Materials Research, Vol. 5, No. 2, 119-124, 2002.


# Determination of $CTOD_C$ in Fibre Metal Laminates by ASTM and Schwalbe Methods

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Received: August 28, 2001; Revised: March 12, 2002

Fibre Metal Laminates (FMLs) have arisen as a demand of the aeronautical industry to use thin sheets with high resistance to fatigue crack growth, high damage tolerance, corrosion resistance and high specific strength. Considering these requirements, FMLs are an advantageous choice when compared to metal alloys currently used. In order to employ FMLs in aircraft structures, designers must hold a deep knowledge of a wide set of their properties including fracture toughness. The aim of this work was to evaluate the available methodologies to measure fracture toughness at instability ($CTOD_C$) in unidirectional fibre metal laminates reinforced with aramid fibres (ARALL®). To achieve this, tests were performed to obtain traditional and Schwalbe *CTODs* by using experimental ASTM based techniques, especially adapted to these laminates. Results achieved point out that Schwalbe method is more appropriate and also that there are differences between both *CTOD* parameters.

**Keywords:** *fibre metal laminates, crack tip opening displacement, composites*

## 1. Introduction

Fibre Metal Laminates (FMLs) are structural composite materials. They consist of thin aluminium alloy sheets bonded alternately with fibre-reinforced epoxy layers. These laminates are increasingly being employed in the aeronautical industry for structural applications, which require thin sheets with high mechanical and fatigue strengths[1]. The first researches on these composites were held in Delft University, Holland, during the 80's[2,3]. Nowadays, laminates commercially available are reinforced with either glass (GLARE®) or aramid (ARALL®) fibres, although there are experiences with other materials combinations[4-6].

Because these materials were developed for aeronautical applications, it is necessary to have a proper knowledge of their fracture and fatigue properties. One of the most remarkable characteristics in FMLs is the crack bridging mechanism. When a fatigue crack grows perpendicularly to the fibres direction, it propagates preferentially through the aluminium layers while a controlled delamination between the metallic layers and the polymeric matrix causes little damage to the fibres. Thus, a large quantity of fibres remains intact behind the crack tip on the aluminium layers taking up part of the loading. This reduces the level of effective crack tip stress intensity factor in the aluminium, diminishing the crack propagation rate. This mechanism produces crack growth rates down to 100 times lower than in monolithic aluminium alloys[7,8]. Due to their excellent fatigue properties, most of the research was focused on this aspect. On the other hand, there are few experimental works on monotonic fracture of these materials[9,10].

From literature[10], and also based on load versus load-line displacement ($P$-$v$) records showing departures from linearity, it was found that determination of fracture toughness by using linear-elastic fracture mechanics is not adequate[11,12]. Fracture toughness evaluation of FMLs should be carried out using elastic-plastic methodologies even when they present brittle fracture or instabilities similar to pop-ins. There are two elastic-plastic parameters widely accepted by the fracture community: $J$-Integral and $CTOD$[13]. Schwalbe's $CTOD$ ($\delta_5$)[14] is a relatively new methodology which fracture community is discussing and analysing. Both parameters are applied to different materials.

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Trabalho apresentado no *IV Coloquio Latinoamericano de Fractura y Fatiga*

In the present work, two *CTOD* based methodologies (ASTM and Schwalbe's *CTOD*) were employed to evaluate critical fracture toughness ($CTOD_C$) of ARALL 2 and 3 laminates with reinforcing fibres oriented transversally to the notch. A comparison between results obtained was made in order to prove the equivalence between methodologies and their applicability to these laminates as to characterise their fracture toughness.

## 2. Materials and Methods

### *Materials*

Unidirectional laminates ARALL 2 and ARALL 3 were tested. These laminates consist of alternating layers of thin aluminium alloy sheets bonded together by fibre reinforced epoxy adhesive. A schematic representation of ARALL 3, of 2/1 stacking sequence, can be seen in Fig.1. All ARALL laminates are reinforced by unidirectional aramid fibres. ARALL 2 is made of sheets of 2024-T3 alloy, while ARALL 3 is made of 7475-T76 alloy and deformed up to 0.5% after cure in order to reverse undesirable residual stress arisen during cure. After this deformation process, stress in the aluminium layers become compressive whereas in fibre-reinforced layers become tensile, thus improving fatigue properties. These laminates are manufactured with different lay-ups, represented by $n/m$ ($n = m + 1$), where $n$ is the number of aluminium layers and $m$ is the number of pre-impregnated fibre layers. Volume fraction of fibres in prepregs is 50%, fibres oriented parallel to the rolling direction of the aluminium sheets[15]. Some mechanical properties and characteristics of these laminates are shown in Table 1[16].

### *Methodologies*

Tests were carried out following mainly a methodology proposed for $J_C$ tests of fibre-metal laminates[17]. This methodology precludes the use of test specimens according to standards (with few modifications) and either avoids or takes into account problems (buckling, indentations, notch acuity, critical point definition, etc.) which arise when ASTM procedures are straightforwardly applied. Studies on the applicability of ASTM and Schwalbe's methodologies to measure *CTOD* on these materials were carried out.

### *Test Specimens*

Test specimens used were of the compact tension type (C(T)), with fibres oriented transversely to the notch. Their dimensions are shown in Fig. 2. The thickness of the specimens corresponded to the laminate thickness itself, much smaller than that preferred by the ASTM standard, although still within the standard. Test specimens were machined in a similar way to ordinary metallic test specimens but they were not fatigue pre-cracked. For FMLs, minimum toughness is achieved by testing specimens with sharp notch instead of fatigue pre-cracked ones[17].

### *Schwalbe* CTOD ($\delta_5$)

Recently, $\delta_5$ was introduced as an experimental technique for measuring Crack Tip Opening Displacement (*CTOD*)[18]. It can be employed to determine crack growth resistance curves as well as initiation or critical toughness values. Several experiments performed have confirmed that $\delta_5$ can be used as an operational definition of *CTOD* with the following advantages[18]: $\delta_5$ 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 calibration functions. This makes it possible to determine $\delta_5$ for any test specimen or structural component having a crack. By this method, *CTOD* is measured on one side surface of test specimens at points located 2.5 mm each side from the tip of the fatigue pre-crack or notch.

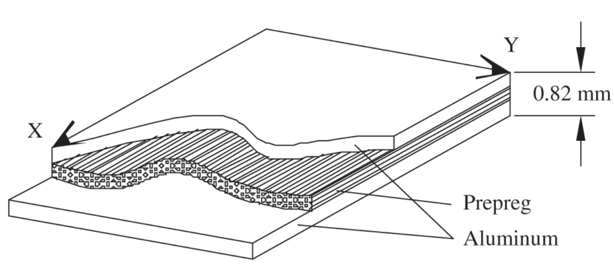


**Figure 1.** Schematic representation of ARALL laminates in 2/1 stacking.

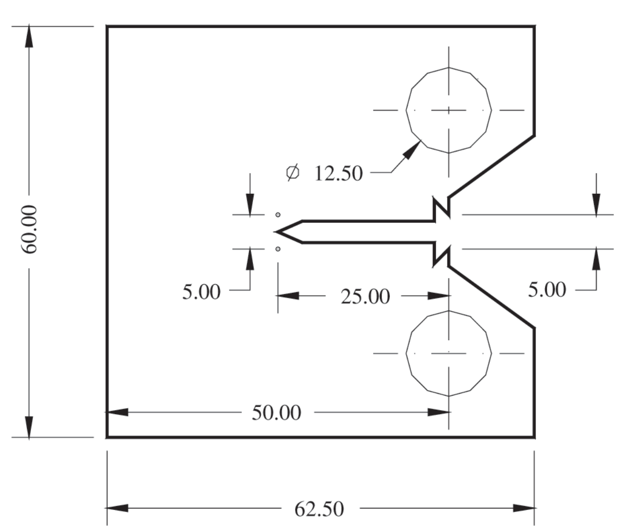


**Figure 2.** C(T) specimen dimensions.

**Table 1.** Basic mechanical properties of ARALL 2 3/2, ARALL 3 3/2 and ARALL 3 4/3 laminates (in the fibre direction)[15].

| Material | $\sigma_{YS}$ [MPa] | $\sigma_{UT}$ [MPa] | $\varepsilon_{UT}$ [%] | $E_T$ [GPa] | $E_C$ [GPa] | $\rho$ [kg/m$^3$] | Thickness [mm] | Metallic % [Vol] |
|---|---|---|---|---|---|---|---|---|
| ARALL 2 3/2 | 337 | 662 | 2.0 | 68.0 | 64.0 | 2300 | 1.35 | 67.9 |
| ARALL 3 3/2 | 565 | 765 | 1.8 | 68.2 | 66.2 | 2300 | 1.34 | 67.9 |
| ARALL 3 4/3 | 565 | 786 | 1.7 | 68.9 | 66.2 | 2270 | 1.83 | 65.3 |

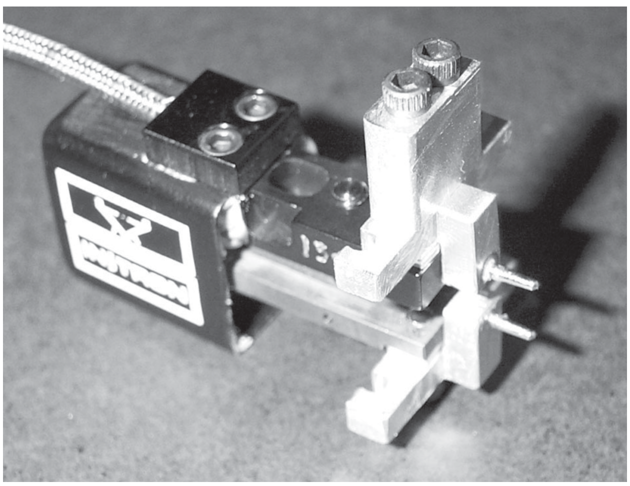

**Figure 3.** Modified commercial extensometer (INSTRON) for $\delta_5$ measurement.

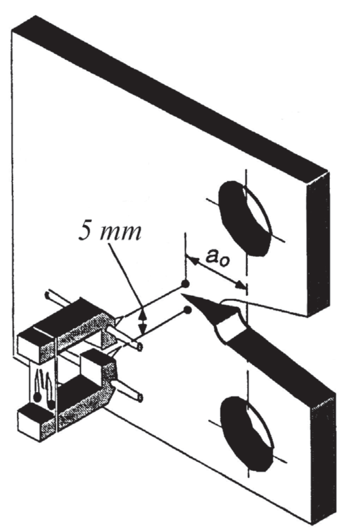


**Figure 4.** Experimental configuration for $\delta_5$ measurements.

Measurements of this parameter were made by means of a modified commercial extensometer (Instron). Knives were substituted by tips having a distance of 5.0 mm in between them. A photo of the modified extensometer is shown in Fig. 3, while Fig. 4 illustrates the experimental configuration for $\delta_5$ measurement in a C(T) specimen.

In order to avoid damage of fibre-reinforced epoxy layers, the marks to fix the extensometer tips on one external aluminium layer were hand-made using a 0.60 mm diameter drill. Depth of the marks was less than the aluminium layer thickness.

*Equations to calculate* CTOD *(δ)*

To calculate *CTOD* according to ASTM, standard equations were slightly modified to adapt them to orthotropic materials. The elastic component was calculated from the relation developed by Paris and Sih[19] for these materials, as follows:

$$G_1 = K_1^{\,2}\sqrt{\left(\frac{a_{11}a_{22}}{2}\right)\left[\left(\frac{a_{22}}{a_{11}}\right)^{1/2} + \frac{2a_{12}+a_{66}}{2a_{11}}\right]} = \frac{K_1^{\,2}}{E'} \qquad (1)$$

where $a_{ij}$ are the components of the compliance matrix of the laminate. *E'* was considered to be an “apparent” elastic modulus of the orthotropic material in the specific direction. The plastic component calculation was performed without modifications. So, the expression used was:

$$\delta = \frac{K_1^{\,2}}{2\sigma_{YS}E'} + \frac{\mathrm{r_p}(W-a_0)v_{\mathrm{pl}}}{\left[\mathrm{r_p}(W-a_0)+a_0+z\right]} \qquad (2)$$

where $a_0$ = original crack length; $K$ = stress intensity factor; $\sigma_{YS}$ = tensile yield limit; $v_{pl}$ = plastic component of the displacement at the crack mouth opening; $z$ = clip-gauge knife height and $r_p$ = rotational factor calculated in accordance with ASTM[13].

*Tests*

Eight specimens were tested: two for ARALL 2 3/2, and three for each ARALL 3 3/2 and ARALL 3 4/3. Tests were carried out under constant displacement rate of 0.5 mm/min in an INSTRON 1125 testing machine. The crack mouth opening displacement (*CMOD*) was measured through a clip gauge in the load-line. In this way *CMOD* and load-line-displacement values coincide.

Critical fracture toughness is calculated at the point where the first significant load drop occurs. The amount of load drop necessary to be considered significant was established in a similar way to the pop-in instabilities characterisation procedure given by ASTM E 1820[13], although conservatively setting at 2% the slope difference between the straight lines instead of the 5% recommended by the standard[17]. Fracture toughness values were in all cases calculated using the initial crack length.

## 3. Results

*P*-*v* and *P*-$\delta_5$ curves obtained from a test specimen of ARALL 2 3/2 and another of ARALL 3 3/2 are presented in Figs. 5 and 6, respectively. These records, as well as those

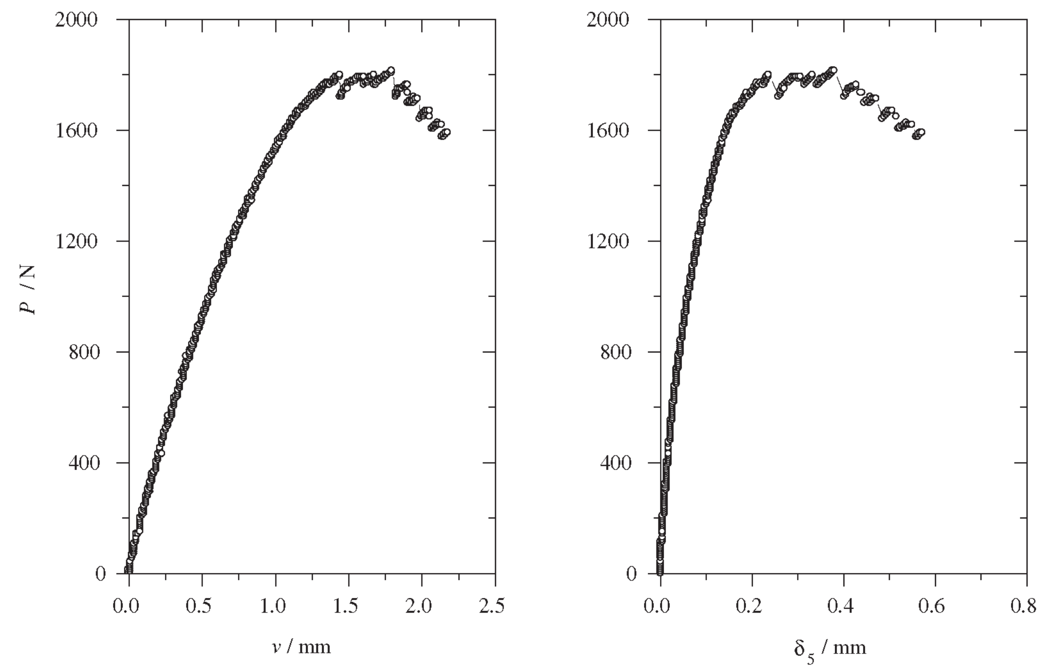


**Figure 5.** *P* vs. *v* and *P* vs. $\delta_5$ curves of ARALL 2 3/2 (test specimen B).

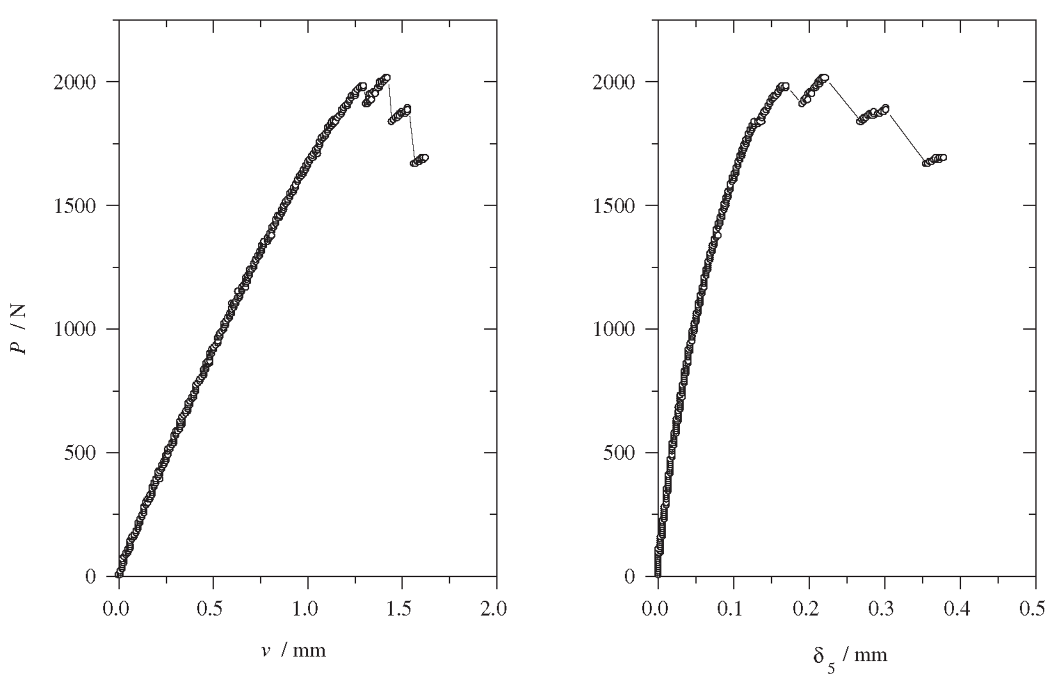


**Figure 6.** *P* vs. *v* and *P* vs. $\delta_5$ curves of ARALL 3 3/2 (test specimen A).

to be introduced later, are representative of the ones obtained in all tests. Critical ASTM values, $\delta_C$, were calculated using equation (2) with $r_p$ values recommended by the standard, while critical $\delta_{5C}$ values were directly obtained from the record. Table 2 shows $\delta_C$ and $\delta_{5C}$ values for every specimen tested. Table 3 shows mean and standard deviation of these values. *CTOD* vs. $\delta_5$ curves for ARALL 2 3/2 and ARALL 3 3/2 laminates are shown in Figs. 7 and 8, respectively.

## 4. Discussion

Instabilities similar to pop-ins occurred during all tests. Thus, characterisation of fracture toughness at instability by using the proposed testing methodology, to which follows a procedure based on pop-in analysis[17], proved adequate. Stable crack growth in the aluminium layers before reaching the critical point was not observed.

*CTOD* values for ARALL 2 were higher than those for ARALL 3 in all cases as can be seen in Tables 2 and 3. The higher toughness of ARALL 2 compared to ARALL 3 is thought to be related to both its lower mechanical strength –$\sigma_{YS}$ and $\sigma_{UT}$ values– and its higher ductility (see Table 1).

On comparing these results, it is remarkable that the critical toughness values, $\delta_{5C}$, for ARALL composites with lower strength and higher ductility follow the same trend observed in ordinary metallic materials. This brings up the importance of the aluminium layers in this kind of composites whose mechanical behaviour is very different from that of polymeric matrix laminates.

$\delta_{5C}$ values for the two lay-ups studied for ARALL 3 are similar. Preliminary tests with ARALL 3 2/1 (0.82 mm in thickness) agree with this tendency.

$\delta_C$ values for ARALL 3 were, in average, 27.2% lower than those of $\delta_{5C}$ for the 3/2 lay-up and 18.3% lower than those of $\delta_{5C}$ for the 4/3 lay-up, whereas for ARALL 2 $\delta_C$ values were, in average, 13.6% higher than $\delta_{5C}$ values. These differences between critical values led to analyse them in more detail by depicting the evolution of ASTM *CTOD* against Schwalbe *CTOD* (Figs. 7 and 8). It can be seen in these figures that ASTM *CTOD* values were lower than Schwalbe's *CTOD* for small loads. Both materials presented this behaviour. For larger loads, beyond the linear region, this difference in *CTOD* values corresponding to both materials remained approximately constant. This was the zone where ARALL 3 presented instability, Fig. 6. In the case of the more ductile ARALL 2, this difference decreased as displacement increased and, moreover, changed signal approaching the test end.

**Table 2.** Critical values of the ASTM *CTOD* ($\delta$) and SCHWALBE *CTOD* ($\delta_5$).

| Material | Test specimen | $\delta_C$ [mm] | $\delta_{5C}$ [mm] |
|---|---|---|---|
| ARALL 2 3/2 | B | 0.268 | 0.239 |
| | C | 0.218 | 0.189 |
| ARALL 3 3/2 | A | 0.142 | 0.169 |
| | B | 0.115 | 0.169 |
| | C | 0.098 | 0.148 |
| ARALL 3 4/3 | A | 0.119 | 0.145 |
| | B | 0.162 | 0.198 |
| | C | 0.148 | 0.182 |

**Table 3.** Mean and standard deviation values of the results in Table 2.

| Material | Lay-up | $\delta_C$ [mm] | $\delta_{5C}$ [mm] | $\Delta\delta$ (%) |
|---|---|---|---|---|
| ARALL 2 | 3/2 | 0.243 ± 0.035 | 0.214 ± 0.035 | 13.55 |
| ARALL 3 | 3/2 | 0.118 ± 0.022 | 0.162 ± 0.012 | 27.16 |
| | 4/3 | 0.143 ± 0.022 | 0.175 ± 0.027 | 18.29 |

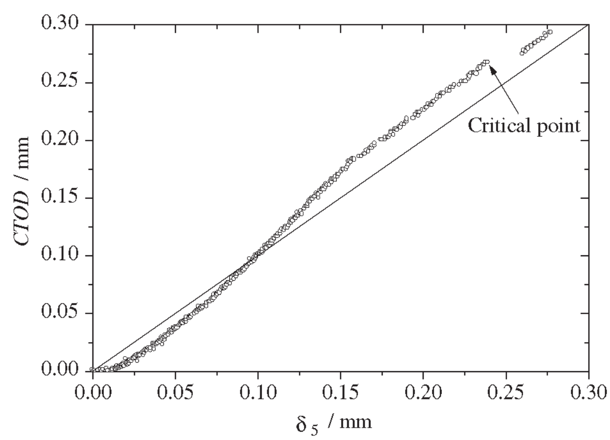


**Figure 7.** *CTOD* vs. $\delta_5$ curve of ARALL 2 3/2 (test specimen B).

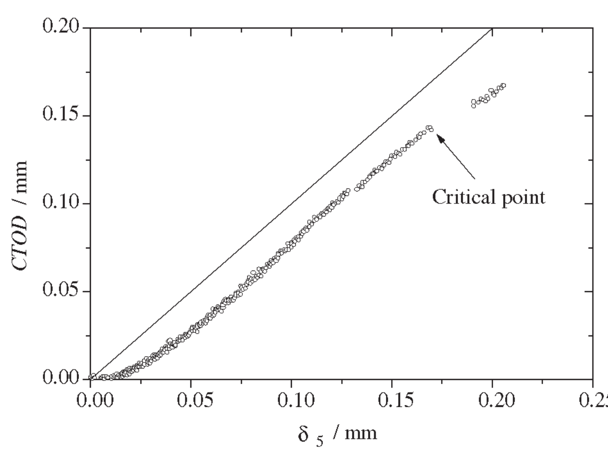


**Figure 8.** *CTOD* vs. $\delta_5$ curve of ARALL 3 3/2 (test specimen A).

At critical points, the elastic component of *CTOD* was larger than the plastic one in ARALL 3, while this relationship was the opposite in ARALL 2.

From these analyses, the difference in *CTOD* values could be due to the combination of an underestimation of the elastic component and an overestimation of the plastic one in the ASTM *CTOD* calculation.

A more detailed analysis will be performed in a future stage in order to evaluate the applicability of ASTM equations for the calculation of elastic and plastic *CTOD* components. Values of $m$, which is a factor in the relation between $\delta$ and $K$ ($m = 2$ in the standard), and $r_p$ will be specifically investigated. As a first approach, and until more specific research is carried out, Schwalbe's methodology, in which *CTOD* is directly measured, has so far proved more appropriate for FMLs. This methodology implementation in a testing laboratory turned out very simple.

## 5. Conclusions

- Instabilities similar to pop-in phenomenon in welded joints of steel were recorded in all load *vs.* displacement curves of laminates studied.
- The use of an experimental methodology[17] developed for these materials proved adequate.
- Critical fracture toughness values were higher in ARALL 2 than in ARALL 3. Besides, $\delta_{5C}$ values in ARALL 3 were similar in both lay-ups studied (3/2 and 4/3).
- In ARALL 3 $\delta_C$ values were lower than $\delta_{5C}$ , whereas in ARALL 2 this relation was the opposite.
- The difference in *CTODs* measured applying the two methodologies could be due to underestimation of the elastic component plus overestimation of the plastic component of the ASTM *CTOD*.
- $\delta_{5C}$ is considered the best choice for *CTOD* measurements in FMLs until further research on $\delta_C$ is performed.

## Acknowledgements

To Eduardo Benotti (U.N. del Comahue) for the machining of test specimens. To CNPq, FINEP, CONICET, CAPES and SETCIP for their financial support. To CNPq for the scholarship of Enrique M. Castrodeza.

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