median strength) is calculated to lie between [4.01-4.31] GPa. This increased accuracy has been possible because of the very large number of data points that were generated using the automated testing system.

Gauge Length (mm)	No. of fibres tested
04	140
20	140
30	200

Table I: No. of fibres tested for different gauge lengths.

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