SIZE EFFECTS ON THE TENSILE AND FLEXURAL STRENGTH OF GFRP LAMINATES

Z.F. Liu*[1], G. Du[1], J.Y. Xiao[1], S.X. Bai[1], W.J. Zhang[1]
College of Aerospace and Material Engineering, National University of Defense Technology, Changsha, China
* Corresponding author (liuzhuofeng@hotmail.com)

Abstract: Size effects on the strength of Glass Fibre Reinforced Polymer laminates manufactured by Vacuum infusion molding process were investigated by means of scaled tensile and three-point flexural tests. It shows that the modulus properties of the laminate are not sensitive to the specimen size, while the strength is decreasing with the increasing of the specimen size. The size effects on the tensile and flexural strength experimental results could all be satisfactorily fitted with a Weibull strength model.

Keywords: GFRP composites; strength; size effects

1 General Introduction

Much testing of fibre reinforced polymer (FRP) composite components has to be carried out on small size models in order to save both time and expense. Similarly, much of the design of composite components is based on material properties derived from small laboratory scale specimens. But the results of the experiments show that: the controlled set of loading, the specimen size and the material conditions could affect the value of the material property measured. And the relationship between the specimen size and the measured strength value has become an important issue in composites design over recent years. It shows that the strength often decreases with specimen size increasing under the same test conditions, which is said to exhibit size effects [1-5]. Several researches have been performed about the size effects of the FRP composites [4-10], and the composites laminates were usually manufactured by using the prepreg system.

For the past few years, the development and production of the typical Glass Fibre Reinforced Polymer (GFRP) engineering composite components –wind turbine blades were booming in China, which caused the engineering GFRP components to be much larger and thicker. These components are usually manufactured by Vaccum Infusion Molding Process (VIMP). A substantial amount of full size component and structural testing is currently required to qualify a new type of wind turbine blade, which is a very expensive exercise. However, the structure engineers would waive much testing if the size effects of the mechanical strength of the GFRP laminates manufactured by VIMP are well understood. This would result in lower costs, more reliable GFRP composite structures across the blade industry.

In this paper, the size effects on the tensile and flexural strength of the GFRP laminates manufactured by VIMP were investigated by experiments. The results in tension and bending were compared, and the ability of Weibull statistical strength theory to fit the data was assessed.

2 Experiments

2.1 Materials

There are two kinds of GFRP laminates used in experiments, the $[0]_n$ unidirectional glass fibre fabric (EKU1150/50 E, Chongqing polycomp international CORP) reinforced epoxy resin (Huntsman 1564/3486, Huntsman CORP) laminates, and the $[0/45/-45]_n$ 3 axial glass fabric (EKT1200 E, Chongqing polycomp international CORP) reinforced the same epoxy resin (Huntsman 1564/3486) laminates. All laminates for testing were manufactured by the vacuum infusion molding process (VIMP).

The standard cure cycle (80℃, 4h) recommended by Huntsman CORP was used for the thinner laminates, less than 4 mm thick. A previous investigation about the curing stage of the thick laminates by the authors

[11] showed that the thicker laminates had to dwell in the low temperature stage for a period of time to allow even heat distribution throughout the thickness direction of the laminates, and diminish the possibility of an exothermic reaction (heat energy that caused uncontrollable temperature rise within thick laminates). The curing stage of the laminates which was thicker than 4mm was decided by experimental results and given in the previously published paper [11]. The volume fraction was measured by resin burn-off, giving a value of about 57%. The laminates tensile and flexural test specimens were prepared by automatic machining.

2.2 Tensile Tests

All of the tensile specimens have the same area geometry dimension. Changing the numbers of reinforced fabric layers ***n*** to acquire a series of specimens with different thicknesses. 8 kinds of tensile specimens were manufactured and tested, $[0]_n$ and $[0/45/-45]_n$, for ***n***= 2, 4, 6, 12.

For the unidirectional laminates tensile experiment, specimens usually fail in the grip area however carefully they are tabbed and gripped. This is because there are stress concentrations in the grip area due to the load introduction and gripping. To overcome this problem, specimens must have a tapered cross-section. By machining the constant section laminates, it is difficult to achieve the tapered cross-section. In the present study, specimens were tapered through the thickness by introducing extra plies at the ends during the VIMP process of the laminates manufacturing. As shown in fig.1, the interleaved plies between the continuous plies were prepared in the grip area. The interleaved plies were producing a gradual taper in the ply thickness. The grip area was also tabbed with adhesive and aluminium panel. This method has previously been found to eliminate failure in the tapered section and significantly to increase tensile strength. [12]

All of the tensile specimens were loaded to rupture, and the displacement rate is 2 mm/min. Values of load and strain were logged on a computer data acquisition system.

2.3 Flexural Tests

Three-point bending tests were carried out on 8 kinds of laminates, $[0]_n$ and $[0/45/-45]_n$, for ***n***= 4, 6, 12, 18. The geometry size of the flexural test specimens depends on the thickness ***h*** of the laminate. The length of the specimens is 20***h***, the span is 16***h***, the width is 15mm (***h***<10mm) and 30mm (***h***⩾10mm). Flexural tests were carried out under displacement control to rupture, and the displacement rate of the crosshead is 2 mm/min.

3 Results and Discussion

3.1 Tensile Properties

For the tensile specimens the response was initially linear. Towards the end of the test, the load started to increase less rapidly, eventually reaching a peak and then dropping before catastrophic failure. The strain was increasing throughout the test. Figure 2 shows the typical load-strain response of the 2 kinds of laminates.

Tab. 1 shows the experimental results for the tensile strength and the tensile modulus of the laminate specimens with different thickness. It can be seen that the tensile modulus properties of the composite laminate behave in the same way, in fact, the tensile modulus is not sensitive to defects. The tensile strength, however, is decreasing with increasing volume of the laminate specimen tested.

The reason is that failure tends to initiate from defects or other weak points in the material. The strength of a uniformly stressed volume of composite laminate is determined by the weakest part and so depends on the size of the largest flaw. Defects tend to be randomly distributed, and larger volumes have a higher probability containing a larger defect, giving rise to a size effect. It’s the famous statistical strength theory or statistical weakest link theory.

3.2 Flexural Properties

Tab. 2 shows the experimental results for the flexural strength and the flexural modulus of the laminate specimens with different thickness. It also can be seen that the flexural modulus properties vary very slightly with the size of the specimen, while the flexural strength is decreasing with the size increasing.

3.3 Fit with Weibull Theory

Weibull proposed a statistical distribution model that is widely used in weakest link theory to predict the size effects of brittle materials. In this section the model is applied to treat the experimental results to

see how well it is able to fit the data. According to the simplest two-parameter Weibull model, the probability of survival, ***P(s)***, for a volume ***V*** subject to a stress σ is:

$$P(s) = \exp\left[-\int\left(\frac{\sigma}{\sigma_0}\right)^m dV\right] \qquad (1)$$

where σ_0 is the characteristic strength and m is the Weibull modulus [3] [4]. By assuming equal probabilities of survival, strengths σ_1 and σ_2 for specimens of different volumes V_1, and V_2, can be expressed from eqn (1) :

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_1}{V_2}\right)^{-\frac{1}{m}} \qquad (2)$$

A log-log plot of failure strength versus volume should therefore give a straight line [2]. Fig.3 shows the results for the tensile strength, and Fig.4 shows flexural strength tests plotted on a log-log scale. The Weibull moduli given by the slopes of the graphs were shown in Tab.3.

Fig.3 and Fig.4 demonstrated a reasonable fit with simple Weibull strength theory. Comparison of the Weibull moduli shows that the flexural strength of the specimens decreases rapidly than the tensile strength with the increasing of the volume. The Weibull moduli obtained from the experimental data could be useful for a design of large size engineering components of the same laminates materials.

4 Conclusions

The tensile and flexural properties of the $[0]_n$ and $[0/45/-45]_n$ GFRP laminates specimens were investigated by experiments. There are significant size effects observed in the tests, with strength decreasing with specimen size increasing. The experimental data fitted the Weibull strength model well. The Weibull moduli given by the summarization of the experimental data may be used for a design and reliability evaluation of the full scale composite structures. The strength size effects should be taken into account in engineering practices.

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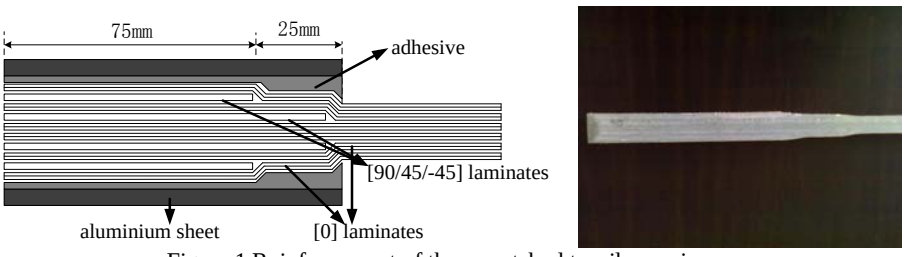
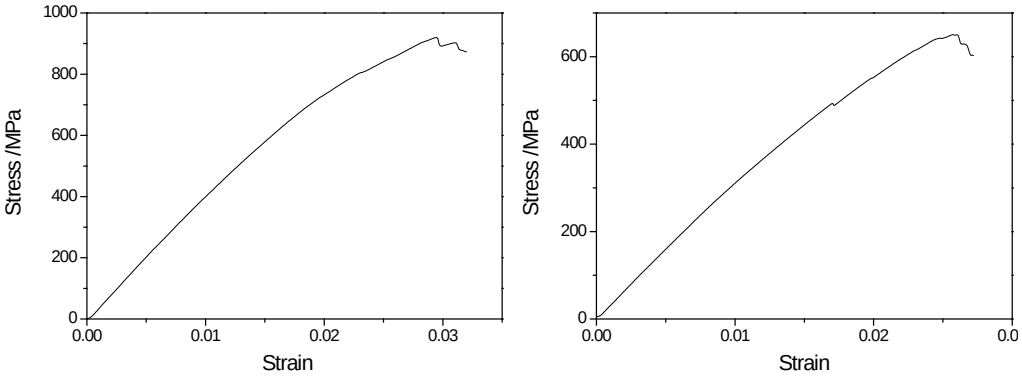
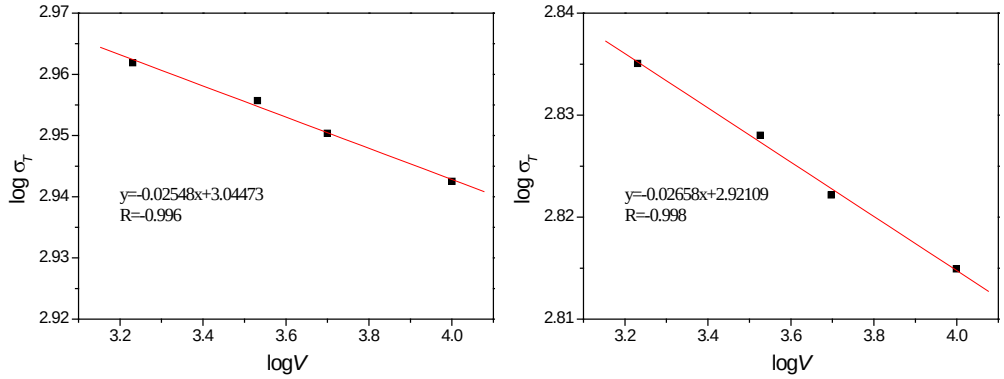


Figure.1 Reinforcement of the unnotched tensile specimen



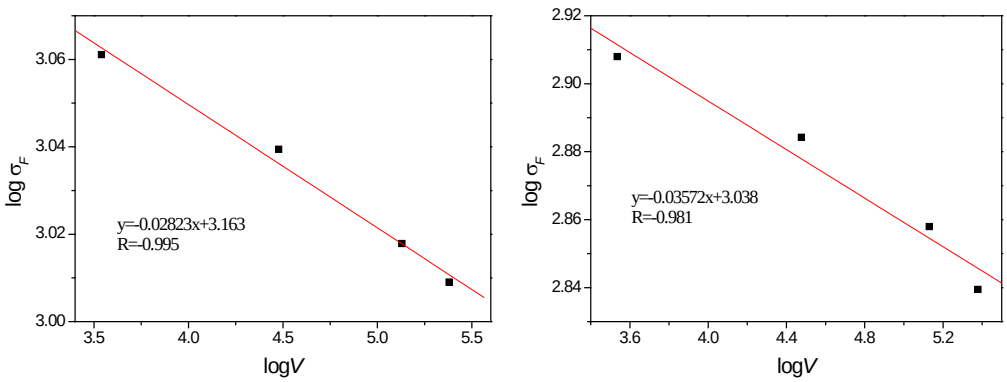
(a) $[UD]_n$ (b) $[0/45/-45]_n$

Figure.2 Typical stress-strain curve of the laminates tensile sample



(a) $[UD]_n$ (b) $[0/45/-45]_n$

Fig.3 Weibull model fit to tensile strength experimental data



(a) $[UD]_n$ (b) $[0/45/-45]_n$

Fig.4 Weibull model fit to flexural strength experimental data

Tab. 1 Tensile test results of the laminates specimens

laminates	Nominal size length×width×thickness /mm	Tensile strength /MPa	*Cv* /%	Tensile modulus /GPa	Number of species
$[0]_2$	100×10×1.70	916	4.4	44.9	9
$[0]_4$	100×10×3.40	903	5.2	44.3	9
$[0]_6$	100×10×5.01	892	4.7	44.5	8
$[0]_{12}$	100×10×10.01	876	3.9	44.6	7
$[0/45/-45]_2$	100×10×1.70	684	3.7	30.6	6
$[0/45/-45]_4$	100×10×3.36	673	4.1	30.9	6
$[0/45/-45]_6$	100×10×4.98	664	2.9	31.1	6
$[0/45/-45]_{12}$	100×10×9.98	653	3.8	30.7	6

Tab. 2 Flexural test results of the laminates specimens

laminates	Nominal size length×width×thickness /mm	Flexural Strength /MPa	*Cv* / %	Flexural modulus /GPa	Number of species
$[0]_4$	68×15×3.40	1151	2.9	35.3	5
$[0]_{12}$	200×15×10.01	1095	2.8	36.5	5
$[0]_{18}$	300×30×14.99	1042	3.8	35.8	5
$[0]_{24}$	400×30×19.96	1021	4.7	37.0	5
$[0/45/-45]_4$	68×15×3.40	809	4.7	29.7	5
$[0/45/-45]_{12}$	200×15×10.01	766	5.5	29.2	5
$[0/45/-45]_{18}$	300×30×14.99	721	4.6	29.3	5
$[0/45/-45]_{24}$	400×30×19.96	691	7.1	29.7	5

Tab. 3 Weibull moduli of the strength size effects of different GFRP laminates

Laminates	Size effects Weibull modulus	
	Tensile strength	flexural strength
[0] fabric reinforced	39.2	35.4
[0/45/-45] fabric reinforced	37.6	28.0