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FRACTOGRAPHIC ANALYSIS OF CO-BONDED CARBON FIBER REINFORCED COMPOSITES JOINTS SUBJECTED TO MODE I DELAMINATION

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Abstract. *In the last few years, applications of polymer matrix composite material reinforced with continuous fibers in the aeronautics industry have increased in a large scale. This type of material stands out from conventional materials in various aspects, such as low weight and high strength; other benefits are obtained in a secondary way, for instance the decrease in fuel consumption in airplanes and space rockets. However, problems commonly experienced by conventional metallic structures when mechanically jointed by rivets or bolted joints are also observed in composite structures. resulting in stress concentration around holes and fiber discontinuities. Co-bonded joints, on the other hand, offer significant advantages over mechanical fasteners such as weight and cost reduction, improved fatigue life, enhanced strength and durability, and avoid holes to fix fasteners that promotes stress concentration. To better understand the behavior of composite joints, this work aims to analyze the fracture aspects in co-bonded joints tested under Mode I using a Scanning Electron Microscope (SEM). The results explain how the delamination process occurs in this kind of joint and its relationship with the experimental data and mechanical properties.*

Keywords: Fractography, Mode I delamination, Co-bonded joints, Adhesive, Composite, Carbon fiber.

1. INTRODUCTION

In recent years there has been an increase in the use of adhesive in all industries and many factors should be considered during adhesive selection process for a given application, such as high strength, design flexibility, damage tolerance and fatigue resistance (Budhe, Banea *et al.*, 2017). The performance of adhesive joints will depend on parameters such as composite bonding methods, adhesive and adherent properties, adhesive thickness, overlap length, stacking sequence, fold angle, among others (Budhe, Banea *et al.*, 2017).

There are mainly three bonding processes: co-curing, co-bonding and secondary bonding to fabricate the joints between composite substrates (Budhe, Banea *et al.*, 2017).

In this work, co-bonding will be the only one analyzed. The co-bonding process is performed when one adherent plate has already been cured and the other is still uncured; they are joined with the adhesive and the system is submitted to the curing process. Co-bonding is usually preferred over the other types because the number of parts and the curing cycles are reduced (Budhe, Banea *et al.*, 2017).

The ability of a structural laminate to withstand the onset and propagation of delamination failure is evidenced by the interlaminar fracture toughness property of the composite. The verification of this ability is based on the experimental characterization of the Mode I interlaminar fracture toughness (Cândido, Rezende *et al.*, 2012). In Mode I the composites exhibits lower toughness value compared to Mode II and Mode III, and the cleavage of the matrix is the main contributor to the resistance (Greenhalgh, Rogers *et al*., 2009).

One of the essential tools to obtain information and understand how the process of composite failure happens is fractography. With this technique, it is possible to identify the fractographic aspects printed in the topology of the fracture surface and to establish the sequence of events during fracture process, confirming or removing the suspicion on which failure modes have occurred (Cândido *et al.*, 2012; Brooks and McGill, 1994).

One of the problems the aerospace is facing nowadays is the structural repair of composites. Additionally composite materials may be susceptible to damage by mechanical loading, environmental conditions and some accidents, such as birdstrikes. If the damage is not extensive, structural repair is the only viable economic solution (Katnam, Silva *et al.*, 2013).

Co-bonded joints have a good performance in repairs. Similar to a composite, the quality and performance resulting from the co-bonded repairs depend on the processing. After inspection of the damaged area, component repairs involve a series of steps: removal of damaged layers, cured substrate material, surface preparation, patch application and consolidation, post-repair inspection and retouching. If the repair process is inadequate, it can lead to wrinkles, thickness variation and voids (Préau and Pascal, 2016).

In order to classify and characterize failure modes, the ASTM D5573-99 (2002) standard will be used adapted to the previously presented material according to Fig.1.

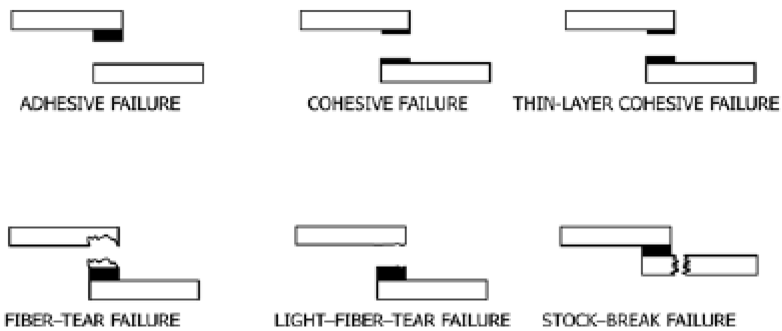

Figure 1. Sketches representing Failure Modes (Adapted from ASTM D5573-99, 2002)

The development of high performance composite aerostructures must comply with several design requirements, such as high strength, impact and interlaminar toughness resistance. The development of these materials required a good quality prepreg with a high strength fiber and a high resistance polymeric matrix. To meet this demand, the polymeric matrix system needs the addition of some compounds, such as thermoplastic particles in its interlayer region. These particles are presented the impact damage resistance of composite laminates. When the composite laminate exhibits some damage that promotes a crack propagation and thermoplastic particles into interlayer provide extra dissipation mechanisms for crack arrestment (Odagir, Kishi *et al.*, 1996). In Figure 2, it is possible to understand where the thermoplastic particles are located.

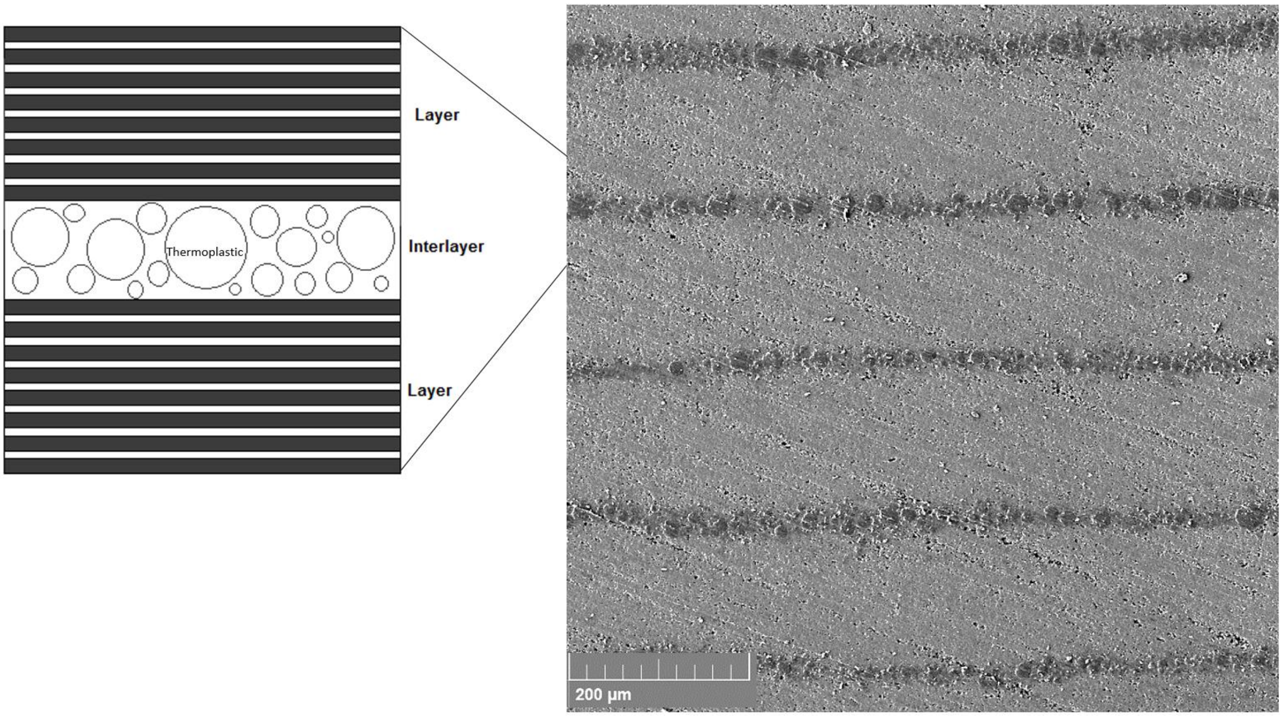

Figure 2: Cross section of a laminate with thermoplastic additive

2. EXPERIMENTAL PROCEDURE

The sample was fabricated with two parts of laminates in the $[0^o]_{13}$ configuration, using Toray® T800/3900-2C unidirectional prepreg and a Loctite® EA9695 adhesive between the two parts. In the co-bonded joints technology (CB), one of the laminates was cured at 177 °C in an autoclave. To form the final laminate, the Peel Ply of the cured plate was removed and the second plate, still uncured, was bonded to it using the adhesive with a polyester net placed in laminate midplane, to maintain the thickness. A Teflon® film was inserted in the same plane of the adhesive to simulate an initial crack. This set up (Fig. 3) was autoclaved and cured at 177 ° C.

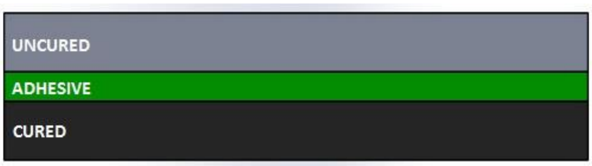

Figure 3. Co-bonded sample

After the manufacturing process, the laminate sample was cut from the plate according to standardized dimensions (170x20x5mm) as described in ASTM D 5528 (2013) to perform the Mode I tests as Fig. 4(a). For this, an Instron® 5500R machine with a 2kN load cell was used. The tests were carried out under displacement control with a constant displacement rate of 1mm/min.

The sample analyzed through the SEM technique was cut in dimensions (45x20mm) which allows the inspection of the whole fracture extension. Then, the sample was cleaned using an ultrasonic bath. After drying, it was metallized with gold using Quorum Q150R metallizer. Finally, the sample was placed in the microscope to be analyzed as shown in Fig.4.b.

Figure 4. (a) Mode I setup configuration and (b) Sample fracture surface.

3. ANALYZES AND DISCUSSIONS

Six samples were mechanically tested in Mode I, but only one sample was analyzed using the SEM, to understand the behavior of the material during the test.

Figure 5 presents an image of the co-bonded sample fracture surface tested under Mode I at room temperature. It can be observed four regions: the initial propagation is an indicative of the delamination beginning that was induced by the Teflon® insert, Fig.5(a); in the first region, Fig.5(b), it can be seen that an unstable propagations occurred between the indicated regions of stable propagation. These areas can be correlated through Fig.6 where it is observed a significant stick-slip like behavior associated with unstable crack growth where the indicated areas are observed.

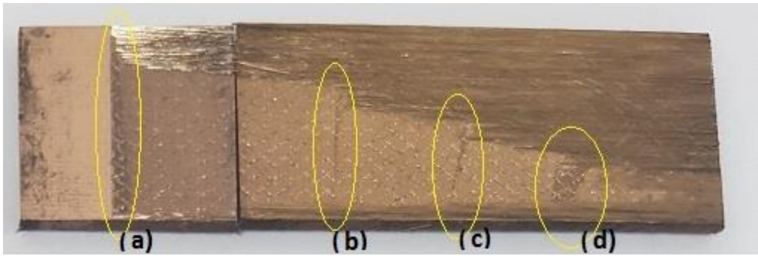

Figure 5. CB sample (a) Initial propagation (b) First region (c) Second region (d) Third region

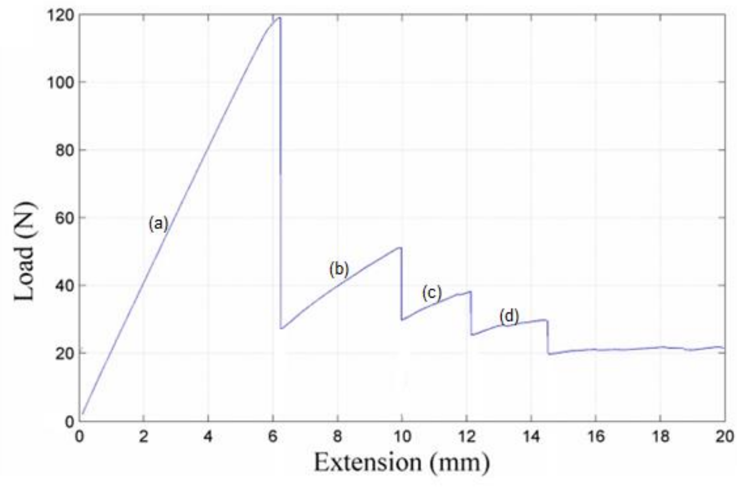

Figure 6. Load versus crack length curve (Brito, Contini *et al.*, 2016)

For a better understanding of the delamination process in CB joint it is necessary to understand deeply the fractographic aspects on the fractured surface. It can be observed that the failure processes were not stable, exhibiting cohesive and adhesive failures. Figure7.a shows the feather appearance, (Cândido, Rezende *et al.*, 2012), indicating the propagation of the failure direction from left to right. In Figure7.b, it is possible to observe the fracture aspects of Fig.5(a), showing a failure change in the adhesive where it is possible to observe a cohesive failure, indicated by yellow arrow, propagating until reach the polymeric matrix forming river marks and scarps (orange arrow).

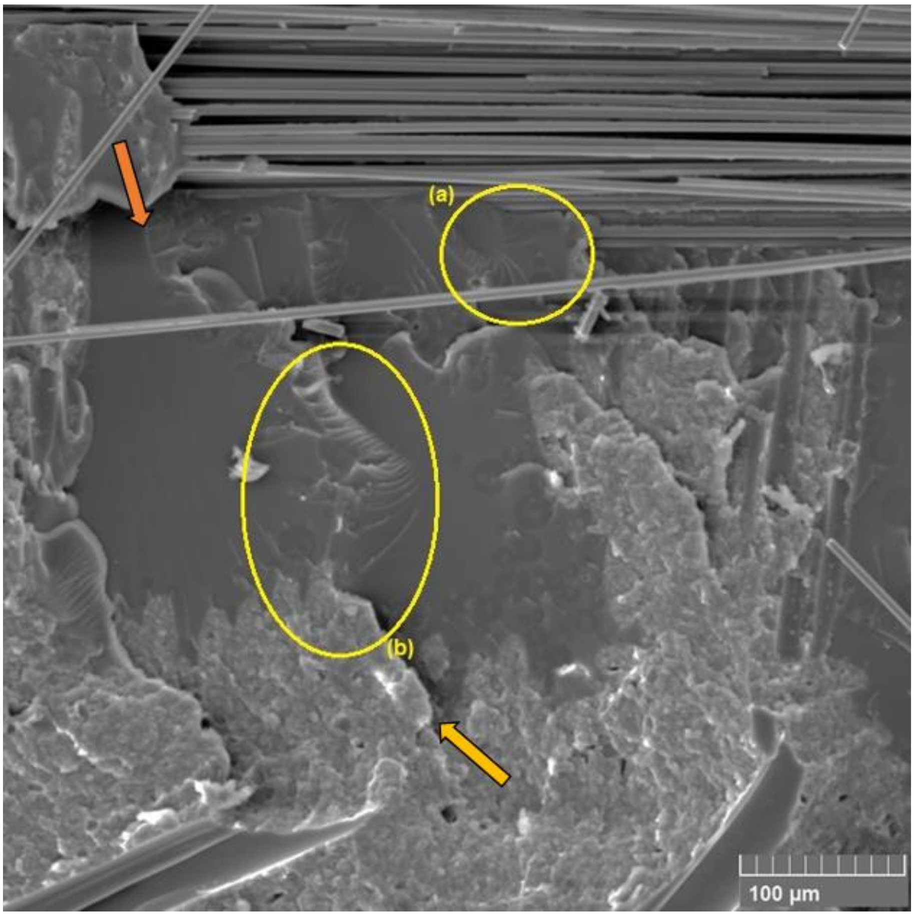

Figure 7. Fracture analysis of the beginning of failure propagation with magnification of 500x (a) Feather model (b) Scarps.

In the others failure regions indicated in Fig.5 (b), (c) and (d), similar aspects are observed. In these regions, there were almost no crack growth as the load increased and reached a critical value of energy release. The crack propagated in an unstable way and the load dropped unexpectedly, creating the larger areas that separate the indicated ones (Brito, Contini *et al.*, 2016). To illustrate what happens in Fig.5 (b), Figure 8(a) shows left-leaning cusps, which indicate the fracture direction: from left to right (Greenhalgh, Rogers *et al*., 2009). In Figure 8(b) is observed a transition that is initially a failure initiated in the adhesive and propagated through the adhesive/adherent, these aspects are named scarps. Another point is the presence of voids, indicated by the blue arrows, which may be present due the volatiles retained during the manufacturing process.

For a deeper analysis of fracture in region presented in Fig.5(c), an enlarged image is shown in Fig.9, The fracture aspects show that a fissure starts (yellow arrow) in the adhesive and crosses a path towards the resin (orange arrow). The same behavior is observed in the regions highlighted by the yellow circumferences. As can be seen, the interface between adhesive and matrix is excellent, so that the propagation that begins in the adhesive travels more easily through the matrix, because the rough adhesive aspect which causes the crack to change the direction of the interface with the matrix.

In the polymeric matrix, it was possible to observe the presence of thermoplastic particles (Sato, Hojo e*t al.*, 2015). The aspect of particles, circles indicated by blue arrows in Fig. 9, is present along the interlayer in the whole delamination extension and the cracks that start in the adhesive surrounding or breaking such particles.

In Figure 10, is possible to see a crack starting in the adhesive (position indicated by the yellow arrow) and traveling along a path towards the resin (position indicated by the orange arrow), passing through the interlayer between adhesive and laminate and reaching the laminate layer where it is possible to observe the fibers impression. After this, the fracture surface presents the same aspect throughout the extent of the delaminated area. In the interlayer, the presence of thermoplastic particles is again observed, where the crack path visibly passes across the particles.

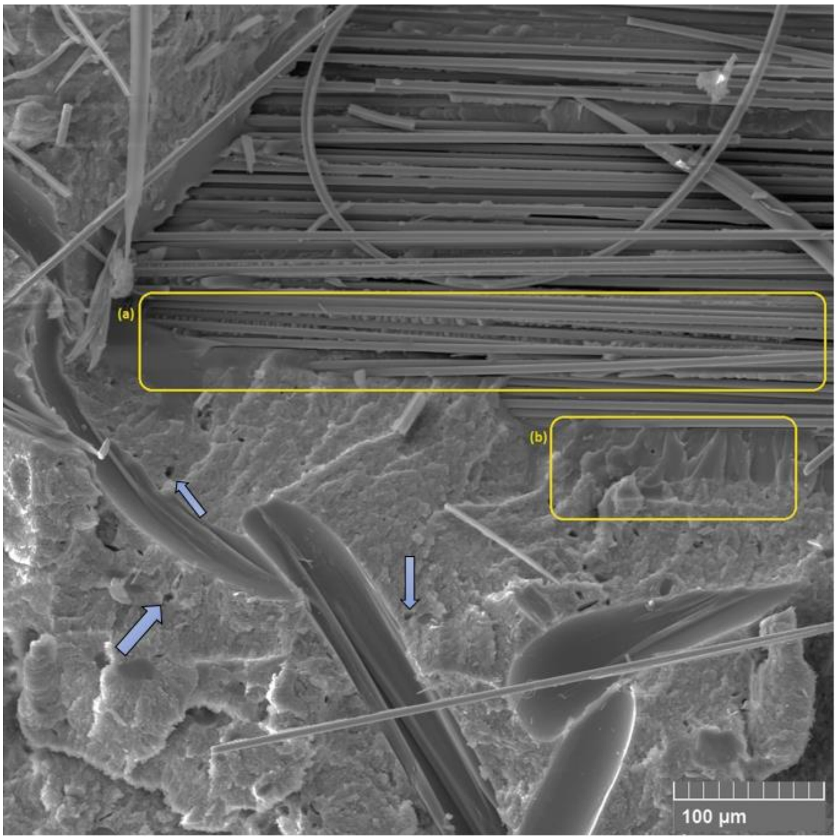

Figure 8. Fracture surface details of region (b) indicated in Fig.5 with magnification of 500x. (a) Left sloping cusps (b) Region between adhesive and resin bag.

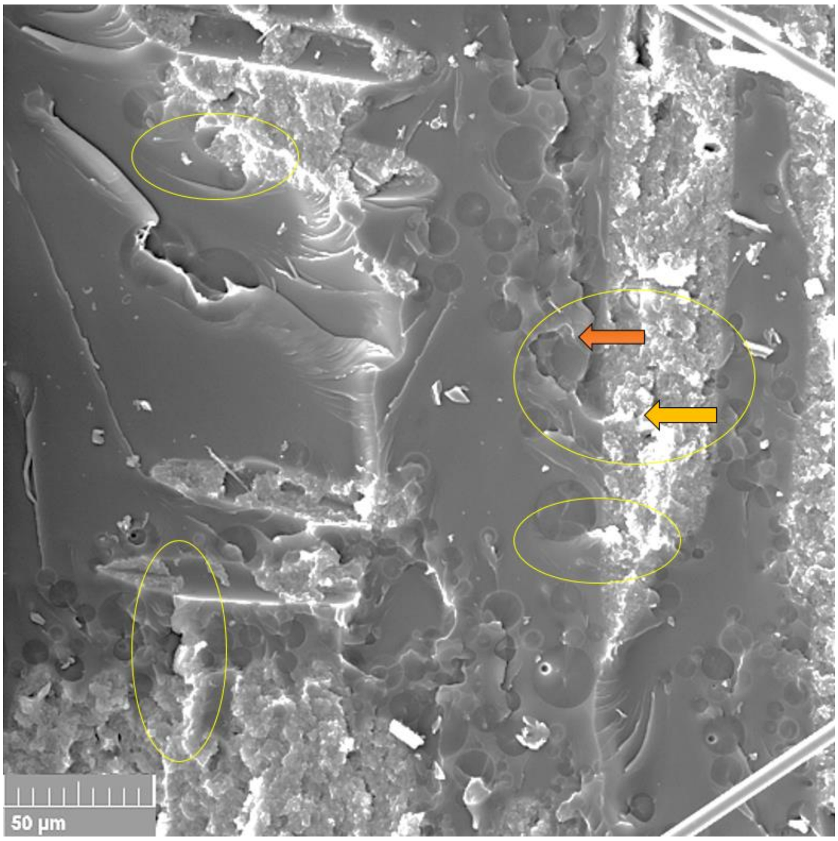

Figure 9. Fracture surface details of region (c) indicated in Fig.5 with magnification of 1000x.

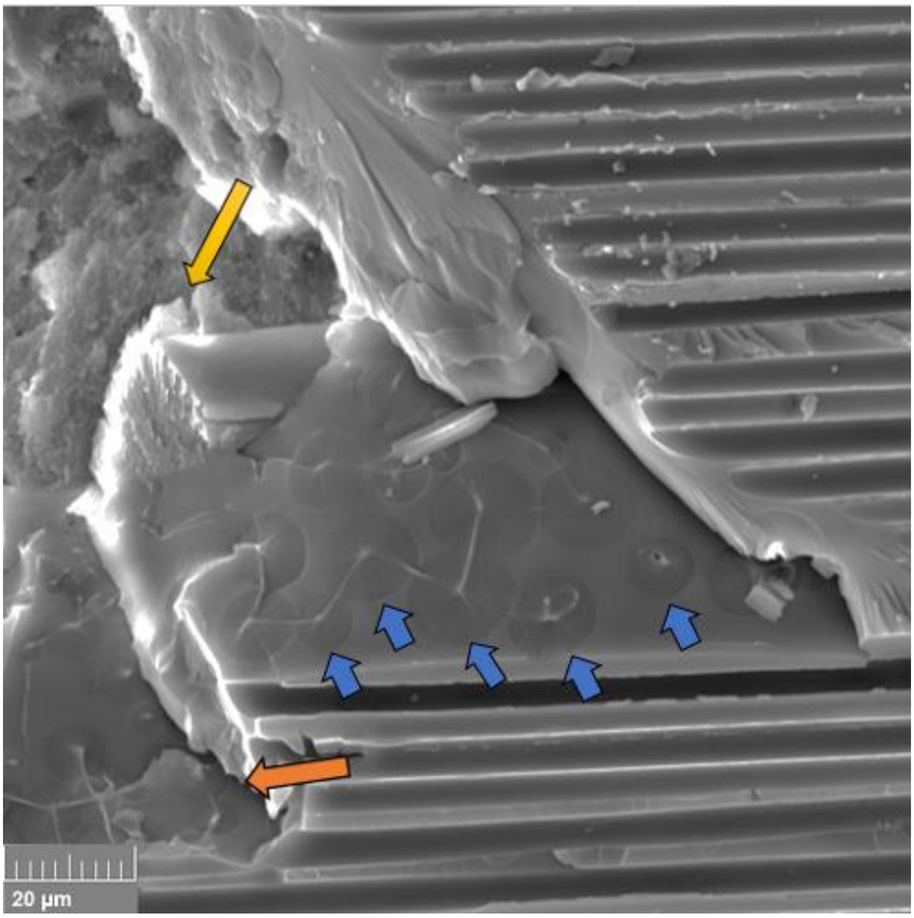

Figure 10: Fracture surface details of region (d) indicated in Fig.5 with magnification of 2000x.

4. CONCLUSIONS

The experimental data obtained from Mode I delamination test were very important to better understand the failure process in co-bonded composite joints. The aspects found in fracture surface were similar, exhibiting an irregular failure pattern printed in the fracture surfaces of the samples.

The fact that crack propagated from the adhesives to the resin as if it was a single material indicates that there was a good interface between the adhesive and the polymeric matrix. Two aspects caused no crack propagation along the adhesive; first, the adhesive had a rough surface, which causes the crack change direction as it grows through the material. The second aspect observed was the thermoplastic particles found along the failure surface, where it was possible to observe that crack passes or turn around the particles and these effects may have caused the change in the crack direction, which should initially take place along the adhesive, however, they were also observed in regions near the carbon fiber tape layer.

5. ACKNOWLEDGEMENTS

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