CHARACTERIZATION OF DAMAGED COMPOSITE LAMINATES USING ELECTRONIC SPECKLE PATTERN INTERFEROMETRY (ESPI)

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Abstract

The degradation of the elastic properties of composite laminates with intralaminar cracks is caused by reduced stress in the damaged layer which is mainly due to two parameters: the crack opening displacement (COD) and the crack sliding displacement (CSD). In this paper these parameters are measured experimentally providing laminate stiffness reduction models with valuable information for validation of used assumptions and for defining limits of their application. In particular, the displacement field on the edges of a $[0/ +70_4/ -70_4]_s$ glass fiber/epoxy laminate specimens with multiple intralaminar cracks is studied and the COD and CSD dependence on the applied mechanical load is measured. The specimen full-field displacement measurement is carried out using ESPI (Electronic Speckle Pattern Interferometry). By studying the displacement discontinuities, the crack face displacements were measured. A comparison between the COD and the CSD (for the same crack) is performed.

1. Introduction

When cross-ply laminates are subjected to mechanical loading, different failure mechanisms are induced: transverse matrix cracking in 90° plies, delamination between 0° and 90° plies, and fiber fracture in 0° plies. In the case of uniaxial loading, the early stage of damage is transverse matrix cracking in 90° plies. The transverse cracks develop in the fiber direction and extend across the laminates from the free edges of the specimen. The analysis of transverse cracking is important since cracking reduces the stiffness and strength of laminates. Transverse cracks induce local stress concentrations at crack tips and can initiate significant interlaminar delamination between 0° and 90° plies. Fiber fracture in 0° plies is induced only at high loads in the case of monotonic loading or for large cycle number in the case of fatigue loading.

The degradation of the elastic properties of composite laminates is caused by reduced average axial stress between two cracks in the damaged layer which is mainly due to two parameters: the crack face opening displacement (COD) and the crack face sliding displacement (CSD).

Many theoretical analytical and numerical models have been developed to calculate the reduced stiffness [1-7]. All of them are based on idealized assumptions, for example, assuming linear elastic material behavior even in high stress concentration region at crack tip as well as linearity in shear loading and assuming idealized geometry of these cracks which would not change during the service life [2].

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In a linear model these quantities are proportional to the applied load and, therefore, the COD and CSD should be normalized to be used in stiffness modeling. The effect of material properties on the normalized COD was studied experimentally using optical microscopy of loaded damaged specimens in [3,4]. It was shown that the measured COD profiles and average values are affected by the constraining layer orientation and stiffness.

To establish the link between the damaged laminate thermo-elastic constants and the microdamage parameters (COD and CSD) a theoretical framework was developed in [1,5]. It was shown that the details of the relative displacement profile along the crack surface are not important: only the average values of these quantities enter the stiffness expressions directly.

The effect of geometrical parameters and properties of the surrounding layers on the COD and CSD was studied using FEM in [1,5]. Analysis revealed that only two parameters are of importance for the normalized average COD and CSD: the modulus ratio of the cracked and the support layers in direction transverse to the crack and the ratio of their thickness. Based on this analysis simple empirical relationships (power laws) were suggested.

The COD and CSD dependence on crack density was analyzed theoretically in [6] and studied using FEM in [7]. It was shown that if the crack density is high the stress perturbations of two neighboring cracks interact and the average stress between cracks at the given applied load is lower. It means that the COD and CSD of interacting cracks are smaller than for non-interactive cracks.

All these studies and analyses assume a linear elastic material with idealized geometry of cracks. The only correct way to validate these assumptions is through experiments. To study experimentally the COD and the CSD, the full-field measurement technique Electronic Speckle Pattern Interferometry (ESPI) [8-11] was used in this work.

The main objectives of the present study are to visualize the displacement field on the edge of a [0, $+70_4$, -70_4]s Glass Fiber/Epoxy (GF/EP) laminate specimen with multiple transverse cracks and to analyze the crack face displacement dependence on the applied mechanical load. Using the displacement map, it is possible to obtain the displacement profiles along the tensile-axis. The different profiles drawn along the specimen edge at several distances from the mid-plane correspond to the different plies. By studying the displacement discontinuities, we can measure the crack face displacements corresponding to the cracks in the measurement field. A comparison between the COD and the CSD (for the same crack) is given in this paper.

2. Experimental technique and material

2.1. Experimental technique: ESPI

The principle of ESPI is based on the interference of two coherent laser beams: reference beam and observation beam. For in-plane measurement, the surface is illuminated by a coherent beam and the surface roughness causes multiple phase differences that create random interference. Hence, a Charge Coupled Device CCD camera sensor collects a randomly distributed light intensity called speckle. Then, the first resulting speckle interferogram is transferred to a computer, and saved in memory. If a point of the surface is subjected to a displacement, the local speckle pattern undergoes the same displacement. The intensity of each speckle grain is also likely to vary because of the phase difference created by the displacement. Then the speckle interferogram is changed. This second interferogram is subtracted pixel by pixel from the first one. The result is rectified and displayed as a set of bright and dark fringes, known as correlation fringes, which constitute a contour map of the displacement of the object surface.

In our case, the surface is illuminated by two coherent beams that form the same angle ¯ with respect to the normal studied surface, so the corresponding speckle patterns also interfere. Figure 1 shows a schematic setup for the in-plane deformation measurement by ESPI.

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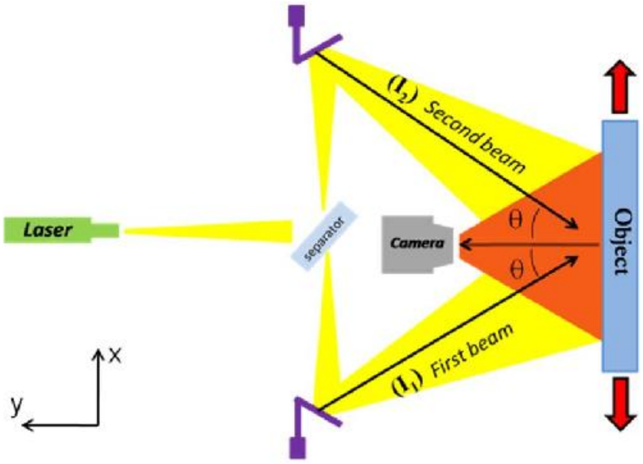

Figure 1. Schematic of ESPI setup.

$U(x,z)$ is the relative displacement along the X-axis corresponding to a passage from an initial loading state to a final loading state which means that this relative displacement corresponds to a Δ± increase of the average stress applied to the specimen. ESPI can provide full-field deformation information of different materials with a very high-precision. However it has a very high sensitivity, which corresponds to a fraction of the laser wavelength, in our case we expected about 15 nm as sensitivity [8]. Hence, the results can be easily influenced by external factors such as noise and vibration. For that reason tests should be carried out in relatively quiet circumstances. Excessive displacement can be a source of de-correlation [12].

2.2. Material

The [0, 70_4,-70_4]s laminate was made of glass fiber/epoxy using vacuum bag technique. The thickness of the laminate is 2.75 mm. The elastic properties obtained in tests on unidirectional and angle-ply composite specimens are, see [4]: longitudinal modulus E_1(GPa) = 44.7, transverse modulus E_2(GPa) = 12.7, poisson's ratio ν_{12} = 0.297, in-plane shear modulus G_{12}(GPa) = 5.8. Specimens of 20 mm width were reinforced with GF/EP end tabs in the gripping area.

A free length between tabs was 110 mm. The tensile loading to introduce damage in form of microcracks was applied using an INSTRON tensile testing machine with displacement rate of 1 mm/min. Cracks initiate first in the -70 layer, which is two times thicker than the +70 layer and propagate through the whole width of the specimen.

3. Results

3.1. Normalized relative displacement measurement

The specimen edge is illuminated by two beams which come from the same laser that has a $= 0.638«m$ as wavelength. These beams illuminate the object at equal but opposite angles ±¯ to the surface normal (see figure 2).

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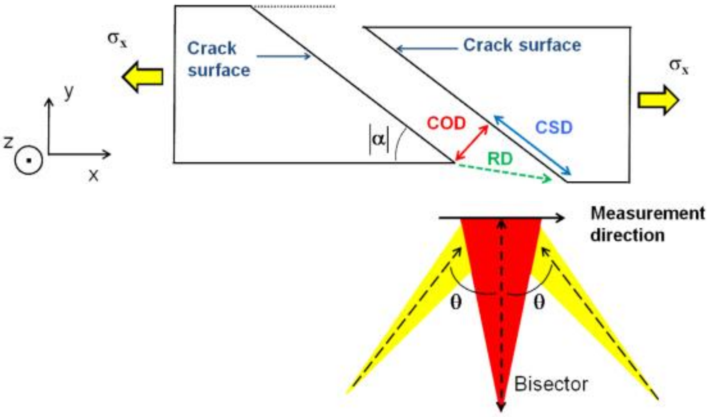

Figure 2. Symmetric illumination

Using this method of illumination, the measurement direction is in the X-axis direction which is the tensile-axis. Figure 3 shows the X-displacement profile in the central ply (-70°) when the cracks were first initiated. The displacement discontinuities caused by the cracks are clearly visible

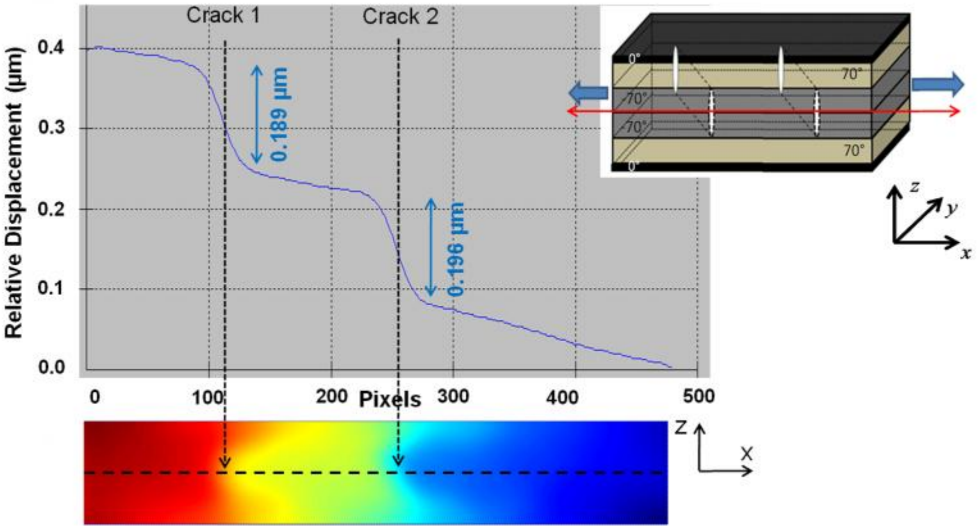

Figure 3. Profile of the relative displacement along the mid-plane (on the specimen edge) corresponding to a variation of the relative average stress $\Delta\pm = 0.497MPa$

These displacement jumps indicate the presence of two cracks in the region of study. The displacement slope (strain) is smaller in the area at the vicinity of the crack surfaces. It certainly results from the boundary condition with traction free crack surfaces. Just before and after a displacement jumps, we detected small regions where the displacement slope (strain) has a minimum. We have calculated the displacement jumps by evaluating the displacement difference between these regions of low strain.

Because of the 70° fiber orientation, the crack displacement discontinuity measured on the edge is not directly COD and neither the CSD. It is a projection of both these displacements on the specimen edge plane (Figure 2). By definition, the crack opening displacement (COD) is transverse to the fiber direction and the sliding displacement (CSD) is in the fiber direction. The displacement jump is defined as a relative displacement (RD) which is related to the COD and the CSD by this relationship:

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$$RD_x = COD \times \sin|\sim| + CSD \times \cos|\sim| \qquad (1)$$

where ~ is the fiber orientation of the damaged studied plies.
The displacement gap observed on the edge corresponds to a certain change in the applied average stress $\Delta\pm$. In other words $\Delta\pm$ is the increase of the average stress applied to the sample ($\Delta\pm = \pm_{final} - \pm_{initial}$). Hence, the presented displacement data correspond to this load change.
In order to perform comparative analysis for several applied load levels the relative displacement (RD) has to be normalized with respect to the relative average stress $\Delta\pm$. The separation of the values of the COD and the CSD is explained in the following section.

3.2. Normalized crack opening displacement

The object is illuminated by two beams. To measure directly the COD, theses two beams have to illuminate the object at equal and opposite angles to the fiber direction axis, which means the bisector of the angle between the first and the second beam has to be in the same direction as fibers of the studied layer (Figure 4). In this case, the measurement direction is transverse to the fiber direction. Hence, using this method of illumination, we can measure directly the COD.

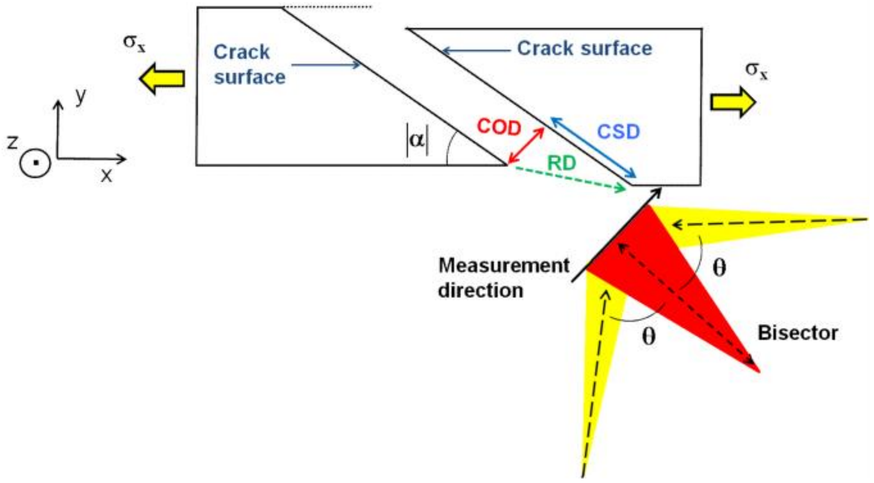

Figure 4. Non symmetric illumination

For the same crack, we measured the average normalized relative displacement RD_{an} and the average normalized crack opening displacement COD_{an} separately, and then we deduced the average normalized crack sliding displacement CSD_{an} using equation (1).

3.3. Comparison between COD and CSD for $[0/70_4/ -70_4]S$ GF/EP laminate

According to predictions using the methodology developed by one of the authors in WWFE III [13], the effect of CSD on thermo-elastic properties may be as significant as the effect of COD.

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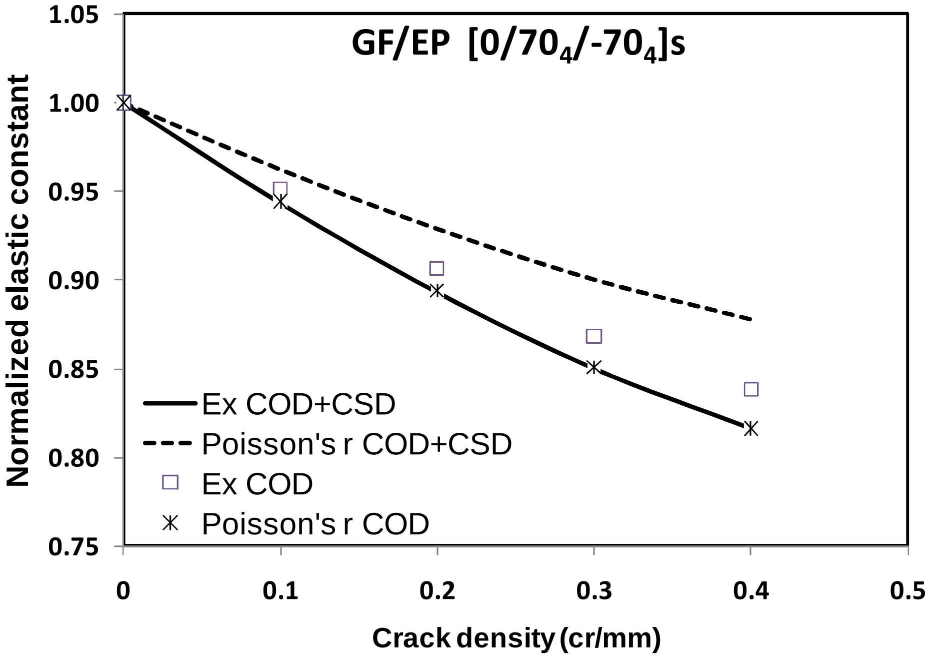

Figure 5. Predicted axial modulus and Poisson’s ratio reduction of GF/EP laminate with cracks in -70 layer.

In Figure 5 predictions of the axial modulus and Poisson’s ratio reduction of GF/EP [0/70$_4$/-70$_4$]s specimen with cracks in -70 layer is shown. Lines correspond to predictions accounting for COD and CSD effect. Predictions under assumption that CSD can be neglected are shown with symbols. It is clear that for this laminate neglecting CSD we are predicting too high axial modulus and very low Poisson’s ratio. However, in these calculations CSD is obtained from FEM model and the used values have never been experimentally validated. For example, for real cracks CSD could be significantly lower due to fiber bridging. This section is aimed to present some preliminary results showing that CSD is indeed of the expected magnitude.

Cracks appeared first in the -70 layer, which is two times thicker than the +70 layer and propagated unstably through the whole width of the specimen. At higher applied stresses, cracks appeared in the +70 layer. Looking from the specimen edge they were usually located close to existing large cracks in the -70 layer. Still, there is no enough evidence to say that the +70 layer cracks were caused by the -70 layer cracks. Nevertheless the presence of cracks in +70 layer affect the opening displacement of the cracks in the -70 layer. It is especially true because at least in the edge region these both cracks seemed to be connected by local delamination. Therefore, the data obtained on the specimen edge may not be representative for sliding and opening displacements inside the material. The obtained trends should be considered as indicative only.

The sample was loaded at four different strain levels. For each strain level, the crack density was measured. Using the displacement map, the displacement profiles were drawn (not shown) along the axial direction at the mid-plane (in the middle of -70° layer) to measure the relative displacement of each detected cracks. The separation of the values of the COD and the CSD is described in section 3.2. The ratio COD/CSD was calculated from these measurements for four different cracks at different crack densities.

The positions of these cracks in the -70° layer are shown in Figure 6 (a). The results presented in Figure 6 (b) show that the COD is larger than the CSD and the ratio increases by increasing the crack density.

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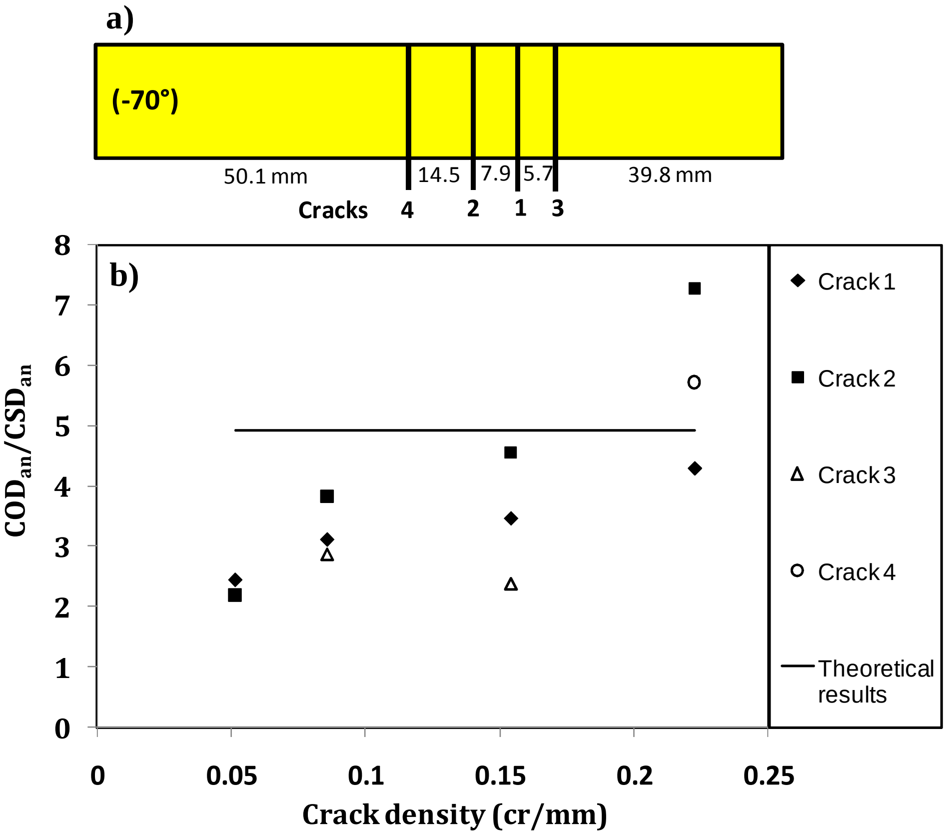

Figure 6. a) Positions of cracks in -70° layer, b) A comparison between the COD and the CSD in -70-layer

The theoretical value of CODan/CSDan ratio in Figure 6 (b) was calculated using fitting expressions obtained using FEM, see [1,5]. Using equations (40), (41) in [1] and equations (17), (19) in [5] we can calculate the ratio of the average normalized values of COD and CSD for non-interactive cracks. Under assumption that average values may have similar ratios as displacement ratios on the midplane, the calculated and experimental values can be plotted in the same figure, see Figure 6 (b), and compared.

The experimental and theoretical results show rather large difference. The calculated ratio for the considered laminate is about 4.9 whereas the measured ratio varies from 2 to 7.5. The differences in the analyzed case can be caused by many factors. For example, idealized geometry of cracks (straight, perpendicular to the midplane, zero delaminations) is assumed which would not change during the increasing loading. Presence of cracks in the +70 layer is not included in the model and neither the interface delamination between both crack systems.

Therefore, in spite of the large data scatter in Figure 6 (b) and large difference between theoretical and experimental values, these results confirm that the sliding displacement has values of the same magnitude as the opening displacement and therefore it cannot be neglect in stiffness calculations.

4. Conclusions

Measurements on the edge of $[0/70_4/-70_4]_s$ GF/EP laminate with cracks in -70 and +70 layers were performed to estimate the significance of sliding, CSD in this laminate and simulations were performed to demonstrate its effect on stiffness. In spite of secondary damage modes (+70-layer cracks, delamination) disturbing the results, it was shown that the normalized CSD in the -70 layer is

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about 3-7 times smaller than the COD which is in a reasonable agreement with the FEM based estimated ratio 5. The presented results prove that Electronic Speckle Pattern Interferometry ESPI can be used to measure directly the crack opening displacement and deduce the crack sliding displacement. A comparison between these two parameters shows that the COD for this laminate is slightly bigger than the CSD.

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