A FUNDAMENTAL NUMERICAL STUDY OF WEIBULL MODULUS ESTIMATION USING SINGLE HYBRID COMPOSITE TEST

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Keywords: Weibull Modulus, Fibre Failure, Fragmentation, UD Hybrid Composites

ABSTRACT

In this paper, the effects of Weibull Modulus on the response of hybrid composites are studied numerically to find a method to back calculate the Weibull Modulus of the numerical model. This is to find a new method to estimate the Weibull Modulus of single carbon fibre reinforced composites more easily. Instead of using several samples at different sizes, one sample with multiple fracture is used. Using thin-plies, it is possible to achieve multiple fracture of carbon layer, embedded in between glass layers in a glass/carbon hybrid. This typically leads to a tri-linear pseudo-ductile stress-strain curve whereas the middle part of the stress-strain curve has a small positive slope. Different Weibull Moduli are used to build different models. The numerical results show that higher values of Weibull Modulus results in lower slope values. Different Weibull random distributions are used, and it is observed that independent of the details of the distribution, the stress-strain curves are similar showing that it is possible to back calculate the Weibull Modulus from the slope of the second-part of the stress-strain curve.

1 INTRODUCTION

It is well accepted that the failure of brittle materials including carbon or glass fibre composites are controlled by the defect size and also that larger samples have higher chances of having larger defects. This means that bigger samples have lower strength values, and that the strength of a material is not only a material property but also dependant on the size of the tested sample.

In 1951, Wallodi Weibull proposed a statistical distribution function that could predict the probability of survival of chains using weakest link theory which is now widely used for composite material.
Weibull's statistical distribution allowed to find the strength of a sample with known size V_2 using two sets of parameters: (1) Reference size strength $\bar{\sigma}_1$ called *scale factor* known at a reference volume V_1 and (2) the power m called *shape factor* or *Weibull modulus* using equation (1) [1].

$$\bar{\sigma}_1{}^m V_1 = \bar{\sigma}_2{}^m V_2 \qquad (1)$$

The effect of size of a specimen or component on its strength (size effect phenomenon) hasn't been seriously applied in design codes and one of the main reasons for that is the difficulty of estimating the shape factor or Weibull modulus m. The previously proposed method to calculate Weibull modulus of composite laminates includes testing several scaled samples to measure the failure stress of the material at different volumes [2]. Given the natural scatter in composites experiments, to be able to see a meaningful effect on the material strength at different size, the ratio of different volumes of tested materials, i.e. V_1 and V_2 should typically be large e.g. at least two or three orders of magnitude different. This is a typically challenging task. Most laboratories are only equipped to test coupon samples close to standard tensile size and testing samples significantly smaller or bigger requires specialised facilities.

In this paper, a new characterisation method, based on application of hybrid composite configurations is proposed. Interlaminar hybrid composites, made from sandwiching low strain and high strain composite laminates have four failure processes: (i) premature high strain material failure after the first crack in the low strain material, (ii) Catastrophic delamination of the high strain material after the first crack in the low strain material, (iii) gradual failure of the low strain material and (iv) the gradual failure of the low strain material followed by diffused delamination at the interface between the two laminates. In a glass fibre /carbon fibre hybrid composite, typically the carbon fibre layers have lower failure strain and act as the low strain material and the glass layer is the high strain material.

An analytical method has been developed to predict the failure process of hybrid composites [3] and such damage modes were grouped on a chart with absolute and relative thickness of the low strain material on the horizontal and vertical axes to achieve Damage Mode Maps [4]. Figure 1 shows an example of a damage mode map for E-glass/TR30 carbon hybrid laminates.

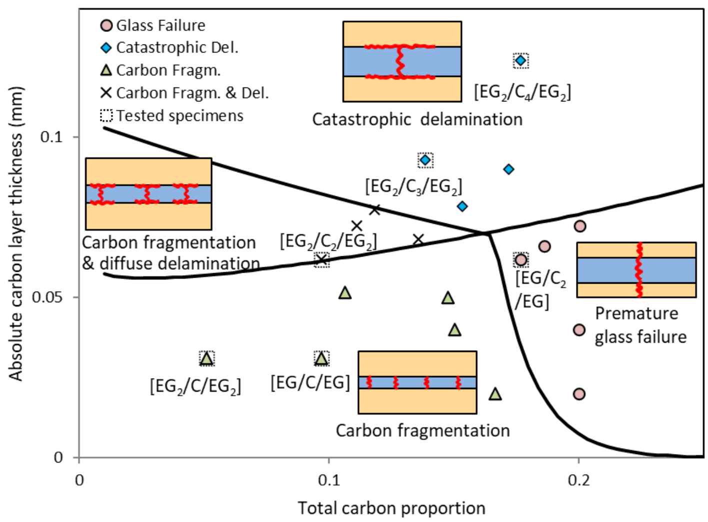

Figure 1: The damage mode map of E-glass/TR30 carbon with the results of tested and FE (numerically) modelled laminates adapted from [4]

Recently, the idea of using hybrid laminates with multiple fragmentations to find the Weibull Modulus has been proposed [5]. Basically, instead of testing several specimens with different sizes, the change of the volume of the fragmenting material is used to predict the change of the material's strength at different volumes. However, the method to detect the failure points were based on carefully checking the recorded videos and matching that with the low strain material failure points on the stress-strain curves. This is a time-consuming step and if could be avoided, can significantly reduce the difficulty of finding the Weibull Modulus using one hybrid configuration sample.

In this paper, a fundamental numerical study of the feasibility of back calculating the Weibull Modulus implemented into a Finite Element model is carried out. The fragmentation process of similar hybrid configurations with different input Weibull Moduli are modelled and only the obtained stress-strain curves with gradual failure are used to back calculate the Weibull Modulus used as an input to the model. The obtained results show that applying different Weibull Moduli to the low strain material leads to changes of the plateau stage of the stress-strain curves. Different methods of estimating the remaining stressed volume of the low strain material are explored and a new analytical method for predicting the Weibull Modulus of the materials based on only the stress-strain curves are presented.

2 NUMERICAL MODELLING

Different 2-D Finite Element (FE) models of $[0_G/0_C]_s$ laminate where G and C indicate Glass and Carbon layers respectively were implemented in the Abaqus FE package. To model fragmentation of the carbon layer, repeated cohesive element rows were included in between the carbon layer elements (inside the carbon layer). Interfacial delamination is captured by using cohesive elements at the interface between the glass and carbon layers. Python scripting was used to generate the cohesive elements arrangement as schematically shown Figure 2. The models include 1000 potential fragmentation lines in the carbon layers. Each row or line of cohesive elements in the carbon layer have the same tensile strength value (σ). Weibull random distribution, equation (1), was used to generate a random distribution of strength values for the cohesive element rows in the carbon layer. In this equation, σ^0 is the reference strength value for the reference volume of the material, m is the Weibull modulus and η is a random variable between 0 and 1.

$$\sigma = \sigma^0 \left[ln\left(\frac{1}{1-\eta}\right)\right]^{\frac{1}{m}} \tag{1}$$

Plane stress elements CPS4R used for carbon and glass layers and cohesive elements COH2D4 used for modelling interfacial damage and delamination as well as the fragmentation in the carbon layer fragmentations. The method used for modelling is similar to the method used in [6].

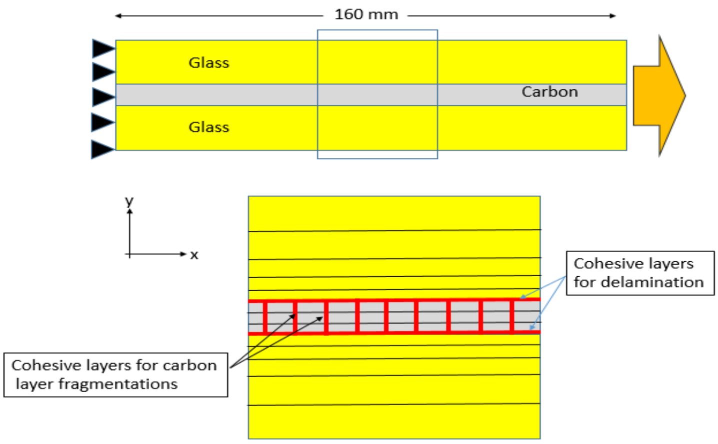

Fig. 2. Schematic of the FE models and the applied cohesive elements to capture the carbon layer fragmentation as well as delamination between the glass and carbon layers

The pseudo-ductile unidirectional thin-ply carbon/epoxy–glass/epoxy hybrid composite with [SG/TR302/SG] configuration was used for numerical simulation. This configuration shows multiple carbon layer fragmentations and approximately smooth and long plateau region [7]. The plateau slope in this configuration rises slightly, this mechanical behaviour is evidence of increasing failure strength of carbon layer fragmentations by decreasing the effective length of the carbon layer. Two approximately deterministic knee points correspond to the first fragmentation and the fragmentation saturation point are another important feature of this configuration used for the analytical method.

3 FINITE ELEMENT RESULTS

Obtained numerical results e.g. in Figure 3 show the direct relationship between the input Weibull moduli and the output plateau slope of the stress-strain curves. Lower Weibull modulus e.g. m=20 means higher variation and therefore larger plateau slope whereas higher Weibull moduli e.g. m=40 means lower plateau slope. The best-matched Weibull modulus to the experimental results were found to be around m=40.

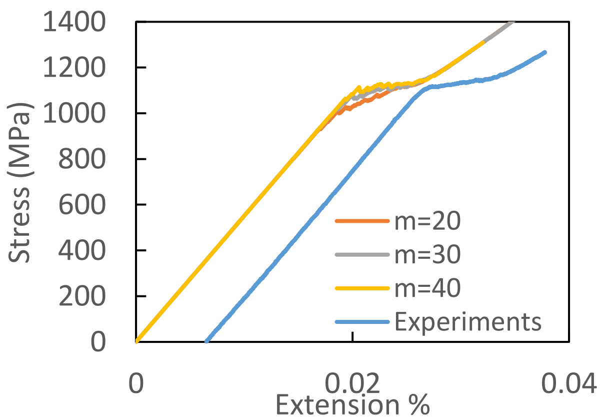

Fig. 2. Stress-extension of the models and tests

4 WEIBULL MODULUS BACK CALCULATION

The numerically (FE) obtained stress-strain curves with known input Weibull moduli were used to back calculate the input Weibull modulus. Every fragmentation in the carbon layer causes a reduction in the volume of the loaded low strain material. The strain in the low strain material (carbon layer), σ_L, can be estimated using the equation below.

$$\sigma_L = \sigma_{@LF} \frac{E_L(t_L + t_H)}{E_H t_H + E_L t_L} \qquad (1) \qquad (1)$$

Whereas $\sigma_{@LF}$ is the stress at the laminate level or the total force divided by the total cross sectional area of the laminate at the plateau stage of the stress-strain curve. t and E are thickness and Young's modulus of the Low and High strain materials. Details of how this equation is derived can be found in [3].

The equivalent reduced Low Strain material sample volume can be found by the proposed analytical method. Table 1 shows a typical failure strain and remaining volume of the carbon layer calculated for one of the FE models with m=40.

The obtained results provide a clear proof that the proposed analytical method has estimated the Weibull modulus of the material accurately. This can significantly reduce the complications and costs of characterizing the size effect properties of composites i.e. estimating their Weibull modulus.

Stress-strain curve point	Strain in carbon (%)	Remaining material volume (mm^3)
Initiation	2.03	185
Saturation	2.14	21

Table 1. Typical strain and volume calculated from plateau of the stress-strain curve

9 CONCLUSIONS

A new method for finding the Weibull modulus of composite layers based on single hybrid configuration tests is proposed. Sandwiching the test material between higher strain material can lead to multiple fracture of the test material with the lower failure strain. This means that the at each new fracture, a new fracture stress and volume of loaded material changes. A new analytical method for estimating the stress and volume of the test material is proposed.

Different FE analyses of different hybrid configurations with different Weibull moduli has shown that indeed the Weibull modulus has a significant impact on the plateau stage of a pseudo-ductile hybrid stress-strain curve. A new analytical method to back calculate the Weibull modulus assumed for the FE models is proposed and the obtained results matched well the Weibull modulus values.

This method can significantly reduce the complexity, number of tested samples and sample sizes for finding the Weibull modulus of composite layers. The main limitation of this method is the ply-thickness. To achieve multiple-fragmentation, relatively thin plies or high interfacial fracture toughness are required. For composites with standard epoxy resin, this ply thickness is typically around 50-80 microns. If other techniques for enhancing the interfacial fracture toughness are used, it is possible to use this method for finding the Weibull modulus of standard ply thickness of about 125 microns.

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