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A REVIEW OF FAILURE MECHANISMS OF COMPOSITE LAMINATES UNDER QUASI-STATIC AND FATIGUE LOADS FOR AERONAUTICAL STRUCTURAL PURPOSES.

José Fernando Cárdenas Barbosa, Volnei Tita, and Marcelo Leite Ribeiro

University of Sao Paulo USP – Sao Carlos School of Engineering EESC, Sao Carlos, Sao Paulo, Brazil.
artefacto@usp.br

Abstract: There are many factors to be considered when a composite aeronautical structure is designed. Present review contains the main quasi-static and fatigue failure mechanisms of composites as CFRP and GFRP, including fractographic features. Finally, the relationship between CFRP laminate damage and change in its electrical properties is presented as a promising structural health monitoring method.

Keywords: Composites, Fatigue composites, Electrical change method, Fractography, Failure Modes

INTRODUCTION

Aeronautical structures traditionally are made of aluminum but day-by-day more composite materials are used in order to improve lift to weight ratios. Structures designers must know the quasi-static and fatigue behavior of the used composite. That is why the present review about composite laminate failure mechanisms, is part of a bigger research that aims to study for the first time the waveform influence in fatigue failure of aeronautical composite laminates (particularly in the CFRP and the GFRP) under certain conditions of carrying and environment.

COMPOSITE QUASI-STATIC FAILURE

Under longitudinal tensile, according to Tiwari (2018), exists different failure modes. First as shown in Fig 1 (a) the composite can be divided into two parts, normally when volume fraction (Vf) is low, but if Vf is intermediate, commonly the composite as shown in Fig 1 (b) presents fiber pull up. Finally, if the Vf is high, debonding and delamination occur.

Figure 1 (c) Explains according to Meng (2015) that the failure process stars from matrix cracking while fibers being intact, then the cracks jointed and propagate until the fiber barrier where the interfacial debonding occur and protrude until certain extents to enable cracks to open. The failures contour the fiber (Fiber bridged) and continue propagating until next fiber and so on.

Figure 1 (d) shows a fracture surface of the carbon fiber reinforce polymer (CFRP) as indicated by Kumar et al (2012). The characteristic surface shows chevron lines emanating from the crack origin and three distinct regions: crack origin, propagation, and final failure. In the propagation region as shown in Fig 1 (e) fiber radials let know the propagation direction while in the final failure area shows random fiber fracture direction as shown in Fig 1 (f).

Figure 2(a) represents the longitudinal compression case. The general mechanism is shown in Fig 2 (b) where the matrix tries to keep the fiber aligned while the fibers star to buckling, generating cracks and debonding. The first detailed failure mechanism is shown in Fig 2 (c), and is called matrix transverse tensile, due to the Poisson's ratio. The second is shown in Fig 2 (d) and is the shear buckling when the Vf is large and the third failure mechanism is the extensional buckling when the Vf is small, as shown in Fig 2 (e). The last is the Shear fracture at 45° typically shown in Fig 2 (f). If the compressive load is further increased, the shear buckling undulatory shape of Fig 2 (d) could cause a local failure in the form of kink band, detailed in Fig 2 (g) with its characteristic variables and an optical micrograph of the case is presented in Fig 2 (h).

Figure 3 shows other composites loadings and its failures modes. In Fig 3(a) is shown the transverse tension governed by the matrix properties, where it could present debonding or fiber split. The angled fail depending the stacking sequence can occur from zero to ninety degrees. Some examples are available in Reifsnider (1983).

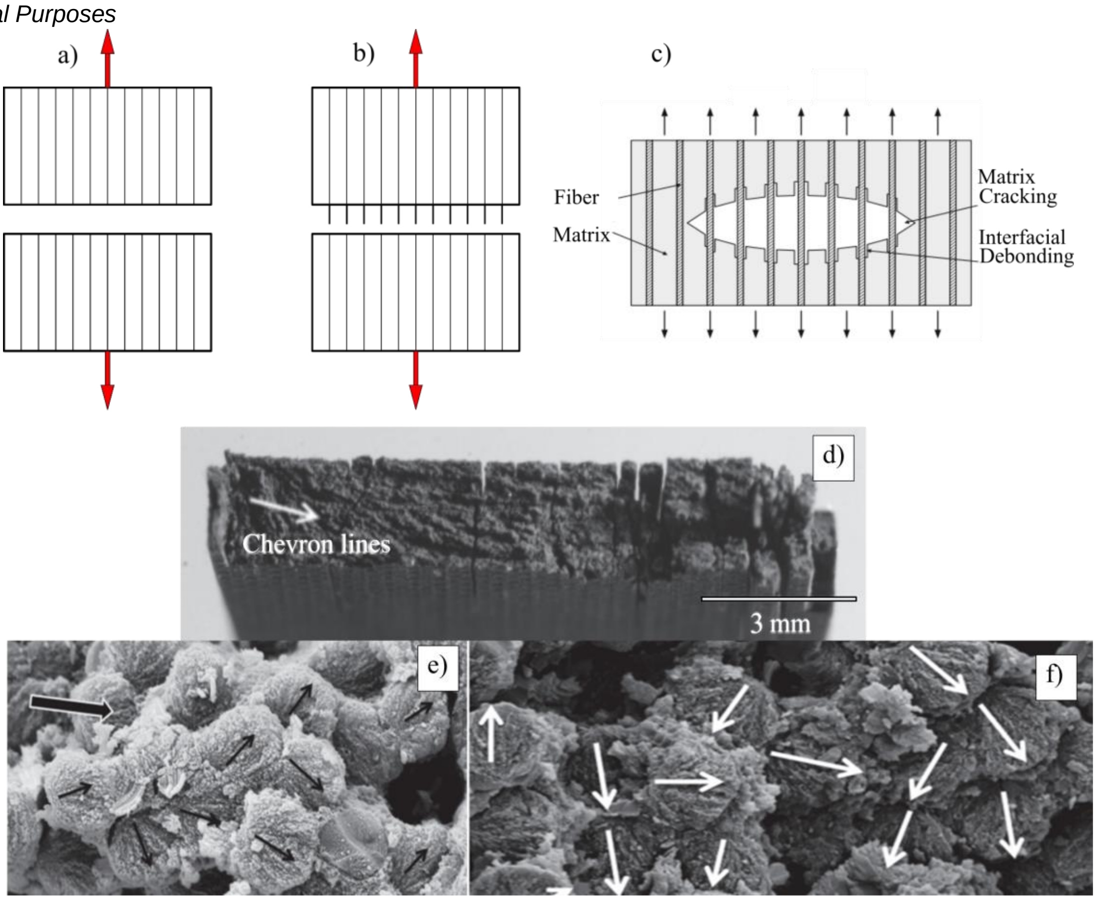

Figure 1 – Longitudinal tensile of composite failure. Adapted from Tiwari (2018), Meng (2015) and Kumar et al (2012)

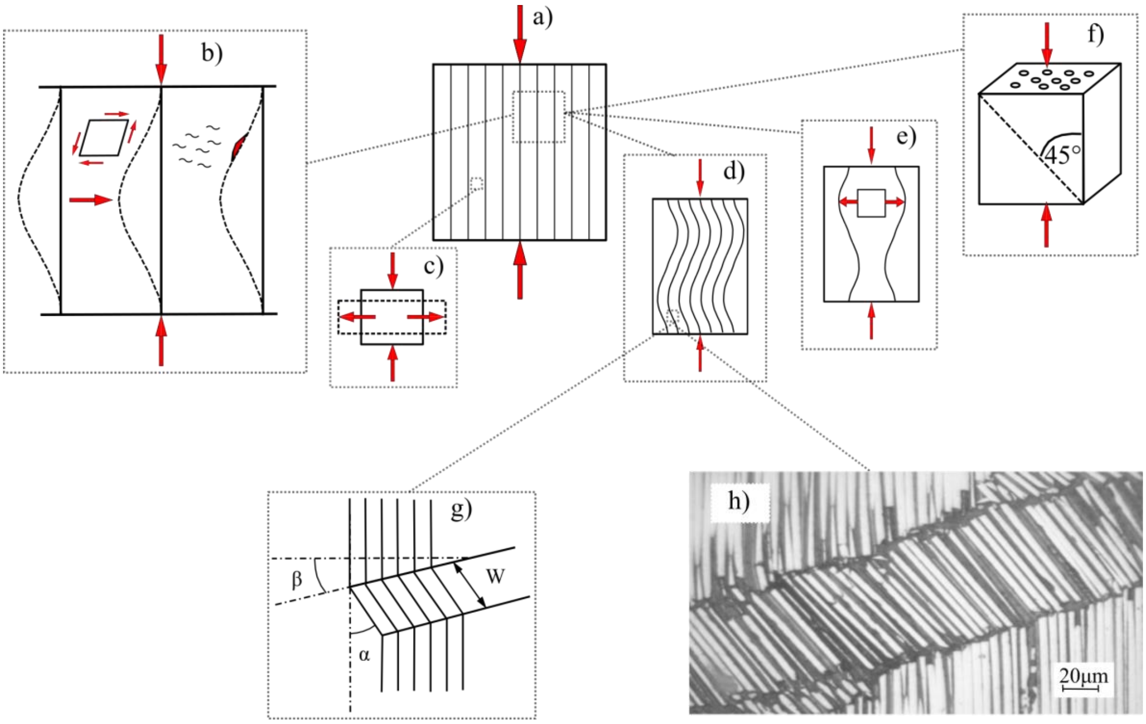

Figure 2 – Longitudinal compression failure mechanisms. Adapted from Tiwari (2018), Giurgiutiu (2016) and Soutis (2008)

In Fig 3 (b) is shown the transverse compression also governing by the matrix shear properties and can present debonding and crushing. Fig 3 (c) presents the in-plane shear, where the matrix failures are parallel to fibers sometimes with debonding. Giurgiutiu (2016) explains as shown in Fig 3 (d) the transverse shear failure, where the matrix and/or the fiber fail by crushing.

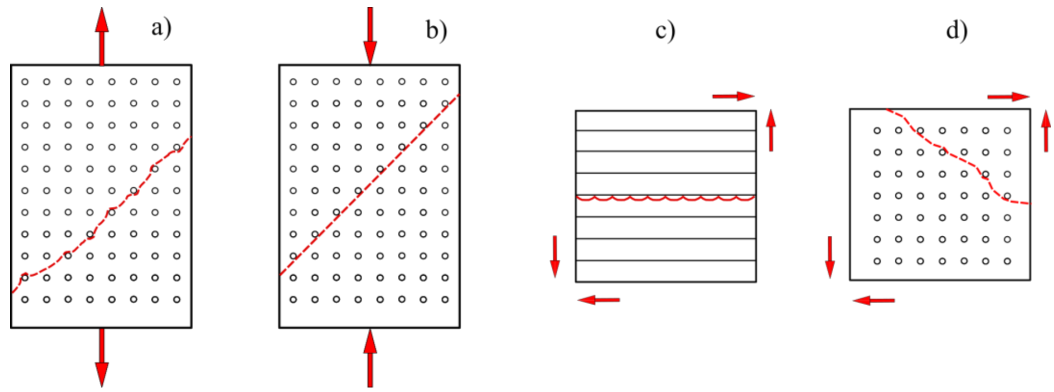

Figure 3 – Others typical failures modes. Adapted from Tiwari (2018), Reifnider (1983) and Giurgiutiu (2016)

COMPOSITES FATIGUE FAILURE

The deformation-life diagram (ε-N) represents the fatigue life of a laminate where εc and εm means deformation of composite and matrix. The unidirectional parallel fiber case shown in Fig 4 (a) and explained in Fig 5, is composed of three parts. The failure mechanism in the region I is governed by fiber breakage on different points, where the local stress or strain applied is greater than supported by the fiber. If the matrix is more brittle as in the case of epoxy, the local stress in the fiber is maintained and then the multiple fractures joint until final failure. Region two is governed by a mixture of mechanism: breaking fibers, debonding and bridging. Region Three remains the steel endurance limit because multiple matrix cracks appear but have not enough driven force to propagate through the fibers or create bridges, but if it occurs is at low rates. Figure 4 (b) shows the strain-life in the off-axis loading case, where cracks initiate anywhere but propagate in the fiber direction until the unstable length of failure.

The region where a crack is propagated and where is not are clearly distinguished using fractography as shown in figure 6. The propagation occurs as function of the stress intensity factor (ΔK), in the matrix, but just until a barrier of propagation (the fiber) as explained previously in Fig 1 (c).

As indicated by Read (1995), "more useful composite materials are formed by the combination of several laminae in various directions" in order to support loads requirements. Figure 7 (a) resume the fractures modes in laminated composites while Figure 7 (b), (c) and (d) are fractographies of interlaminar, intralaminar and translaminar as failures modes.

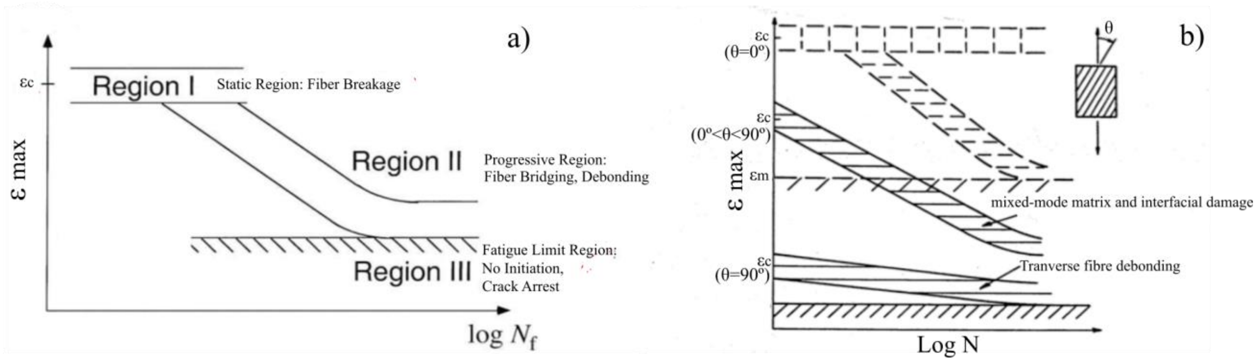

Figure 4 – Strain-Life diagram. a) Unidirectional parallel fiber b) Off-axis unidirectional loading.

Adapted from Talreja (2003)

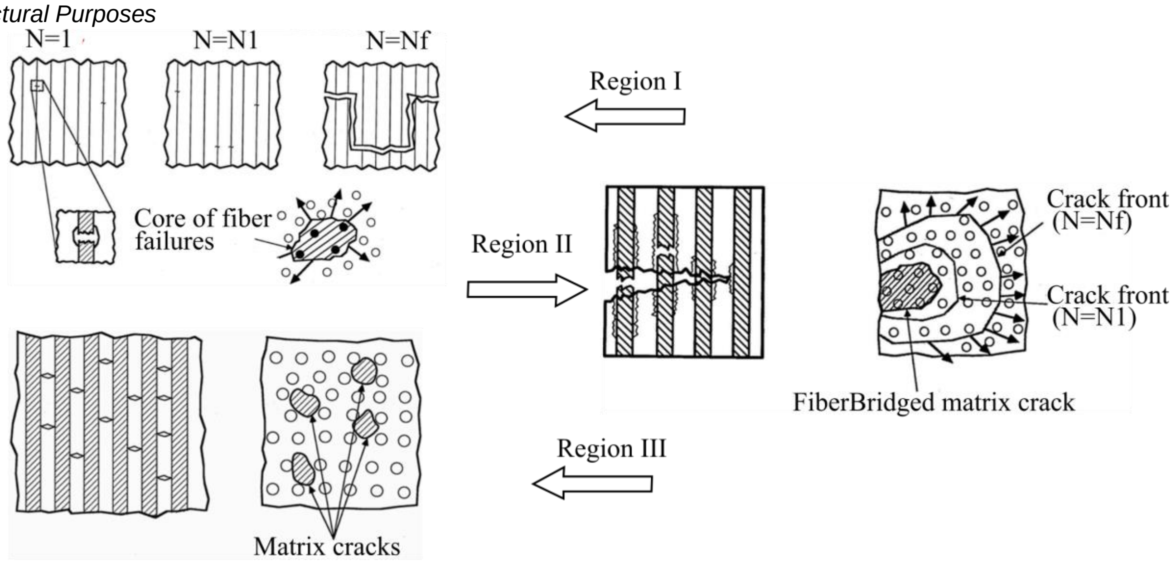

Figure 5 – Failure mechanisms in each region of the strain-life diagram. Adapted from Talreja (2003).

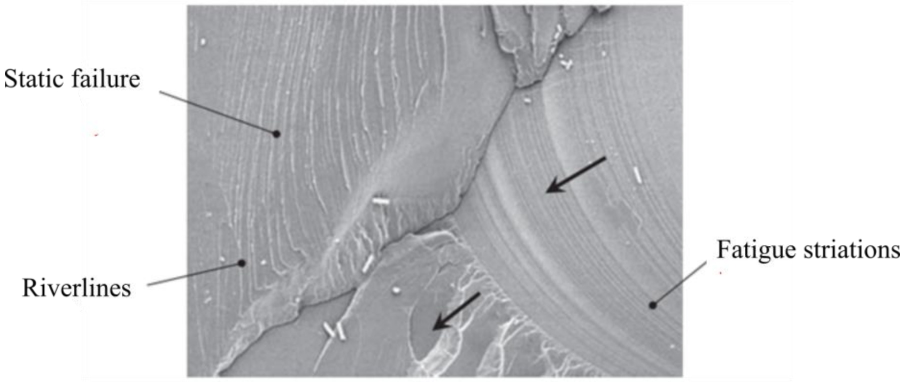

Figure 6 – Fatigue striation and static failure on epoxy fracture surface. Adapted from Greenhalgh (2009)

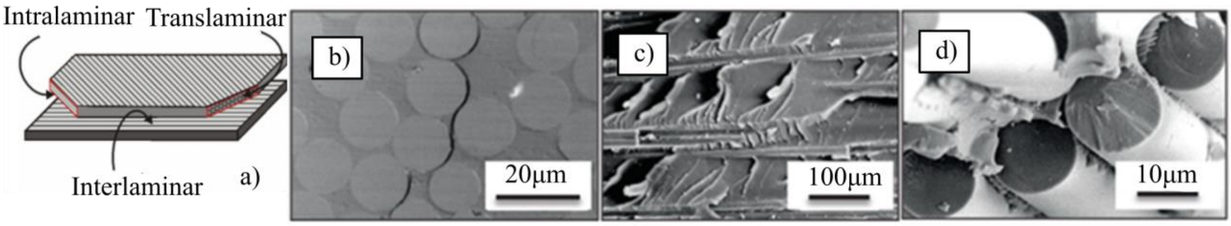

Figure 7 – Fracture modes in laminates composites. Adapted from Jollivet (2015)

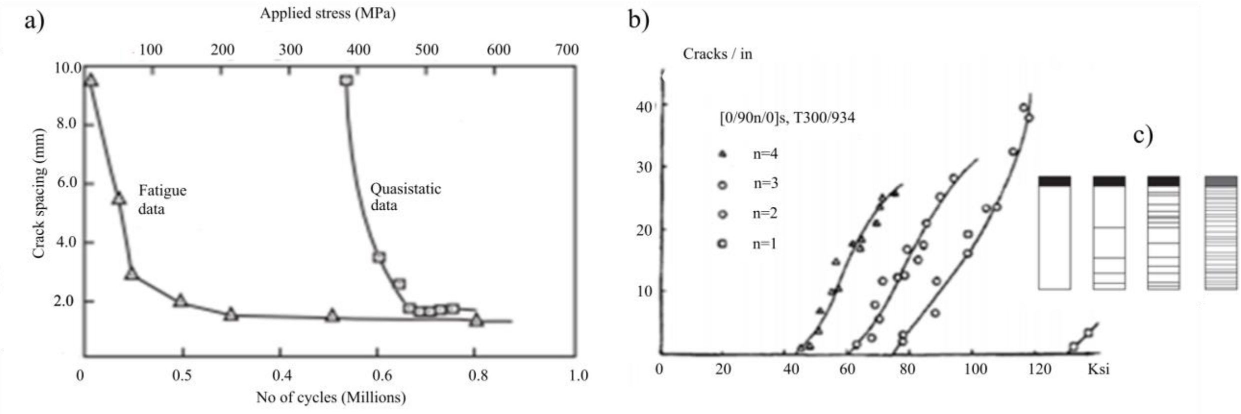

Figure 8 – Examples of characteristic damage state.

a)[0,90,45]s Laminae loaded b) [0,90n,0]s Transverse crack density c) X-ray evidence of CDS by Reifnider (1983)

Reifsnider (1983), proposed the Characteristic damage state (CDS) as a measure of the health state of laminae and remaining life. It was found that the number of cycles in a fatigue test influences the number of cracks in each off-axis ply. The process stops when the ply attains a saturation crack spacing that is characteristic of the material and stacking sequence but the spacing between cracks is virtually identical to the quasi-static case or any fatigue load as shown in Fig 8 (a). Fig 8 (b) shows how CDS change according to the 90° plies number and Fig 8 (c) shows X-radiographs of transverse cracks formation under increasing loading.

According to Chandra (2008), when a composite is loaded in axial tension, each layer has its own stress state as shown in Fig 9 (a), generating intralaminar multiple cracking with its own CDS, as shown in Fig 9 (b).

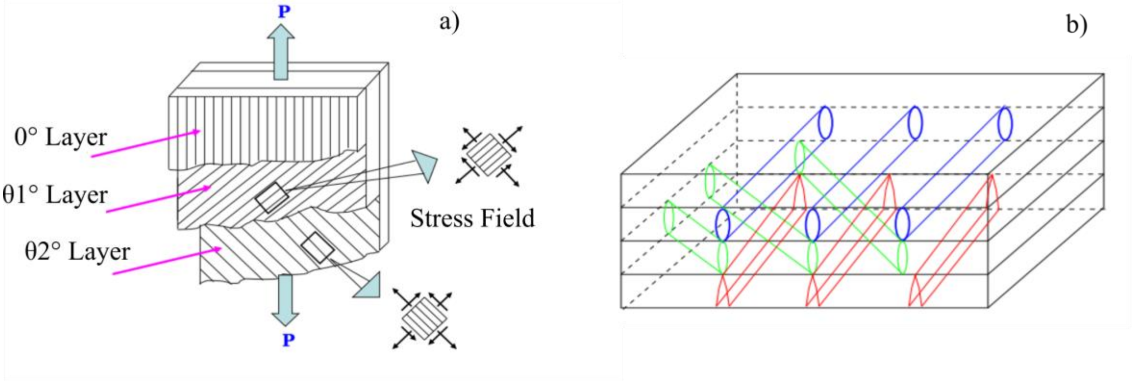

Figure 9 – Generally symmetric composite loaded in axial tension. Adapted from Chandra (2008)

a) Representative volume element **b) Ilustration of multiple cracking in [0,90,θ1, θ2]**

COMPOSITES DAMAGES EVIDENCE USING ELECTRICAL PROPERTIES

For both quasi-static and fatigue loading, some properties such as strain or CDS as shown in Fig 9, are related to the change of other electrical properties as voltage drop or resistance change. For different laminates of CFRP under axial loading has been found that it is possible to calculate the damage or health of the composite, using the change in electrical properties due to the conductivity of fibers in the axial direction.

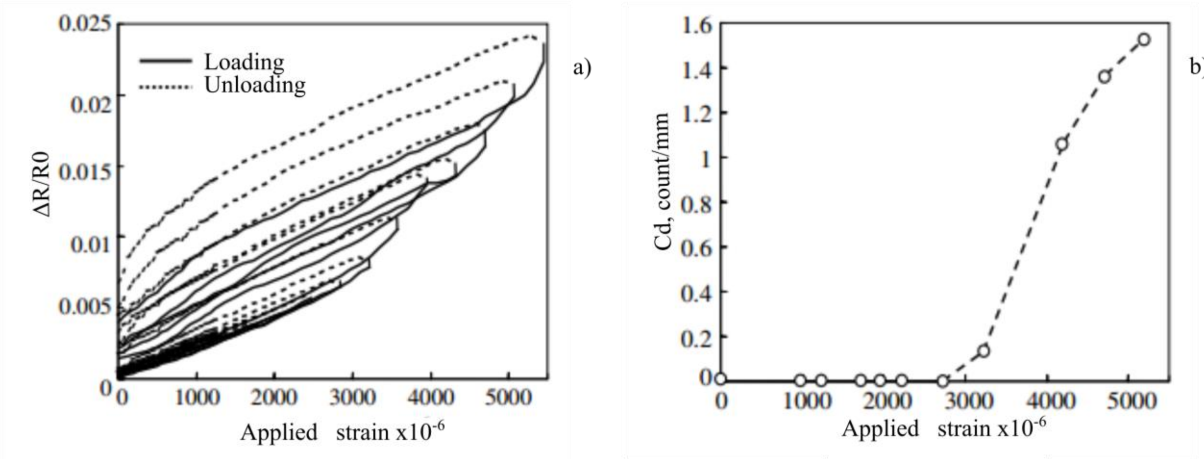

Figure 10 – Composite damage by electrical change method. Todoroki et al. (2005)

a) Applied strain vs resistance change **b) Applied strain vs crack density**

For example as indicated by Todoroki et al. (2005), if is measured the relation between applied strain vs resistance change, as shown in Fig 10 (a) of a $[0/90/0]_T$ ply, and the relation between applied strain vs crack density as shown in Fig 10 (b), its possible to calculate indirectly the crack density of the composite, using its resistance change. A variation of the technique used by Todoroki et al. (2008), is to use the electric potential method instead of resistance change. Fig 11 (a) shows the voltage drop change vs applied strain of a laminate and Fig 11 (b) shows the crack density vs applied strain of different segments in the laminate, in order to calculate the crack density as a function of the change in voltage drop.

Other authors are studying if the change in electrical properties also could be used to know the kind of failure in the composite.

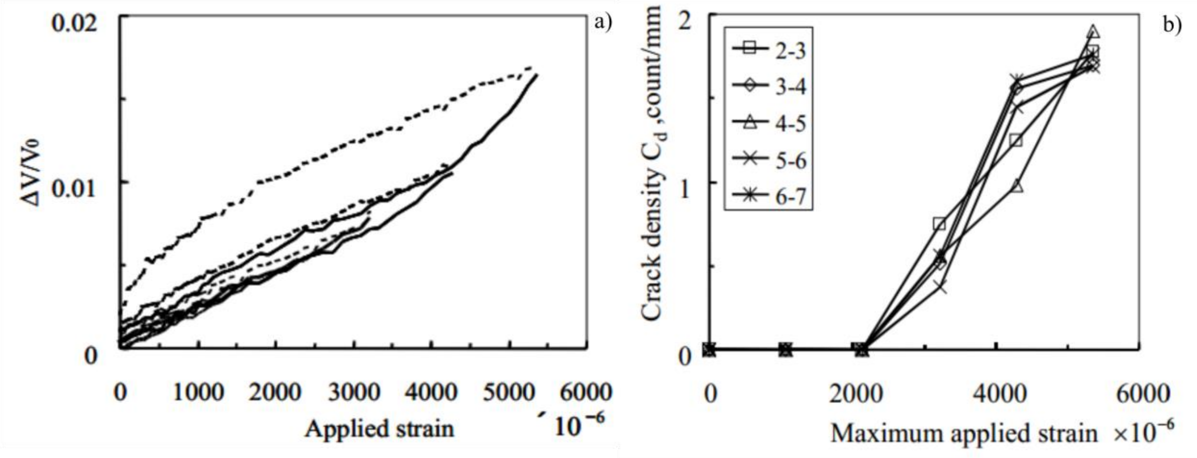

Figure 11 – Composite damage by electrical change method. Todoroki et al. (2008)

a) Applied strain vs potential change **b) Applied strain vs crack density**

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