A STATISTICAL APPROACH TO EVALUATE THE EFFECT OF MANUFACTURING QUALITY ON TRANSVERSE CRACKING IN CROSS PLY LAMINATES

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Keywords: *Composite laminates, Transverse cracking, Weibull distribution, defects*

1 Introduction

Most studies of the effects of manufacturing defects such as voids have focused on composite strength properties, e.g. the interlaminar strength [1]. The current study investigates how irregularities in the manufacturing process affect progressive damage in the subcritical regime. This effort is along the lines of a broader strategy for performance evaluation of composites coined as defect damage mechanics by Talreja [2]. In this approach one accounts for the effect of defects on the initiation and progression of damage as an integral part of the evaluation of materials response. The traditional approach is to evaluate the effects of defects and damage separately in homogenized composites.

As the most studied problem in damage of composite materials, the transverse cracking in cross ply laminates was taken as an example to illustrate the effect of manufacturing induced defects on damage evolution. Laminated plates were produced under different manufacturing conditions to intentionally introduce defects, and then subjected to axial tension along the 0^0 direction. The crack density data as function of applied stress was considered for comparison in the present study. To better reveal the physical process of cracking evolution, statistical simulation procedures were developed separately for non-interactive and interactive regimes of cracking evolution.

2 Experiments

Three [0/90]s laminated plates were fabricated using an autoclave process. The prepreg used was HexPly® M10/38%/UD300/CHS. For laminated plate 1, air was intentionally left entrapped between the stacked prepreg layers by not drawing it out during the lamination process, followed by standard curing process. For laminated plate 2, standard process was followed except no vacuum was applied during the curing process. For laminated plate 3, standard process was strictly followed. The coupons cut from three laminated plates were subjected to monotonic axial tension. The two edges of the coupons were polished so that the number of cracks along 70 mm gauge length could be counted under a microscope. The microstructure of three plates was also examined under the microscope.

3 Statistical simulation

The transverse strength is assumed to vary along 0^0 direction following the Weibull distribution:

$$P_s(\sigma_s) = 1 - \exp\left(-\left(\frac{\sigma_s}{\sigma_0}\right)^m\right) \qquad (1)$$

where σ_0 and m are the characteristic strength and distribution shape constants, respectively. The variation of strength is mainly affected by the randomly distributed defects such as voids.

3.1 Non-interactive regime

In the non-interactive regime, which is the initial stage of cracking evolution, the stress perturbation by preexisting cracks is highly localized and therefore can be neglected. Using the discrete elements adopted in Monte Carlo simulation [3], the 90^0 plies were discretized into small elements of length l_0 along 0^0 direction. Random strength according to Weibull function was assigned to the element as local strength. The formation of cracks

then can be viewed as the failure of the corresponding elements. Thus the number of cracks per unit length is the number of failed elements whose local strength is not higher than the longitudinal tensile stress:

$$\rho = \frac{1}{l_0} * P_s(\sigma_{xx}^{90}) \tag{2}$$

where ρ is crack density and σ_{xx}^{90} is the transverse tensile stress in 90^0 plies, which is calculated by classical laminate theory and depends only on the applied tensile stress for a given laminate.

3.2 Interactive regime

If applied loading keeps increasing, the cracking evolution gets into interactive regime, in which the perturbation stress cannot be neglected. Therefore, the failure of an element, or the formation of new crack, is not only dependent on the local strength, but also on the local stress. An iterative numerical procedure was developed to track the formation of new cracks at each step of the increasing applied stress. The key is to calculate the failure probability of each element at every step:

$$\lambda_{x_j}^{(n)} = \frac{P_s(\sigma^{(n)}) - P_s(\sigma^{(n-1)})}{1 - P_s(\sigma^{(n-1)})} \tag{3}$$

where $x_j = j*l_0$ is the local coordinate of the j-th element between two preexisting cracks, $\sigma^{(n)}$ and $\sigma^{(n-1)}$ are the local stress of the element at step n and n-1, respectively. These stresses can be solved as function of external loading, crack spacing L_i, and local coordinate x_j by a suitable method such as Hashin's variational approach [4]. Since all elements with strength lower than $\sigma^{(n-1)}$ have already failed in previous steps, the strength probability distribution of the surviving elements cannot be the same as the initial Weibull function. An adjustment to the probability function has been made in Eq. (3) for this consideration.

To calculate the average crack spacing at each step, the distribution of crack spacing must be known. For non-interactive regime, Manders et al [5] found that the crack formation is a Poisson process, from which it can be shown that the crack spacing is exponentially distributed with an accumulative probability:

$$P_L(L) = 1 - exp\,(-\rho L) \tag{4}$$

Taking the end of non-interactive regime as the initial state of the numerical iteration for interactive regime, the change of the distribution of crack spacing at each step can be tracked by following the process that each segment between two cracks are divided by new crack into two small segments. The possibility of this process at step n is:

$$\begin{aligned} P_{x_j}^{(n)} &= P_{L_i - x_j}^{(n)} \\ &= P_{L_i}^{(n-1)} * \frac{\lambda_{x_j}^{(n)}}{1-\lambda_{x_j}^{(n)}} * \prod_1^i (1 - \lambda_{x_j}^{(n)}) \end{aligned} \tag{5}$$

In the computer program, the increment of applied stress at each step is kept small so that the probability of forming more than one crack in any segment could be neglected. In this way, any possible situation has been examined by applying Eq. (5) to segments with different length while the initial state is according to Eq. (4).

4 Results

Fig. 1 shows the cracking evolution as function of applied stress. Under same applied stress, plate 1 made with air-entrapped lay-ups consistently has highest crack density, followed by plate 2 cured without applying vacuum; plate 3 made by standard process has lowest crack density. The prediction from our statistical simulation agrees well with experimental data.

To better understand the process of multiplication of cracks, the predictions according to non-interactive and interactive regimes are shown in Fig. 2. It suggests that the cracking evolution gets into the interactive regime when crack density is higher than 0.1/mm. After that, the experimental data become increasingly lower than the prediction from non-interactive regime because of the presence of preexisting cracks on further multiplication. By considering this effect, the numerical iteration for interactive regime yields good prediction. The

prediction in Fig. 1 is obtained by merging the predicted crack density curves from non-interactive and interactive regime at a relatively low level of crack density.

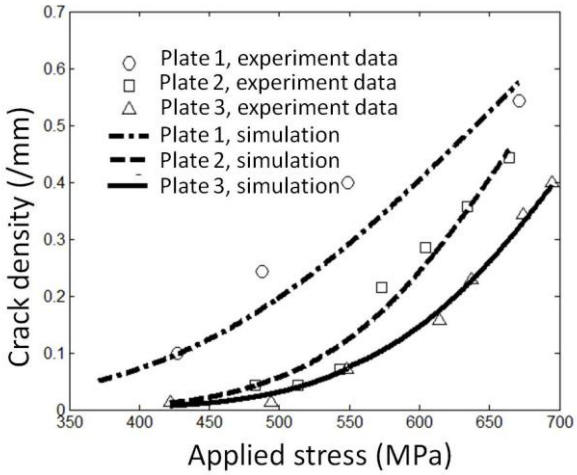


Fig. 1 Crack density as function of applied stress

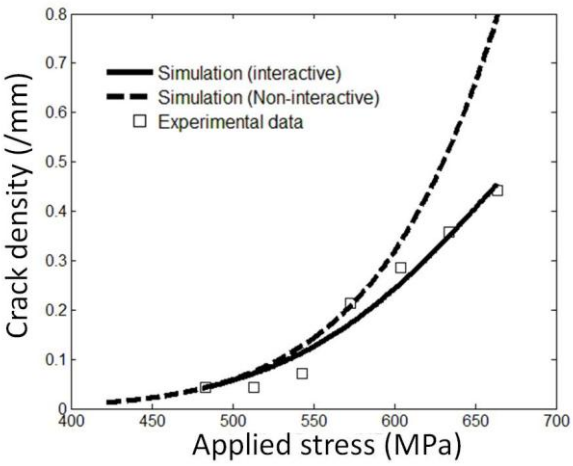
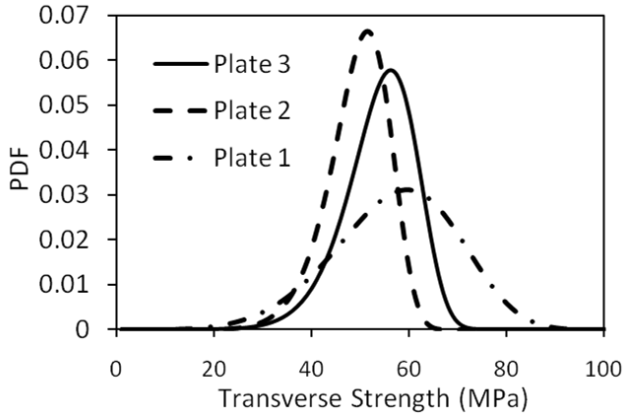


Fig. 2 Interactive and Non-interactive regime

The transverse strength probability density function is fitted by crack density data through the statistical model. For damage analysis of laminates, elements with lower strength are more of interest. From Fig. 3, the volume percentage of the weak elements ($\leq$ 40MPa) in plate 1 is the highest, followed by plate 2. This explains why these plates have higher crack density than plate 3. It should be noted that the lowest strength in plate 1 is approximately 20 MPa which is much lower than the value of 30MPa for the other two plates. This difference explains why



the onset stress for the first crack is much lower for plate 1.

Fig. 3 Weibull distribution of transverse strength

As Fig. 3 illustrates, the statistical distribution of strength obtained from crack density data through our model offers a tool to quantitatively describe the manufacturing quality, and link it to the damage analysis of laminates.

The mechanism underlying the strength distribution in Fig.3 is rooted in the microstructure of laminates, which is mainly controlled by the manufacturing condition. For example, more voids are observed in plate 1 and plate 2 compared to the plate manufactured with standard processes. Fig. 4 shows the voids in plate 2. These voids may account for the lower range of strength distribution in Fig.3, especially for plate 2.

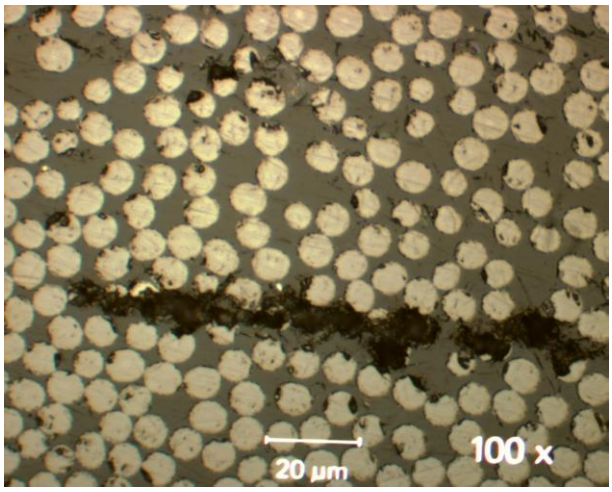


Fig. 4 Voids in 90^0 layers observed in plate 2

5 Conclusion

The effect of manufacturing quality on the transverse cracking evolution in cross ply laminates was studied. Experimental observation as well as modeling study show that laminates manufactured under good quality control have low crack density and high stress for the onset of crack multiplication. The Weibull distribution of strength could be obtained in our statistical model by fitting the crack density data. Through that, our model offers a tool to quantify the manufacturing quality and link it to the damage analysis of laminates.

References

[1] H. Jeong "Effects of voids on the mechanical strength and ultrasonic attenuation of laminated composites". *Journal of Composite Materials*, Vol. 31, No. 3, pp 276-292, 1997

[2] R.Talreja " Defect damage mechanics: broader strategy for performance evaluation of composite". *Plastics, Rubber and Composites*, Vol. 2, No. 4, pp 49-54, 2009

[3] Z.Sun , I. Daniel, and J. Luo, "Modeling of fatigue damage in a polymer matrix composite". *Materials Science and Engineering A*, Vol. 361, No. 1-2, pp 302-311, 2003

[4] Z. Hashin, "Analysis of cracked laminates: a variational approach". *Mechanics of Materials*, Vol. 4, No. 2, pp 121-36, 1985

[5] P. Manders, TW. Chou, FR. Jones, and JW. Rock, "Statistical analysis of multiple fracture in 0/90/0 glass fibre/epoxy resin laminates". *Journal of Materials Science*, Vol. 18, No. 10, pp 2876-89, 1983