J-INTEGRAL VERSUS CTOD δ_5 FRACTURE TOUGHNESS OF UNIDIRECTIONAL FIBRE-METAL LAMINATES

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***Abstract**: Fiber-metal laminates are structural composite materials developed for aeronautical applications. The most important application of these materials is in parts of the upper fuselage of the new Airbus A380. The application of fiber-metal laminates to structures demands a deep knowledge of a wide set of properties, including fracture toughness. The objective of this work was to evaluate the effect of crack orientation on the relation between critical J-Integral and CTOD δ_5 fracture toughness of unidirectional Arall laminates. Small C(T) specimens with notches parallel and perpendicular to the fibers direction were tested. A study of the relation and equivalence between J_C and δ_{5C}, which heavily depend on the yield strength and on the stress state, was performed motivated by apparently contradictory experimental results. These results can be explained by the direction-dependent yielding properties of Arall laminates. The best equivalence between J_C and δ_{5C} was obtained considering plane stress state and using the effective yield strength, both for Arall laminates notched parallel and perpendicular to the fibers direction.*

***Keywords**: Arall, Fiber-Metal Laminates, Fracture Toughness, J-Integral, CTOD δ_5.*

1. Introduction

Unidirectional Arall® laminates belong to the first generation of fiber-metal laminates (FMLs). They were created and developed for aeronautical applications at the Technical University of Delft, Netherlands [1][2]. The main characteristic of these laminates, which are reinforced by unidirectional aramid fibers, is their very low fatigue crack propagation rates if compared to traditional aeronautical Al alloys. This singular behavior arises from the fiber-bridging mechanism, which restricts the opening of the crack in the loading part of the fatigue cycle, thus diminishing the crack growth rate [3][4]. Although fiber-metal laminates were basically developed taking advantage of the bridging mechanism, they also present several additional benefits over the monolithic alloys, i.e. higher specific strength and resistance to corrosion, lightning strikes, impact, and flame penetration [5]. Glare laminates, which are an evolution of Arall ones and reinforced by S2 glass fibers, are being used in large parts of the upper fuselage of the Airbus A380 [2][3]. Arall laminates have been used in several secondary applications, including doors, flaps skin and covers [6]. In all the cases the fiber reinforcement could be oriented following the loading characteristics of the structure [5]. Fiber-metal laminates are produced with different lay-ups of the type m/n, with m layers of aluminum bonded by n fiber-epoxy prepreg layers ($m = n + 1$) and can be manufactured as thin sheets of dimensions either similar to those of the commercial Al alloys or with larger dimensions, including low complexity shapes and double curvature panels [5]. Figure 1 illustrates an Arall laminate of lay-up 3/2.

The application of FMLs to aeronautical structures demands a deep knowledge of a wide set of mechanical properties, including their fracture toughness [7]. Recently, a testing methodology to evaluate the fracture toughness of FMLs based on elastic-plastic fracture mechanics (J-Integral and CTOD of Schwalbe, δ_5) and using small C(T) and SE(B) specimens was proposed [8]. Following this methodology the fracture toughness (J_C, δ_{5C}) is calculated at a critical point corresponding to the occurrence of either full or partial instabilities (similar to pop-ins) or at the beginning of the maximum load plateau.

The objective of the present work was to evaluate the fracture toughness of unidirectional Arall laminates with notches parallel and perpendicular to the fibers direction. Additional discussion was developed on the dependence of the fracture toughness on crack orientation and on the relation and equivalence between the parameters used for toughness evaluation (J-Integral and CTOD δ_5), which strongly depend on the yielding properties.

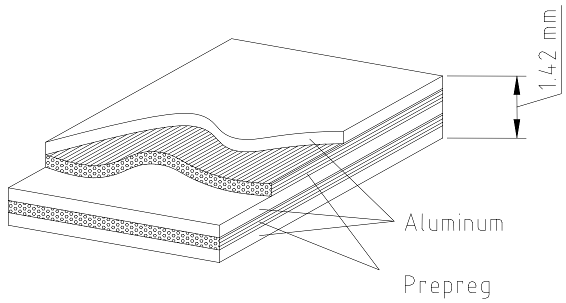

Figure 1 - Schematic representation of 3/2 Arall laminates.

2. Materials and Methods

Unidirectional commercial Arall 2 and Arall 3 laminates, with fibers oriented parallel to the rolling direction of the Al layers (0.3 mm in thickness), were tested. Arall 2 was tested in lay-up 3/2, whereas Arall 3 was tested in lay-ups 2/1, 3/2 and 4/3. Arall 2 is made of 2024-T3 alloy. Arall 3 is made of 7475-T76 alloy and is subjected to a permanent stretch after curing for reversing undesirable residual stresses, improving their fatigue resistance [1][2]. Tensile yield and ultimate strength in the fibers direction, as well as other characteristics of those laminates are presented in Table 1 [9]. In that table the effective yield strength (σ_Y), as defined by ASTM [10] and calculated by the following equation is also shown.

$$\sigma_Y = \frac{\sigma_{YS} + \sigma_U}{2}\,, \tag{1}$$

where σ_{YS} is the tensile yield stress and σ_U is the ultimate tensile stress.

Table 1 – Mechanical properties of the tested FMLs [9]

FML		Arall 2	Arall 3		
Lay-up		3/2	2/1	3/2	4/3
σ_{YS} [MPa]	L	337.0	524.0	565.0	565.0
	T	206.0	331.0	269.0	289.0
σ_U [MPa]	L	662.0	710.0	765.0	786.0
	T	303.0	386.0	351.0	344.0
σ_Y [MPa]	L	499.5	617.0	665.0	675.5
	T	254.5	358.5	310.0	316.5
$E_{tensile}$ [GPa]	L	68.0	67.5	68.2	68.9
	T	52.0	53.1	48.9	46.2
v	LT	0.34	0.35	0.35	0.35
	TL	0.27	0.25	0.25	0.25
G [MPa]	LT	17.2	19.3	17.9	15.8
	TL	16.5	17.9	16.5	15.8
Density		2.30	2.35	2.30	2.27
Thickness [mm]		1.35	0.82	1.34	1.83
Metallic vol. [%]		67.9	73.8	67.9	65.3
Pos-stretching [%]		0.0	0.4	0.4	0.4

Observations: L orientation means parallel to fibers direction. T orientation means perpendicular to fibers direction in the plane of the sheet.

Fracture toughness evaluation was performed at room temperature on C(T) (50.0 mm wide) specimens with a/W = 0.5 and notches oriented both transversely and parallel to the fibers direction. Obviously notches oriented transversely to the fibers (T orientation) are the most important ones from the engineering viewpoint, because unidirectional FMLs are expected to be used oriented in unidirectional loaded components with the highest stresses in the fibers direction. The tests were carried out following a proposed methodology developed for FMLs fracture toughness determination [8].

2.1. *J*-Integral calculations

According to the proposed methodology [8], the *J*-Integral value is calculated by summing the elastic and plastic components, as follows:

$$J = J_{el} + J_{pl}\,, \tag{2}$$

where J_{el} and J_{pl} are the elastic and plastic components of *J*-Integral.

The elastic component of *J* was calculated using the relation between *G* and *K* for orthotropic materials [11]:

$$J_{el} = G_I = \frac{K_I^2}{E'}\,, \tag{3}$$

where *E'* is the “apparent” Young’s modulus in the specific direction, defined as

$$\frac{1}{E'} = \sqrt{\left(\frac{A_{11}A_{22}}{2}\right)\left[\sqrt{\frac{A_{22}}{A_{11}}} + \frac{2A_{12} + A_{66}}{2A_{11}}\right]}\,. \tag{4}$$

The A_{ij} are the compliance matrix components written in the form $\varepsilon_i = A_{ij}\,\sigma_j$ (j = 1, …, 6) [11], and calculated as follows:

$$A_{11} = \frac{1}{E_1};\, A_{12} = \frac{-\nu_{12}}{E_1} = \frac{-\nu_{21}}{E_2};\, A_{22} = \frac{1}{E_2};\, A_{66} = \frac{1}{G_{12}}\,, \tag{5}$$

where ν_{ij} is the Poisson’s modulus in the *ij* direction. Equation (4) is applicable only if the crack plane coincides with one principal direction [11], as it did throughout this work. Note that the A_{ij} values (so the *E'* value) depend on the orientation of the notch. In all cases the *x* axis coincides with the notch plane and $\sigma_1 = \sigma_x$; $\sigma_2 = \sigma_y$, …, $\sigma_6 = \tau_{xy}$.

On the other hand, the plastic component of *J* was calculated according to ASTM from the following equation:

$$J_{pl} = \frac{\eta A_{pl}}{b_0 B}\,, \tag{6}$$

where η = 2 + 0,522 b_0/W for C(T) specimens [10], A_{pl} = plastic component of the area below load vs. load-line displacement records, *B* is the specimen thickness and *b* is the specimen ligament length.

2.2. CTOD δ_5 measurements

CTOD δ_5 was introduced as an experimental technique for measuring Crack Tip Opening Displacement (CTOD) [12]. It can be employed to determine crack growth resistance curves as well as initiation or critical toughness values. Several experiments performed have confirmed that δ_5 can be used as an operational definition of CTOD with the main following advantage [12]: δ_5 is measured locally next to the crack tip and independently of the global behaviour. As a consequence of direct measurement of the crack tip displacement, there is no need of mathematical models nor calibration functions. This makes it possible to determine δ_5 for any test specimen or structural component having a crack. By this method, the CTOD is measured on one side surface of the test specimens at points located 2.5 mm each side from the tip of the fatigue pre-crack or notch. On the other hand, the traditional BSI methodology seemed to be not appropriated for CTOD measurements in FMLs, mainly because the plastic-hinge model showed not applicable for these materials [13]. So, δ_5 seems to be the better methodology for CTOD measurements of FMLs.

Measurements of δ_5 were made by means of a modified commercial extensometer whose knives were substituted by tips having a distance of 5.0 mm between them. Pictures of the modified extensometer and the experimental configuration for δ_5 measurement in a C(T) specimen are shown in Figure 2. In order to avoid damage in the fiber-reinforced epoxy layers, the marks to fix the extensometer tips on the specimen were hand-made using a 0.60 mm diameter drill. Depth of the marks was lesser than the thickness of the external aluminum layer.

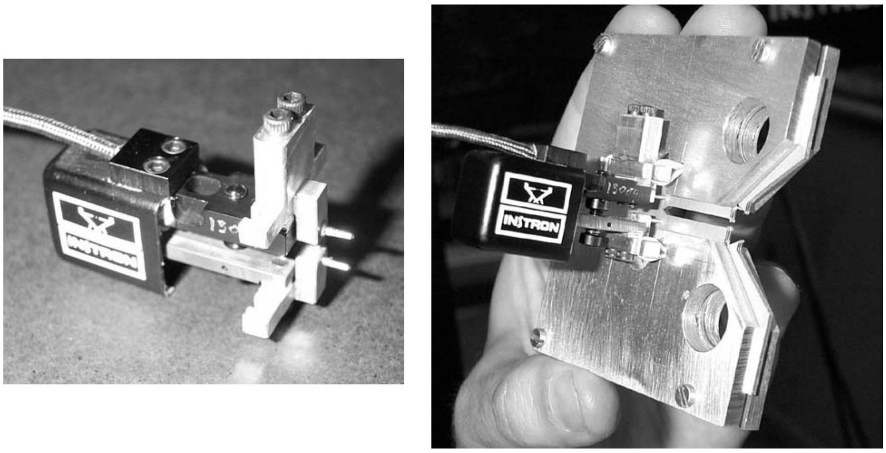

Figure 2 - On the left, the modified extensometer for δ_5 measurements. On the right, the extensometer mounted on a C(T) test specimen ready to be tested.

2.3. *J*-δ_5 relation for metallic materials

The proposed relation between δ_5 and *J*-Integral for metallic materials in the case of contained yielding of the ligament is given by the following equation [14][15]:

$$\delta_5 = \beta_1 \sqrt{\frac{J}{E} + \frac{J}{m\sigma_Y}\left[\frac{P}{P_Y}\right]}, \qquad (7)$$

where β_1 = 2.41 mm$^{1/2}$ and m = 1 for plane stress, and β_1 = 2.09 mm$^{1/2}$ and m = 2 for plane strain. P_Y is the applied force at the attainment of net section yielding of the cracked cross section [15][16]. Please note that the subscript Y in Equation (7) means yield in a general manner. As can be seen from Equation (7), the relation between J and δ_5 heavily depends on the tensile yield stress and on the stress state, accounted by m.

3. Results

As an example of differences in mechanical behavior between orientations, Figure 3 shows load vs. load-line displacement (*P-V*) records of Arall 3 3/2 notched in T and L orientations. These records are representative for all the laminates tested.

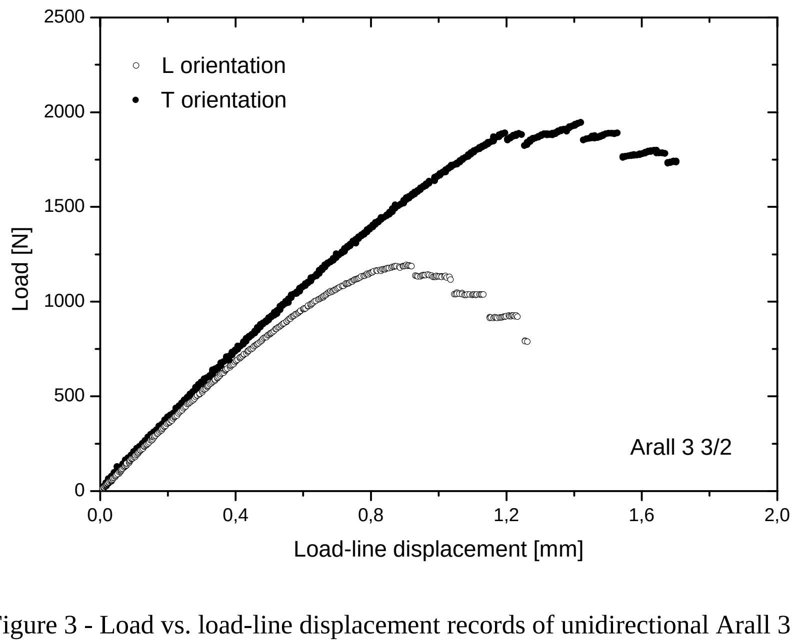

Figure 3 - Load vs. load-line displacement records of unidirectional Arall 3 3/2.

Table 2 shows mean values and standard deviations of the sample of the evaluated fracture toughness (J_C and δ_{5C}). The size of the samples was at least three specimens of each condition. Figure 4 shows the experimental mean fracture toughness (J_C vs. δ_{5C}) for all the tested materials and orientations, including experimental error bars. The individual experimental fracture toughness (J_C vs. δ_{5C}) of each specimen is shown in Figure 5.

Table 2 – Experimental fracture toughness (J_C and δ_{5C}, mean values and standard deviations of the sample).

FML		Arall 2	Arall 3		
Lay-up		3/2	2/1	3/2	4/3
J_C [kJ/m^2]	L	56.48 ±4.45	67.76 ±22.15	49.28 ±6.86	49.61 ±1.70
	T	101.76 ±6.54	101.09 ±10.59	88.29 ±8.78	95.02 ±11.11
δ_{5C} [mm]	L	0.242 ±0.038	0.194 ±0.015	0.202 ±0.039	0.188 ±0.026
	T	0.191 ±0.026	0.176 ±0.007	0.163 ±0.010	0.167 ±0.028

Observations: L orientation means notches parallel to fibers direction. T orientation Means notches perpendicular to fibers direction.

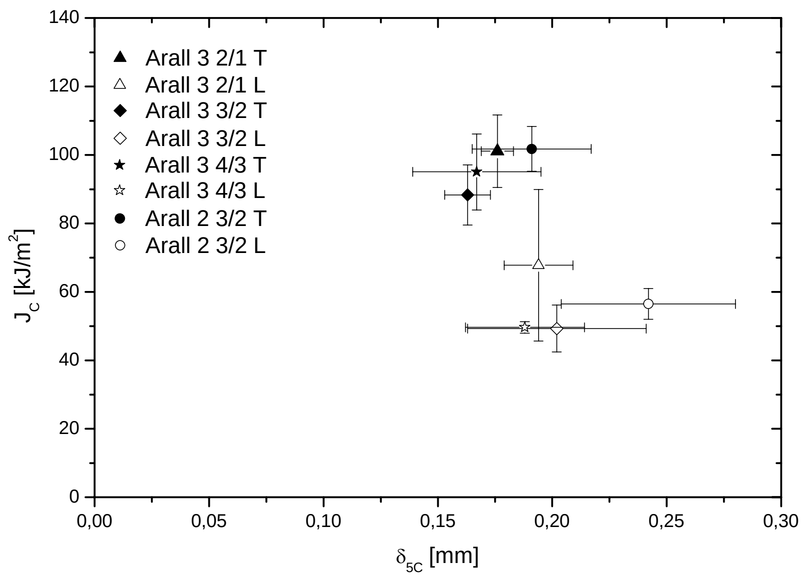

Figure 4 - Mean fracture toughness (J_C vs. δ_{5C}) of unidirectional FMLs from small specimen tests.

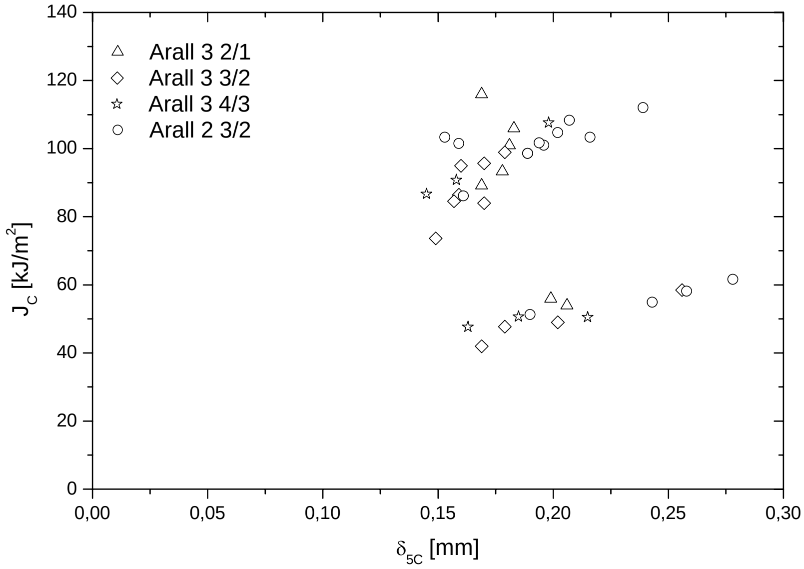

Figure 5 – Individual fracture toughness values for all the FMLs tested.

Figure 6 and Figure 7 show individual J_C values plotted against the product $\sigma_{YS}\ \delta_{5C}$ and $\sigma_Y\ \delta_{5C}$, respectively. In both figures the identity line was also drawn.

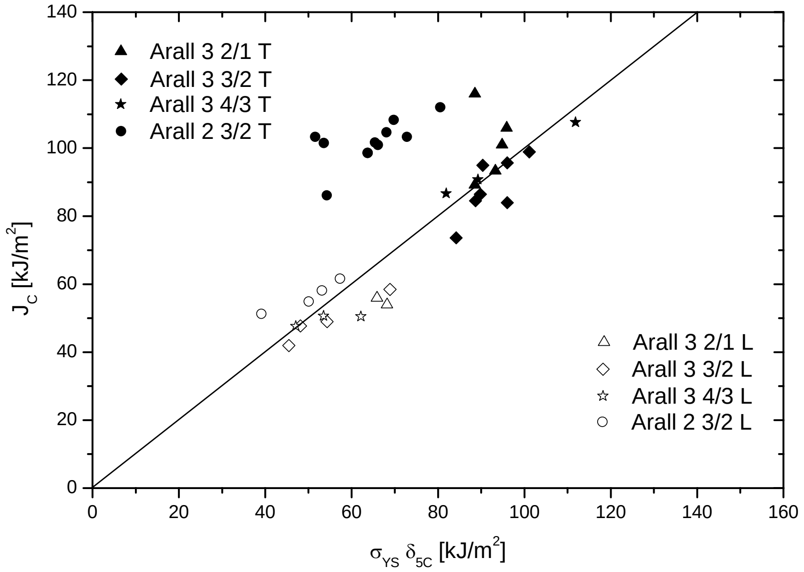

Figure 6 – J_C vs. $\sigma_{YS}\ \delta_{5C}$ (individual results).

4. Discussion

As can be seen from Figure 3, the fracture toughness tests of small specimens of Arall gave *P*-*V* records showing different amounts of non-linearity. Based on this behavior, the elastic-plastic fracture mechanics should be used [8]. All the Arall laminates tested, with notches both perpendicular or parallel to the fibers, presented instabilities in the records similar to pop-ins in welded joints [10]. So, the fracture toughness was evaluated at the first significant instability point [8][17]. From the records it is clear to see that specimens having notches perpendicular to the fibers (T orientation) supported higher loads and displacements before fracture than the ones notched parallel to the fibers (L orientation), as expected.

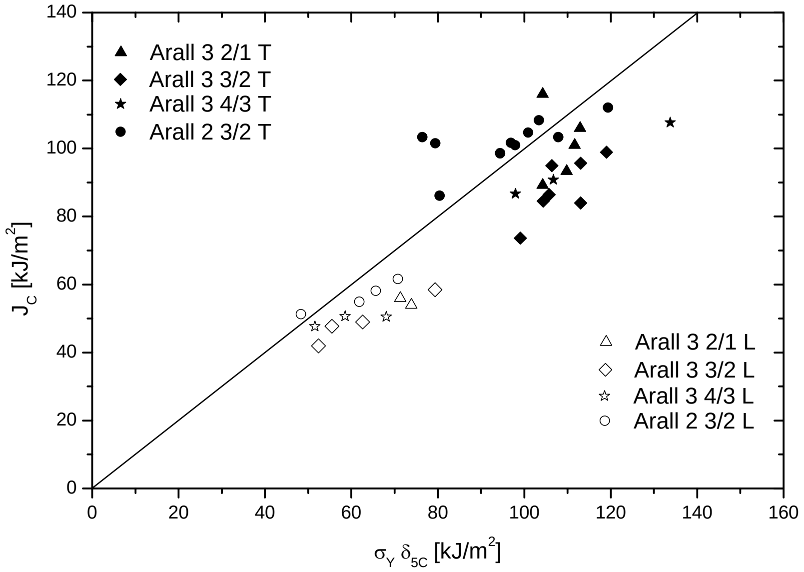

Figure 7 - J_C vs. $\sigma_Y\ \delta_{5C}$ (individual results).

From Table 2 and Figure 4 it can be observed that Arall 3 did not show statistical differences between toughness values (J_C or δ_{5C}) for the different lay-ups, when tested with notches in the same orientation. Still focusing on Figure 4, if analyzed in terms of mean J_C, all the FMLs tested in the T orientation showed higher toughness than in the L orientation. There was a well defined gap between both orientations. When analyzed in terms of mean δ_{5C}, all the laminates tested presented mean δ_{5C} values in L orientation higher than the values in T orientation. An apparent contradiction is present in the results: fracture toughness measured in terms of the two elastic-plastic parameters shows opposite tendencies. Focusing on J_C values, specimens tested with notches in T orientation were tougher than those with notches in L orientation, as expected. When focusing on δ_5 as fracture toughness, the opposite is true. At this point the obvious questions are: which notch orientation is most critical? Is there any wrong fracture parameter?

To answer these questions it can be reminded that when CTOD (traditional or δ_5) is related to J, there is always a yield-related stress (σ_{YS} or σ_Y) making both parameters equivalent (see Equation (7)) [14][15]. When the individual fracture toughness values are plotted (see Figure 5), there is a clear linear relationship between the individual J_C and δ_{5C} values. This relationship is stronger when Arall is tested with notches parallel to the fibers direction, that is, when the fracture toughness is more dependent on the metallic layers. If δ_{5C} values were normalized by either the yielding or flow stress, both fracture parameters seem to be equivalent. Moreover, when J_C and δ_{5C} were related using m = 1 (plane stress) and the effective yield stress as defined by Equation (1), the experimental points fell close to the identity line, as can be seen in Figure 6 and Figure 7. So, the apparent discrepancy between J_C and δ_{5C} for the same material notched in the two principal directions is related to the differences in yielding between these orientations, and can be explained by the anisotropy of the unidirectional FMLs.

Analyzing the equivalence between J_C and δ_{5C} based on the results of each individual laminate, the higher the difference between yield stress and ultimate stress, the better the correlation between J_C and δ_{5C} using the effective yield stress. It is interesting to remark that when the J_C values were used for residual resistance predictions of M(T) specimens having notches perpendicular to the fibers direction, the results obtained relating the plastic zone corrections in terms of σ_Y instead of σ_{YS} also showed better experimental agreement [18].

5. Conclusions

- According to both elastic-plastic methodologies used for fracture toughness evaluation (J-Integral and δ_5) and analyzing mean values, Arall 2 3/2 was the toughest FML, even notched parallel or perpendicular to the fibers direction.
- There were no statistical differences between the fracture toughness of different lay-ups of Arall 3 even when notched parallel or perpendicular to the fibers.

- Focusing on J_C values, Arall specimens tested with notches in T orientation were tougher than those with notches in L orientation. When focusing on δ_5 as fracture toughness, the opposite is true. This apparent contradiction can be explained by the yield-related equivalence between these two elastic-plastic parameters.
- The best overall equivalence between J_C and δ_{5C} was obtained when δ_{5C} values were normalized by the effective yield stress and using $m = 1$ (plane stress). This was true for unidirectional Arall notched parallel or perpendicular to the fibers direction. The higher the difference between yield stress and ultimate stress, the better the correlation between J_C and δ_{5C} using the effective yield stress.

6. Acknowledgements

To CNPq, FAPERJ, CAPES and SeTCIP (Project Brazil/Argentina 014/99) for their financial support. To CAPES (ProDoc Program) for the fellowship of Enrique Castrodeza. To Eduardo Benotti (University of Comahue) for machining some specimens and devices.

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