Microstructural analysis in asymmetric and non-balanced composite cylinders damaged by internal pressure

Gerson Marinucci* , Arnaldo H. P. de Andrade

Science and Technology Materials Centre
Nuclear and Energetics Research Institute

Av. Prof. Lineu Prestes, 2242- ZIP CODE:05598-900- São Paulo- Brazil

Abstract

Damages in matrix and in fibre have been studied in asymmetric and non-balanced composite cylinders that were loaded to failure in mode 2 (unrestrained end) internal pressure, developing an uniaxial state of stress, specifically hoop stress. The samples tested, in a total of five cylinders, were collapsed by internal pressure of 15 MPa. Optical and scanning electron micrography of fractured surfaces of the cylinders are presented and they show that the failures occurred by matrix failures, as debonding, transversal cracks and delamination and fibre failure, as transversal and longitudinal failures. The fracture types and modes were also determined.

Keywords: cylinders, filament winding, hydrostatic test, damage mechanisms.

1. Introduction

One of the benefits that can be obtained by the use of composite materials of continuous filaments, is the advantage that can be taken of its properties on the longitudinal direction. The process to obtain these results, recommended for manufacturing cylindrical and spherical structures, is filament winding. Components manufactured by filament winding can have one of the highest strength-weight ratio among the materials used for structural applications, such as the ones used in aerospace, race cars, nuclear and petrochemical industries.

Continuous reinforced composites can exhibited three types of fracture: intralaminar, interlaminar e translaminar, each one relating the plane of fracture to the plies of the composite and each type of fracture can occur under mode I, mode II and mode III.

Damage analyses of continuous fibre reinforced composites have been the subject of several studies. Many of them describe failure in I-beams [1-2] and in plates [3-9], that were produced in many different configurations, using glass and carbon fibre as reinforcement. The fractographic features in these works were obtained in sheet specimens tested in different loading conditions, such as in tensile, compression, shear, bending, impact and interlaminar fracture in mode I.

* corresponding author:

marinuci@ipen.br

The anisotropy which characterizes the polymeric composites, makes much more difficult the analysis of the failures and the identification of the failure mechanisms. Puck and Schneider [10], on initial work on this subject, present a theoretical and experimental procedure in which GRP (glass fibre reinforced plastics) hoop winding tubes were loaded by pure transverse tension and pure longitudinal/transverse shear. The authors also discuss the cohesive failure and adhesive failure on the tubes.

Tests in cylinders can be classified in three modes, designated as mode 1, mode 2 and mode 3. Mode 1 and mode 2 refer to internal pressure tests. In mode 1, the cylinders have closed-ends, which cause biaxial tension (hoop and axial tension) when loaded, while in the mode 2, the cylinders have unrestrained-ends, which cause uniaxial tension (hoop tension) when loaded. Mode 3, differs from the internal pressure tests, in which it uses a tensile test machine that load the cylinders in axial direction.

Filament winding cylinders subjected to hydrostatic loading can show, as main characteristic of failure evidence, weepage in the external surface of the cylinders. A study that describes the weepage mechanism in pipes with helix angle of 55º, tested according to mode 1 or mode 2 type tests, was carried out by Jones & Hull [11]. They noticed that the occurrence of weepage was due to transverse cracks in the layers of the composite. However, before the macroscopic evidences can be noticed, microscopic internal damages have already occurred. Beaumont & Anstice [12] studied the micromechanisms of fracture in hybrid composites in monotonic loading and Marloff and Raghava [13] examine macroscopic and microscopic failure of a graphite/epoxy composite using biaxial stress tests on filament wound thin wall cylinders with symmetrical layers. Bai *et al* [14] investigated the microstructure of composite tubes by image processing to qualify the microstructural defects produced during manufacturing. Their observations of specimens loaded to 20-50% of the ultimate tensile strength showed that the main damage initiation mechanisms were microcracking and delamination.

Studies on polymeric composites are wide-ranging but proportionally there are less work done on fractrographics analyses of cylinders that show simultaneously hoop and helical layers (angle-ply).

In this work, microstructural analyses were performed in composite cylinders with hoop (90º) and helical (25º) winding to characterize the failures that occur in the matrix and in the fibre after the collapse in hydrostatic tests. The cylinders show an non-balanced and asymmetric construction and were collapsed by a pressure of 15 MPa using a monotonic loading. Analyses were also performed to determine the types and modes of fracture in the cylinders after collapse.

2. Materials and experimental details

The cylinders were manufactured by a filament winding technique with no pressure barrier (liner), therefore, the structural plies were wound around a cylindrical mandrel, and they are open at the ends, that is, with no domes. The hydrostatic test device was built in a way that the cylinders can move in the axial direction during the test. The samples were tested in mode 2, in which the hydrostatic pressure produce circumferential loading, causing therefore only uniaxial state of stress (hoop stress) in the composite structure.

Interweaving method was used for the construction of the helical layers. In this method, each complete cover of the mandrel represents in fact two layers over the mandrel, this means, one layer at +θ and another at -θ, where θ represents the winding angle related to the axis of the mandrel.

Five cylinders were made using carbon fibre T300 with 6000 filaments and epoxy-anhydride system was used as the matrix. The cylinders were identified as C1 to C5 and the stacking sequence used was $[90^{\circ}/\pm 25^{\circ}/90^{\circ}/\pm 25^{\circ}/90^{\circ}_{2}]_{T}$. Thus, the cylinders have a non-balanced and asymmetric structure related to the 90º intermediate layer.

After the collapse, the cylinders loose completely their structural integrity, which makes extremely complex to obtain samples for analysis in the scanning electron microscopy (SEM). In this case, special care must be taken not to introduce extra damage by the cutting action. Equipment with cutting disks, even with synthetic diamond, is not recommended for this work. So, a laser method was used to cut fractured areas. This method of cutting polymeric composites is not yet disseminated. Preliminary work had been done to establish cutting parameters [15].

For the SEM analyses performed in this work, laser cutting allowed to obtain samples from fractured areas, as it is shown in figure 1, that were extremely difficult to access, even when using pneumatic and manual tools.

Figure 1- Macroscopic aspect of the cylinder C1 after the collapse.

Due to the polymeric component in the composite cylinder, a deposition of a thin layer of gold and paladium were sputtered onto the fracture surfaces using Au/Pd cathode to minimize static charging by the SEM electron beam

3. Results and discussion

An examination of the collapsed cylinders show different failure modes, as shown in figure 1. Macroscopically, there is evidence of a long longitudinal crack, having a translaminar fracture in mode I. This failure is characteristic of structures that are loaded only in tensile stress in the hoop direction under hydrostatic pressure. The failure opened the cylinder in the longitudinal axis from one end to the other.

In spite of pure uniaxial hoop loading, evidences of shear tension were observed in planes of maximum shear stress, causing helical cracks at 45º in relation to the cylinders axis, as shown in figure 2. This phenomenon may have increased by the stacking sequence used to build the cylinders, which resulted in non symmetrical geometry, that caused undesirable bending and torsional effects. These effects can be anticipated by a mathematical analysis presented by Jones [16], due to the presence of the coupling matrix (named as matrix [B]), that appears as a consequence of the asymmetry. The presence of the matrix [B] in the mathematical analysis, shows that the loading could not have only produced extensional and shear deformations but also bending and torsion deformations in the structure.

Figure 2- Helical cracks in the cylinder C3.

Thin wall cylinders built with multiple layers, develop a hoop stress that is higher in the internal surface than in the external one. This leads to the reasoning that the fracture would start in the inner helical layer, because this layer is the first one to exceed the strength limit of the composite, decreasing the structure capacity to stand loads. The layers, that do not fracture, then start to be submitted to increase loads put in the cylinder. This will lead to the fracture of the other layers, when again the loads create stresses higher than the strength limit of these layers. The collapse will happen when the strength layers, which have not been fractured yet, start to fracture. Though, before this, some microscopic damages are accumulated in the matrix, in the fibres and in the interfaces.

Microscopic damage in the matrix is related to intralaminar and interlaminar failures. Intralaminar failures are those related to debonding, caused by failure adhesion between fibre/matrix interface, and transversal cracks, that occur transversally to the load direction. Interlaminar failures are those related to delamination.

Helical layers usually tend to present matrix failure. This is due to the loading component in the transversal direction to the fibres that leads to tension in this direction. In this case, the fibres behave as descontinuities in the matrix, producing stress concentration, that will cause debonding in the fibre/matrix interface and microcracks transversal to the loading direction. Figures 3 and 4 show respectively a debonding failure in the cylinder C2 and a transverse crack in the cylinder C4, both occurring in helical layers of 25º, characterizing an interlaminar failure.

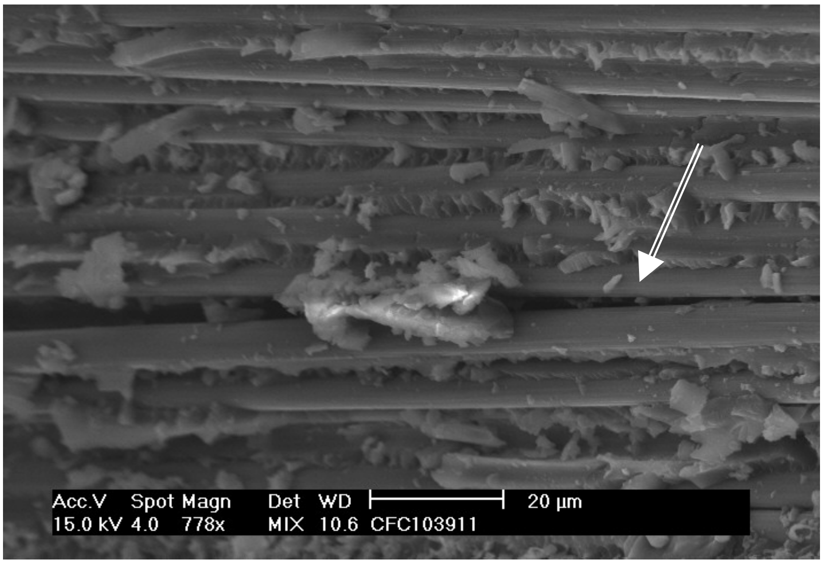

Figure 3- Debonding effect in the helical layer of 25º of the cylinder C2.

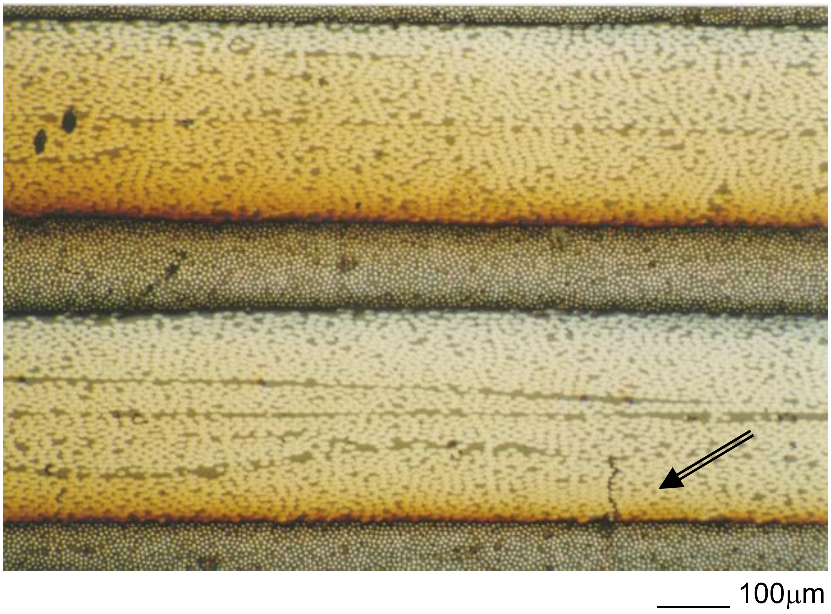

Figure 4- Transverse crack in the matrix of the cylinder C4 (first helical layer).

Delamination from interlaminar failure is the worst damage that can occur in a composite, because once it happens it does not find a barrier to avoid its progress. In many studies involving polymeric composites, the authors assume a state of plane stress and consider only the tension σ_{xx}, σ_{yy} and τ_{xy} or in the cylindrical coordinates $\sigma_{\theta\theta,}$ σ_{zz} and $\tau_{z\theta}$. In fact, because the layers show different elastic constants in a hybrid composite and/or different stiffness matrix, when they are arranged among themselves according to different angles related to the global axes, there is the possibility of displacement between adjacent layers of the composite after loading. The shear stress $\tau_{r\theta}$ and τ_{rz} which arises between the layers and strongly in the layers close to the ends of the cylinders (free edge effects), lead to the consideration, mainly in this region, of the classical model of tridimensional state of stress, as shown in figure 5. These shear stresses, when higher than the strength of the interlaminar layer, can produce cracks in the cylinder, which propagates through the interface causing delamination. Figure 6 identifies a failure by delamination between the helical layer of 25º and the hoop layer of 90º, characterizing an interlaminar failure. The arrow indicates the path of cracking. Figure 7 exhibits a micrography of a transversal section of one of the cylinders after the collapse, showing the delamination phenomenon in all of the composite layers.

While damage occurs progressively in the matrix, the fibres, which control the strength limit of the composite, also suffer fracture. Initially, there is no meaningful loss of strength but a concentration of stress in the neighbors filaments. The breakage of filaments can occur due to the effect of loading or even during the polimerization due to the phenomenon of matrix contraction, that can cause tensile and compressive stresses in the filaments. It is also necessary to consider that during the manufacturing some breakage can occur due to physical contact of weak filaments with the metallic components of the winding machine.

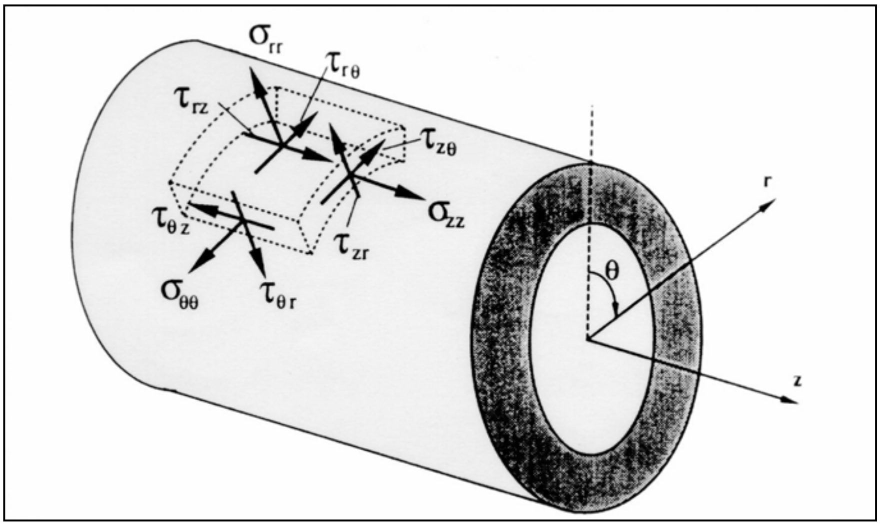

Figure 5- Illustration of the tridimensional state of stress in the cylinders.

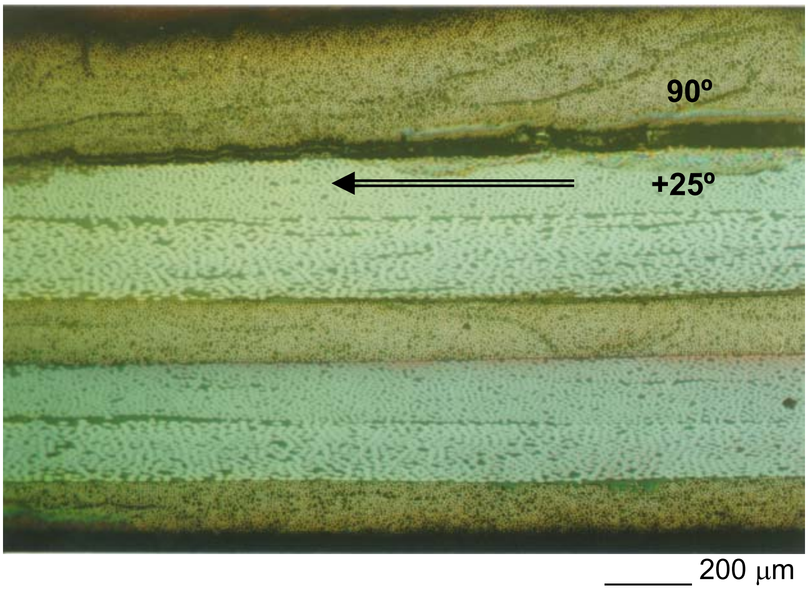

Figure 6- Delamination between the helical layer of 25º and the hoop layer, in a sample of the cylinder C4.

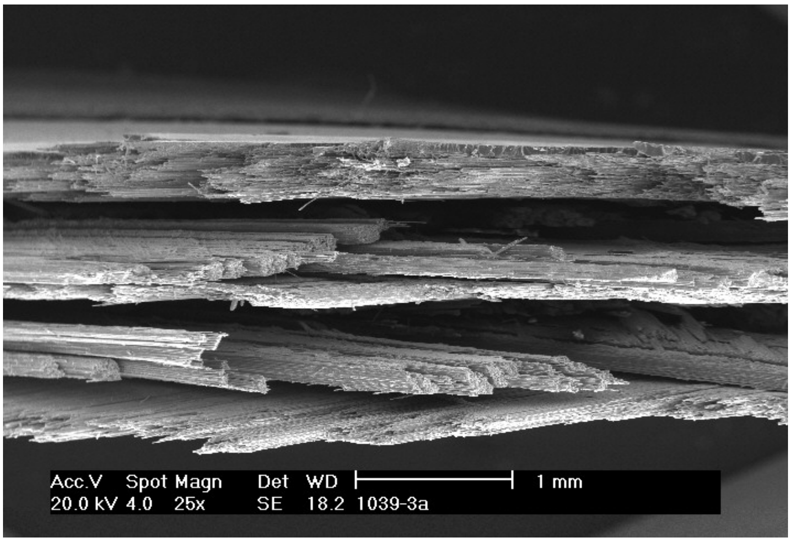

Figure 7- Photomicrographs showing the transverse section of the cylinder C5, outstanding the delamination among the layers.

Fibres fracture in the direction of the main tension is the worst damage that can happen to polymeric composites that use continuous filaments, as they are effectively responsible for the structural strength of the composite. Figure 7 shows the layers, in the ascending order, totally separated in a clear indication of shear interlaminar failure of mode II.

One example of fractured filaments in hoop direction is shown in figure 8. This figure shows the intermediate layer of 90º of a sample of cylinder C1. The breakage of filaments (f) caused some cracks in the matrix (m), producing localized debonding (d). If these cracks had continued along the filament they would have resulted in an increased debonding effect at fibre/matrix interface, eliminating the capacity of these filaments to withstand the loading. In this region, eventually due to the increased loading, a stress concentration could occur, causing the failure of filaments that are in the nearest neighborhood, which eventually would result in the failure of the layer. A model proposed by Bader [17] to explain failure behavior of uniaxial fibre composites is shown in figure 9.

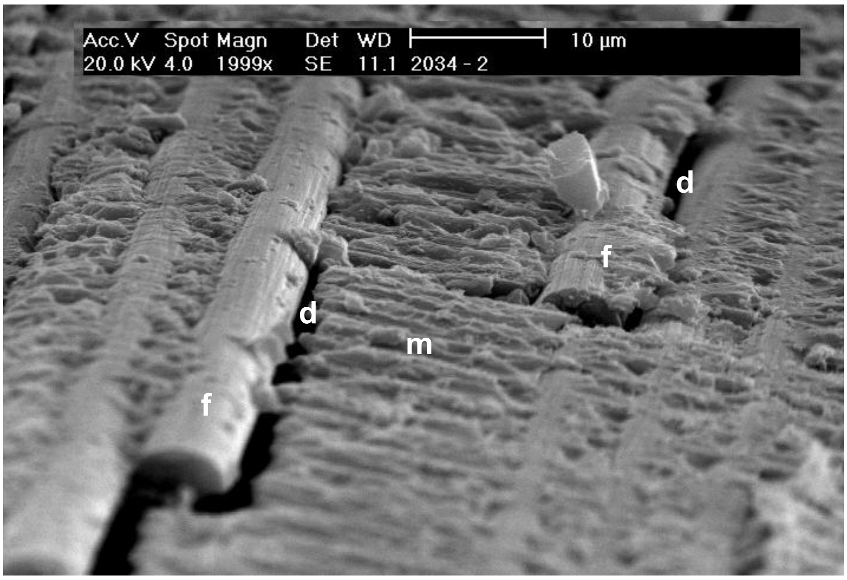

Figure 8- Fractured fibre in the hoop layer of cylinder C2.

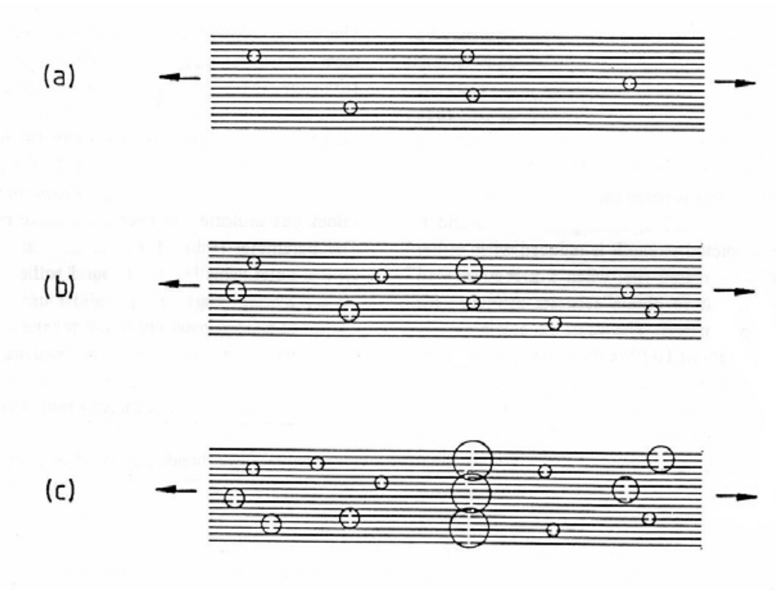

Figure 9- Schematic failure sequence for the brittle fracture mode [17].

Although the fracture of the fibres begins in the inner helical layer, causing failure of the filaments by transverse tensile stress, composites that have a good bonding interface show a feature, named by Purslow, in his work with plates, wavy radial patterns [6]. Figure 10 exhibits an example of an intralaminar failure caused by transverse tensile stress in cylinder C5.

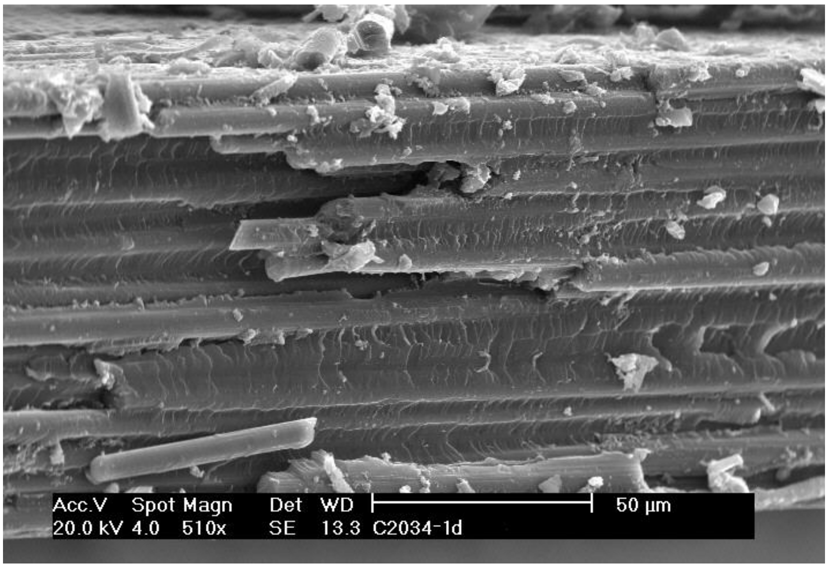

Figure 10- Failure due to transverse stress in the cylinder C3.

Damages accumulate in the matrix and in the interfaces between layers, as well as in the fibres in the helical direction (25º). So, with increased loading, all these micromechanisms of failure become active in multiple areas, not necessarily at the same time. These multiple failures finally lead to the fracture of the fibre in the hoop direction leading to the cylinder failure.

4. Conclusion

Fractured surfaces were analyzed by optical and scanning electron microscopy. Matrix failures, as debonding, transversal cracks and delamination, were observed in the samples. The main characteristic, in relation to the fibre, observed in the micrographic study, is failure in the helical layers due to transversal tensile stress and failure in the hoop layers due to the hoop tensile stress. Failures in hoop layers show a longitudinal crack as a macroscopic evidence.

Failures occurred in multiple types and modes, although none of them on their own was dominant in the fracture process. In the translaminar failures, modes I and II were predominant, while in the interlaminar failure, mode II was predominant.

The macroscopic aspect of the fracture gives evidence of the brittle fracture of the composite.

Acknowledgements

The authors acknowledge the technical support of CTMSP-Centro Tecnológico da Marinha em São Paulo and the financial support of FAPESP- Fundação de Amparo à Pesquisa do Estado de São Paulo.

References

[1] Purslow., D. Composite fractography without an SEM –the failure analysis of a CFRP I-beam. Composites, 1984, 15(1)43:48.

[2] Gilchrist, M. D. ; Kinloch, A. J. ; Matthews, F. L. Mechanical performance of carbon-fibre and glass-fibre reinforced epoxy I-beams: II. Fractographic failure observations. Composites Science and Technology, 1996, 56:1031-1045.

[3] Morris, G. Determining fracture directions and fracture origins of failed graphite/epoxy surfaces. 1979, ASTM-STP 696, 274-297.

[4] Purslow, D. Some fundamental aspects of composite fractography. Composites, 1981, 12(4):241-247.

[5] Bascom, W. D. ; Boll, D. J. ; Fuller, B. ; Phillips, P. J. Fractography of the interlaminar fracture of carbon-fibre epoxy composites. Journal of Materials Science, 1985, 20:3184-3190.

[6] Purslow, D. Matrix fractography of fibre-reinforced epoxy composites. Composites, 1986, 17(4):289-303.

[7] Shikhmanter, L. ; Eldror, I. ; Cina, B. Fractography of unidirectional CFRP composites. Journal of Materials Science, 1989, 24:167-172.

[8] Shikhmanter, L. ; Cina, B. ; Eldror, I. Fractography of multidirectional CFRP composites tested statically. Composites, 1991, 22(6): 437-444.
[9] Shikhmanter, L. ; Cina, B. ; Eldror, I. Fractography of CFRP composites damaged by impact and subsequently loaded to failure. Composites, 1995, 26(2):154-160.
[10] Puck, A.; Schneider, W. On failure mechanism and failure criteria of filament-wound glass fibre/resin composites. Plastic & Polymer, 1969, 37: 33-43.
[11] Jones, M.L.C.; Hull, D. Microscopy of failure mechanisms in filament wound pipe. Journal of Materials Science, 1979, 14:165-174.
[12] Beaumont, P. W. R.; Anstice, P. D. A failure analysis of the micromechanisms of fracture of carbon fibre and glass fibre composites in monotonic loading. Journal of Materials Science, 1980,15: 2619-2635.
[13] Marloff, R.H.; Raghava, R.S. Failure analyses of filament wound graphite/epoxy cylinders under biaxial loading. SAMPE Quarterly, 1985, 17(1):40-45.
[14] Bai, J. , Seeleuthner, P. ; Bompard, P. Mechanical behaviour of ±55º filament-wound glass-fibre/epoxy resin tubes: microstructural analyses, mechanical behaviour and damage mechanisms of composite tubes under pure tensile loading, pure internal pressure and combined loading. Composites Science and Technology, 1997, 57:141-153.
[15] Marinucci, G. Study of laser cutting parameters in carbon fibre reinforced composites. Brazilian Navy Technology Centre, internal report, 1999.
[16] Jones, R.M.- Mechanics of Composite Materials. Scripta Book Company, 1975.
[17] Bader M.G.- Tensile strength of uniaxial composite. Science and Engineering of Composite Materials, 1988,1: 1-11.