THREE-DIMENSIONAL ANALYSIS USING PROBABILISTIC MULTISCALE APPROACHES FOR PREDICTING MACROSCOPIC MECHANICAL BEHAVIOURS AND FAILURE STRENGTH IN UNIDIRECTIONAL CARBON FIBRE-REINFORCED EPOXY COMPOSITES

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Abstract

In this study, we aim to demonstrate how to predict macroscopic mechanical behaviours and also failure strengths of unidirectional composite by taking into account material's variations (distribution of fibre strength and variation of volume fraction) based on a probabilistic multiscale approach. Tensile test has been carried out on a number of composite specimens as a validation result. The strength distribution along fibres estimates through the single fibre test. Image analysis and pyrolysis method have been used to estimate the local and global variations of volume fraction in composite material. Then, finite element analysis with appropriate statistical probability has been performed by introducing physical phenomena. The scale effect has been expected. A good agreement between the numerical predictions and the experimental results has been observed.

1 Introduction

Carbon fibre-reinforced polymer matrix composites have been widely used in various structure applications such as naval, aeronautic and automobile etc thanks to their high specific strengths/resistances and especially their performance to weight ratios. However, this kind of materials presents exceptionally complicated damage process, in particular fibre breakage, matrix cracking and interfacial debonding until ultimate failures. For some applications such as advanced composite pressure vessels, the fibre breakage occurring in a microscopic scale is a majority of damage mechanisms. This material represents a large variability in term of mechanical properties, especially failure strength, due to their brittle characteristics. Consequently, for engineering applications, numerical tools with the high reliability of mechanical properties are required for structural designs.

In recent years, the growing accessibility of fast computers has allowed the development of 3D finite element (FE). The FE models become powerful tools and play important roles in the damage mechanisms. In general, the failure analysis models can be roughly divided into two approaches: deterministic failure and statistical failure analysis. The latter is based on probabilistic approach including statistical scatter of strength along the fibres often modelled by a Weibull distribution. This scatter is due to defects within the fibres which are significantly undersized comparing with the composite structure itself. Therefore, the multiscale method is required and a scale passage needs to be taken into considering.

Various studies have deduced the strength of a unidirectional composite from the fibre strength distribution. Analytical model was used at first [5, 6, 10, 11]. Many of the models were based on the work of Cox [4] which had introduced the concept of shear-lag. This concept considered the effects of the loads transferred from broken fibre to adjacent fibre through matrix resin. The finite element model was used afterward [1, 2, 3, 8, 9]. The use of this method was allowed to obtain more precisely the stress field around broken fibre. Our study aims to improve this finite element approach to predict the strength failure of composite structure.

2 Materials and experimental procedure

2.1 Materials

In this study, carbon fibres T700SC and composites carbon fibre T700SC/epoxy have been used for various testing. The carbon fibres were extracted directly from a fibre bundle. The composite plate was fabricated by filament winding process (this method has been used to fabricate a filament wound composite pressure vessel, the application in the future study). All materials were supplied by CEA, France.

2.2 Mechanical properties

2.2.1 Single fibre test

Single fibre test has been used to estimate the tensile strength distribution of fibre due to the defects in fiber itself. Thirty single fibres T700SC were tested with a gauge length 25mm (Figure 1). Two parameters of Weibull distribution, based on weakest link theory used to describe the experimental results as shown in equation (1).

$$\Pr(\sigma_R \leq \sigma) = 1 - \exp\left\{(-L/L_0)(\sigma/\sigma_0)^m\right\} \tag{1}$$

The previous study based on fibre multifragmentation test [1] concluded that a saturation length of carbon fibre breakage embedded in a resin epoxy is around 0.5 mm. Hitchon and Phillips [7] showed that the failure stress of carbon fibres varied insignificantly between lengths of 0.5 to 5 mm. The Weibull function can be used to extrapolate results from a gauge length of 25 mm to 5 mm and then used for a length of 0.5mm.

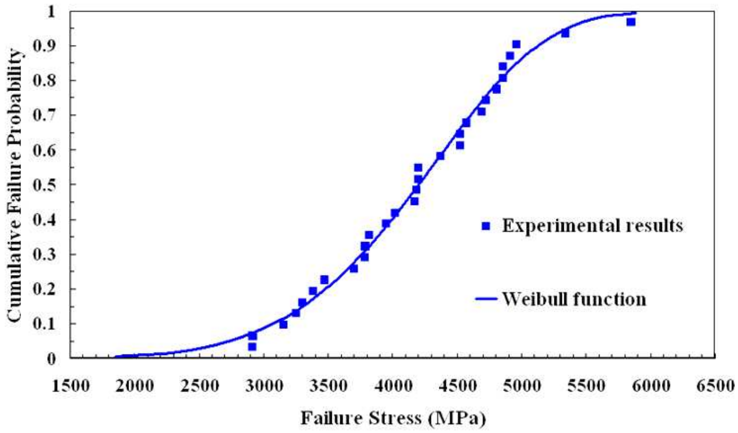

Figure 1. Failure stress distribution of fibre T700SC by single fibre tests with 25mm gage length.

2.2.2 Tensile test

Mechanical properties of unidirectional composite can be characterised by the classical tensile test. Experimental results probably show some scatters in term of modulus and failure strength referring to manufacturing process. Testing specimens were cut from the composite plate (300x300mm^2) in rectangular form using a diamond wheel with the final dimension 270x16x2mm^2. Woven glass/epoxy composite was used as a tab of specimen with 60mm long leaving an efficient testing length of 150mm. All tests were performed using Instron testing machine at a crosshead travel rate of 0.1 mm/min. Strain of material was followed by video extensometer from Instron and extensometer sensors as back-up measurement systems. The tensile results show in figure 2.

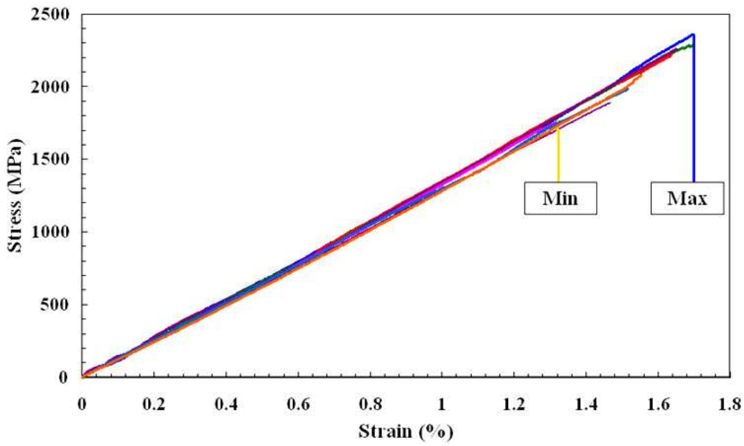

Figure 2. Failure behaviour of composite specimens submitted to tensile test.

2.3 Volume fraction analysis

2.3.1 Image analysis

In this study, image analysis technique has been used to estimate the local volume fraction of fibre in the composite. Preliminary images captured by using an optical microscopic camera, 240 images (30images/zone) were taken from different zones of composite plate. Some post processing images have been performed in order to distingue fibre/resin (also some cavitations) and obtained appropriate image sizes corresponding to the numerical simulation. The total images were 4800 images in this analysis. Volume fraction of each photo can be basically determined by the ratio of fibre’s pixels and total image pixels. This method allowed the local volume fraction to be acquired (Figure 3).

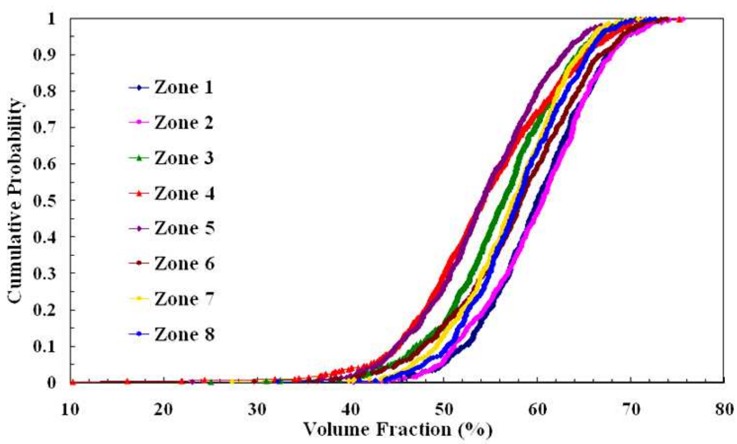

Figure 3. Variation of local volume fraction in various zones by image analysis.

2.3.2 Pyrolysis method

The variation of volume fraction in composite exists not only in microscopic scale, but also in macroscopic scale. A pyrolysis method which is usually used to identify the volume fraction by weight measuring for larger area comparing with the image analysis has been performed in this case. Testing samples were burned in a ceramic stove with temperature of 600°C until all resin burn out. As given density of fibre and resin, testing specimens had to be weighted before/after burning in order to determine the volume fraction. Testing samples were cut from different zones of composite plate with geometry and specific size corresponding to the numerical simulation. The global variation of volume fraction in the composite plate has been investigated (Figure 4) and used with the local variation for the probabilistic multiscale simulation.

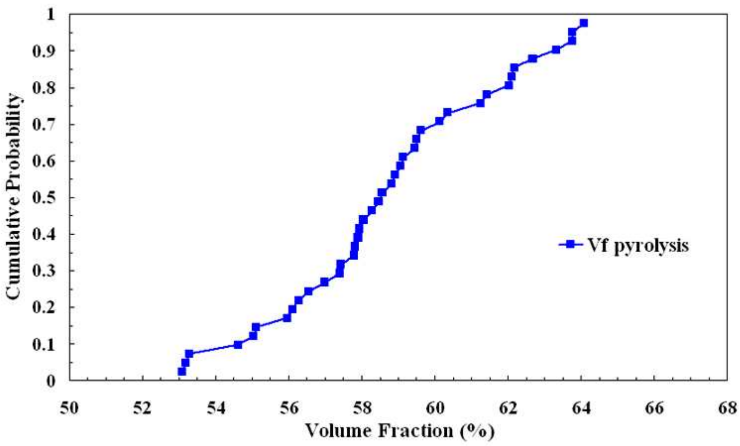

Figure 4. Variation of global volume fraction by pyrolysis method.

3 Multiscale modeling procedure

Numerical simulations based on 3D finite element method associated with a probabilistic multiscale approaches have been carried out as a calculation of macroscopic mechanical properties and failure strength. The results obtained from single fibre test and volume fraction analysis were introduced in the simulation as the material variation inputs. The numerical results have been compared to tensile results as a validation.

3.1 Modeling of the RVE for different volume fraction

First, the simulation was setup in a microscopic scale which fibres and resin can be distinguished. In this scale, a RVE (representative volume element) with constant size (0.054x0.054x8 mm^3) referring to the previous study [1, 2] was modeled. The variation of volume fraction in RVE can be reached by modifying a quantity of fibres in RVE. The RVE contain a defect element each 0.25mm along a fibre corresponding to the saturation length of fibre breakage as concluded by Baxevanakis. The single fibre test result which represents the fibre defect strength was imposed randomly in each defect element of RVE. The boundary condition with periodic type was applied in each plane of RVE.

During interval time of increment, a local stress in each element increase homogeneously while increasing an applied strain. Once the local stress of element reaches the local defected strength, this element will break out. This breakage can be made by sudden drop in stiffness of breaking element. Consequently, this breaking element will create the local stress concentration field which transfers to an adjacent fibre element due to their local different behaviour. If this phenomenon occurs at low stress level, defect elements will break randomly along the RVE depending on their failure strength. The local stress field does not affect to the defect element in neighboring fibres. When the applied stress is sufficiently high, this local stress takes the effect and set them to break continuously, so called localization. The fibre breakage will localize in certain area and a cleavage plane will occur when all fibres along the cross section break out. The RVE will be unstable and rupture as a result, a drop of applied stress can be observed. This maximum applied stress acquired by homogenization method will be the ultimate strength of this RVE. This calculation method uses a ton of computational memory due to the periodic boundary condition. Different volume fraction RVEs with 30 sampling per RVE were carried out in order to generate a probability of strength distribution of RVE with respect to volume fractions. This probability will be used in the macroscopic scale which is represented by laboratory specimen. A fibre arrangement has been taken into account as well. The RVEs containing fibres with different arrangements: regular (square and hexagonal) and non-homogeneous (random arrangement) were generated to study this influence. In this scale, we finally obtained the failure strength distribution with respect to the volume fraction and the fibre arrangements (Figure 5 and 6).

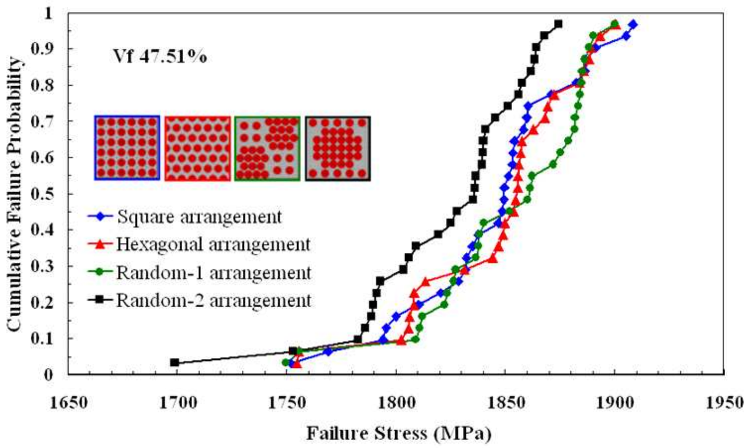

Figure 5. RVE's failure stress with different fibre arrangement at volume fraction of 47.51%.

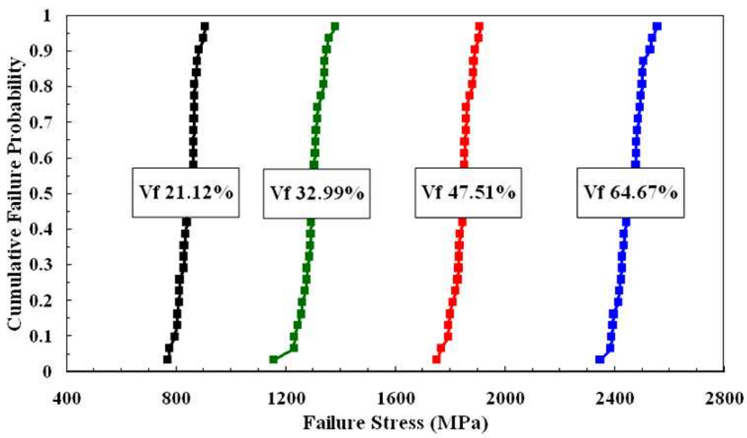

Figure 6. RVE's failure stress with different volume fraction.

3.2 Numerical specimen simulation

As a validation, a numerical specimen simulation has to be performed by introducing results from previous scale as the scale passage. However, we need to concern in the beginning the proper element size and its scale effect. Using the RVE size from previous scale as element size of the numerical specimen will cause more than 200,000 elements. This increases dramatically a computational time. In addition, we aim to apply this approaches to a filament wound pressure vessel, the use of RVEs size will be unacceptable in term of computation time and memory. For this reason, the proper element size needs to be investigated.

According to the numerical results from previous scale, we found that the volume fraction variation affect to RVE's failure strength rather than the defects distribution along fibres. Considering the volume fraction analysis with 2 different methods, the variation of volume fraction cannot be neglected but exists in both local and global levels. The scale effect has been taken in to account via this variation. Besides, the proper size using in this study is around 296 times of RVE in order to reach reasonably computational time and memory for pressure vessel simulation. At this scale, each element represents a bulk of composite which consists of different number of fibres depending on its volume fraction. A stiffness reduction after breakage of element needs to be additionally concerned using results from previous scale. In the same manner with the previous scale's simulation, the breakage of elements occurs initially in random, then localize as a result in drop of applied stress. At this point, the structure supposes to be failed. The macroscopic behaviour of numerical specimen was affected by the variation of volume fraction.

Simulations with RVE's element size have been performed. These results confirmed the insignificant difference with 296 RVE. Finally, the validation of behaviour and failure stress had a good agreement with the experimental results (Figure 7 and 8).

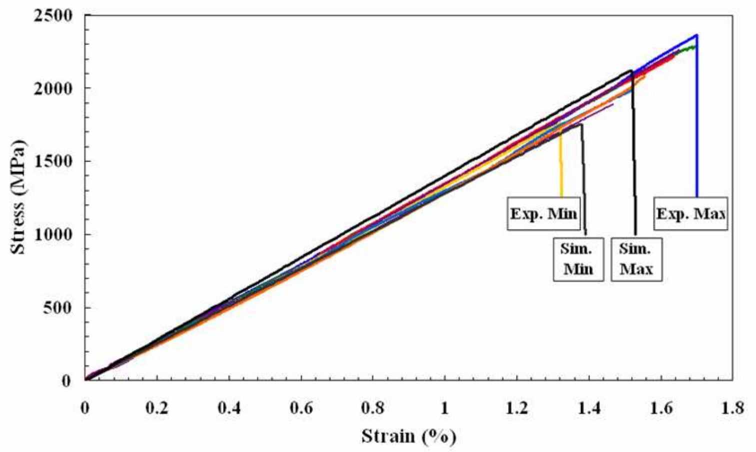

Figure 7. Comparison of failure behaviour.

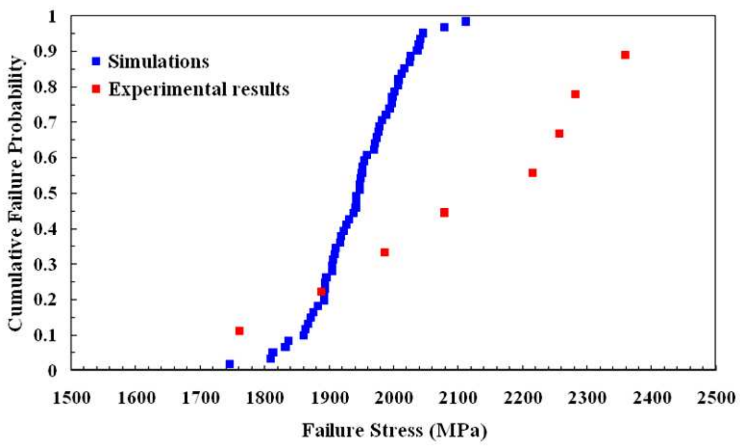

Figure 8. Comparison of failure stress.

4 Conclusions

In microscopic scale, as the single fibre test result was introduced in the numerical simulation, the stiffness drop function and the failure strength distribution of RVE with respect to the volume fraction were established. The effect of fibre arrangements was also integrated in the failure strength distribution.

The volume fraction analysis showed the existence of variation in both of local and global levels. Moreover, we found that the volume fraction variation has more effects than the statistical failure strength of fibres for the prediction of macroscopic failure strength. For this reason, it leads to construct the scale effect from this variation.

In macroscopic scale, the simulation result showed a good correlation with experimental result. In addition, the results from different element sizes were not significantly different by using the scale effect from volume fraction. The validation of this approach has been done.

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