# EVALUATION OF MODE I INTERLAMINAR FRACTURE TOUGHNESS OF FILAMENT-WOUND GFRE COMPOSITE PIPE

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## Abstract

*A common industrial production process for composites is filament winding, widely used for the production of axially symmetric components. The important interlayer properties cannot be evaluated using available ISO and ASTM standards, because of the curved surfaces and partially interwoven fibres. This paper presents a modified test geometry for measuring the critical energy release rate $G_{Ic}$ directly from the real filament wound products.*

*Different specimen geometries were investigated numerically for their stress state at the crack tip and tested experimentally. Results were also compared against flat specimens tested according to ISO/ASTM and made from the same constituent materials as the pipe. Testing specimens taken from real filament wound pipe give more relevant results than making flat specimens especially for fulfilling the test standard´s requirements.*

## 1. Introduction

The production of composites by filament winding has become very attractive in the last decades for the production of high performance composites for different applications. This production technique is gaining a lot of interest due to the very high production rate and other benefits that can overcome the higher initial cost compared with other production methods [1].

Despite the wide use, no standards have been published, by both the ASTM or ISO associations, for the evaluation of the interlaminar properties ($G_{Ic}$ , $G_{IIc}$ and $G_{IIIc}$) for such a type of material.

Delamination is an important problem that can lead to a premature failure of composite structures. Different causes can produce delaminations: contamination during the lay-up, blast loading, accumulation of voids during the production and low speed impact loading during service [2]. The delamination in filament wound cylindrical composites is even more complicated compared to plane structures. The curved surface coupled with the typical asymmetric lay-up can produce a mix mode stress field on the crack tip [3, 4], that can make the delamination even more dangerous. The interlaminar properties are fundamental for the correct evaluation of delamination onset and propagation. These properties need to be evaluated for the filament wound composite also.

The standard test for the characterization of the mode I strain energy release rate, $G_{Ic}$, is the double cantilever beam (DCB) that has been standardized in the ASTM D5528 [5] and ISO

15024 [6] for unidirectional fibre reinforced polymers. The classical DCB test shows different limitations that not allow it to be used for real produced filament wound materials. The problems are originated mainly from the curved geometry that with the classical asymmetric and not unidirectional layup results in a mixed mode crack-tip loading state that can affect the results. An equivalent test method for not flat structures is the Curved Double Cantilever Beam (CDCB) that has been proposed in the literature by Lauke, Friedrich [7] and Foral [8].

The current work analyses the capability of the DCB or the CDCB test methods to evaluate the $G_{Ic}$ of real produced E-Glass/Epoxy filament wound composite pipe with: curved geometry, no embedded crack, not unidirectional and not symmetric layup. Two different DCB test specimens, longitudinal and transverse, have been machined from the pipe. The results obtained on the real produced material are reported. Moreover a Finite Element (FE) analysis has been conducted to evaluate the influence of the sample geometry on the mix mode effect at the crack tip.

## 2. DCB test on real filament wound composite pipe

### 2.1. Used material

The present work wants to investigate the possibility to evaluate the $G_{Ic}$ on real produced filament wound composite pipe. The composite has been produced using: E-Glass fibre of 1100 Tex and epoxy resin. The composite pipe, with an internal diameter of 300mm, wall thickness of 6.3mm, layup of $[\pm 55°]_4$ and a measured fibre volume fraction of $\nu_f \approx 65\%$, was provided by Amiantit/Flowtite Technology AS.

### 2.2. Limitations using the classical DCB test

The DCB test is a common test for the evaluation of the $G_{Ic}$ for composites made with long unidirectional fibres; two standards are currently available: ASTM D5528 [5] and ISO 15024 [6]. The main problem of these standards is the inapplicability to real produced filament wound composite. Table 1 reports all the problems that make it impossible to apply the classical standards for filament wound composites.

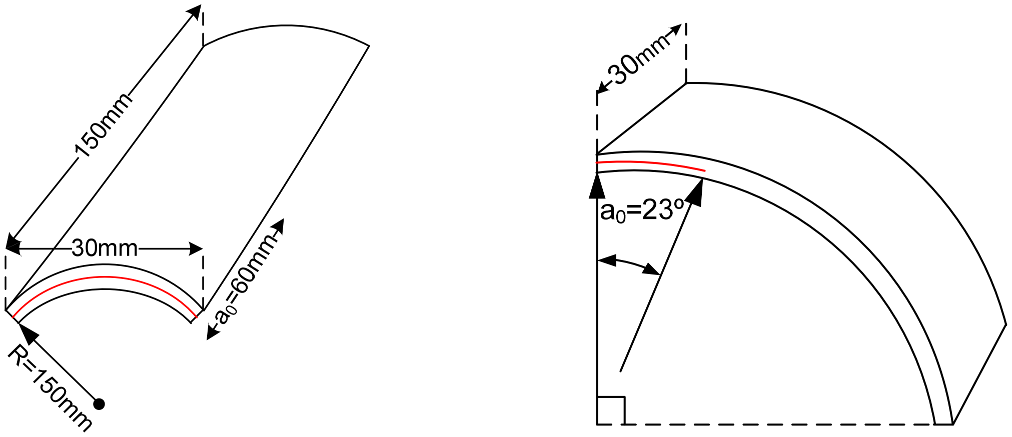
Different authors tried to evaluate the interlayer properties producing quasi-unidirectional curved specimens [2, 9, 10]. However, as discussed later in this paper, these materials are different and may not have the same properties as the real pipe.

| ***Standards (ISO – ASTM)*** | ***Real composite made by filament winding*** |
|---|---|
| Flat specimen | Curved specimen |
| Composite made with unidirectional and symmetric layup | It is impossible to have perfect unidirectional and symmetric layup |
| Pre crack (Teflon layer) embedded in the material during the production process | The pre crack cannot be embedded in the material during the real production |
| $G_{Ic}$ calculation:<br>• **MBT**: Modified Beam Theory<br>• **CC**: Compliance Calibration<br>• **MCC**: Modified Compliance Calibration | Classical evaluation schemes not applicable |

**Table 1:** Limitations for the use of the classical ASTM and ISO standards for the evaluation of the $G_{Ic}$ on real filament wound composite.

*Curved specimens*

The main limitation of the DCB test applied to real produced pipe is the curvature. The DCB test is made to evaluate a pure opening mode I, but due the curved geometry, a mixed mode stress field is obtained at the crack tip. On a pipe, two different sample geometries can be obtained; the samples can be cut in the axial (longitudinal) or hoop (transverse) direction (see Figure 1). The obtained sample presents a different curvature (and also a different lay-up) that influence the mixed mode stress state at the crack tip.



**Longitudinal specimen – axis direction [±55°]**

**Transverse specimens – hoop direction [±35°]**

**Figure 1:** Different specimen geometry obtainable from a real composite pipe

| **Glass Fibre Reinforced Epoxy** | | |
|---|---|---|
| ***Property*** | | ***Value*** |
| *Longitudinal Young's Modulus* | $E_1$ | *39 Gpa* |
| *Transverse Young's Modulus* | $E_2$ , $E_3$ | *8.6 GPa* |
| *Poisson's Ratio* | $v_{12}$, $v_{13}$, $v_{23}$ | *0.28* |
| *In-Plane Shear Modulus* | $G_{12}$, $G_{13}$, $G_{23}$ | *3.8 MPa* |
| *Longitudinal Tensile Strength* | $X_t$ | *1080 MPa* |
| *Longitudinal Compression Strength* | $X_c$ | *620 MPa* |
| *Transverse Tensile Strength* | $Y_t$ ,$Z_t$ | *39 MPa* |
| *Transverse Compression Strength* | $Y_c$, $Z_c$ | *128 MPa* |
| *In-Plane Shear Strength* | $G_{12c}$, $G_{13c}$, $G_{23c}$ | *89 MPa* |
| *Density* | $\rho$ | *2.10e-9 tonne/mm$^3$* |
| **Cohesive zone** | | |
| ***Property*** | | ***Value*** |
| *Elastic modulus in normal direction* | $E$ | *8.6 GPa* |
| *Shear modulus* | $G_1$, $G_2$ | *3.8 GPa* |

**Table 2:** Classical material properties for GFRE from [11]

A finite element (FE) analysis has been done to evaluate the influence of the specimen geometry on the stress field acting at the crack tip. Commercial FE software, ABAQUS 6.10, has been used for all the simulations. Both specimens have been modelled using: solid quadratic element elements with reduced formulation (C3D20R) for the two DCB arms and zero thickness cohesive elements (COH3D8) to evaluate the stress field acting on the crack tip. A mesh convergence analysis has been conducted; for all the models solid elements of 2.5x2.5x2.5mm$^3$ and cohesive elements of 0.8x0.8mm$^2$ have been used. A ratio of one to three has been used between solid and cohesive elements. The influence of the layup has also been investigated; two layups have been evaluated: $[\pm 55°]_4$ balanced asymmetric, the classical for the filament wound composite pipe, and $[\pm 55°]_{2S}$ balanced and symmetric, impossible to be obtained with the filament winding process. For each specimen/layup two crack lengths have been considered ($a_0$=30mm and $a_0$=60mm) to evaluate the mixed mode effect at the beginning and the end of the crack evolution. The classical material properties for GFRE from [11] have been used for all the numerical simulations (Table 2). The average of the normal (for mode I) and shear (for mode II and III) stresses have been calculated at the crack tip for: each model (longitudinal and transverse), crack extension ($a_0$=30mm and $a_0$=60mm) and layup (symmetric and asymmetric). The results are reported in the Table 3.

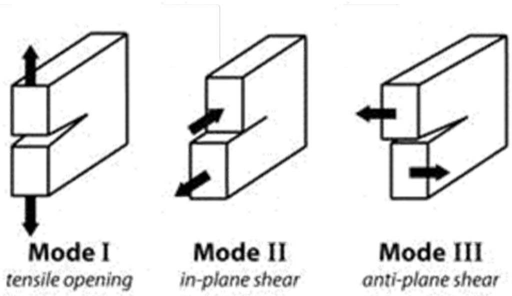


**Figure 2:** Opening modes

From the results reported in the Table 3, the presence of a high anti-plane shear stress (mode III) at the crack tip for both geometries with asymmetric layup is shown. The problem is drastically reduced with the symmetric layup due to the complete absence of the coupling factors between bending and torsion. A symmetric layup cannot be produced by filament winding and will be no longer considered. Using asymmetric layup only, the transverse specimen geometry produces higher normal stress (opening mode I) at the beginning and end of the crack evolution ($a_0$=30mm and $a_0$=60mm) with a decrease of the critical applied displacement for the crack propagation. Regarding the mode II and III, the transverse specimen produces a higher value of anti-plane but lower in-plane shear stresses compared to longitudinal ones. Both two samples produce similar results; small benefit can be found in the transverse one. After these considerations, it is still not possible to define the best specimen geometry; therefore, both geometries have been experimentally tested.

| | | **Asymmetric layup** | | | | **Symmetric layup** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Longitudinal** | | **Transverse** | | **Longitudinal** | | **Transverse** | |
| **$a_0$=30mm** | **Mode I** [MPa] | 116 | | 148 | | 116 | | 147 | |
| | **Mode II** [MPa] | -1.34 | 1.2% | -1.29 | 0.9% | -1.32 | 1.1% | -1.26 | 0.9% |
| | **Mode III** [MPa] | 6.32 | 5.4% | -11.2 | 7.6% | -0.74 | 0.6% | 0.08 | 0.1% |
| **$a_0$=60mm** | **Mode I** [MPa] | 29.3 | | 39.7 | | 29.3 | | 39.6 | |
| | **Mode II** [MPa] | -0.4 | 1.4% | -0.30 | 0.8% | -0.4 | 1.4% | -0.31 | 0.8% |
| | **Mode III** [MPa] | 2.14 | 7.3% | -4.04 | 10.2% | -0.27 | 0.9% | -0.02 | 0.1% |

**all the percentages are function of mode I stress*

**Table 3:** Magnitude of stresses calculated by the numerical simulations for: different specimens geometries, layups and crack length ($a_0$). All the simulations have been conducted with a total applied displacement of 10mm.

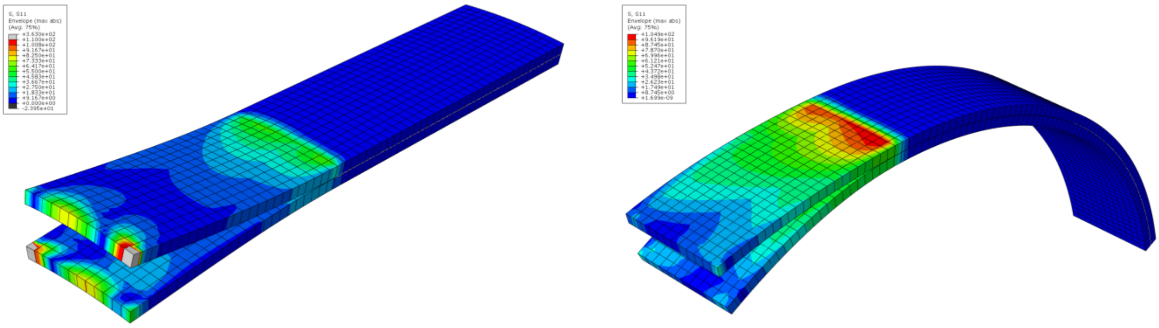


**Figure 3**: Numerical simulations of longitudinal and transverse samples

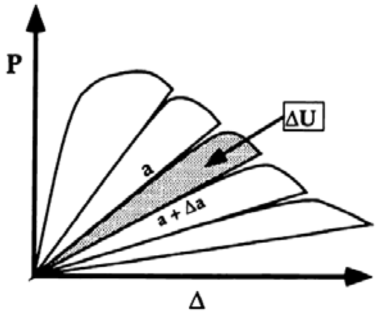
*Pre-crack and hinges*

The DCB test sample needs the presence of a pre-crack, generally made by an embedded Teflon layer placed during the production in the middle plane (for more details see [5, 6]). For the real produced material, the Teflon layer cannot be embedded during the production process. For this reason, the crack has been made using a band saw, with a blade thickness of 0.5mm. This procedure is rough, but still very complex. The use of a support guide can help in the cutting process.

Due to the curved sample geometry also the hinges need to be bent; two hard steel molds have been used. A structural epoxy based adhesive has been used to glue the hinges to the sample and to fill any possible gaps between the sample and the bent hinge. Both the hinges and specimen surfaces have been prepared for the bonding by cleaning and grinding.

*$G_{Ic}$ calculation*

The ASTM and ISO standards [5, 6] provide three different schemes for the evaluation of the $G_{Ic}$ that cannot be used for the curved samples used here. Different data reduction schemes for the $G_{Ic}$ evaluation for curved sample have been proposed in the literature [7, 9, 10]. Even if some schemes are available, the classical area method has been used here for the evaluation of the $G_{Ic}$. Several loading and unloading cycles have been done for each sample to check for plasticity also. In each cycle, the crack length has been monitored/measured using an optical travelling microscope. In Figure 4, the basic procedure for the $G_{Ic}$ calculation (from [12]) is reported.



$$G_{Ic} = \frac{\Delta U}{B \Delta a}$$

**Figure 4:** Schematic load-displacement curve for a delamination toughness measurement - Calculation of $G_{Ic}$ (B specimen width, Δa crack length variation, P load, Δ displacement)

## 2.3. Experimental results

Both transverse and longitudinal samples (Figure 5) have been tested experimentally in an Instron 10kN machine. A travelling optical microscope has been used to evaluate the crack length during the test with an accuracy of 0.5mm. The specimen dimensions are reported in Figure 1.

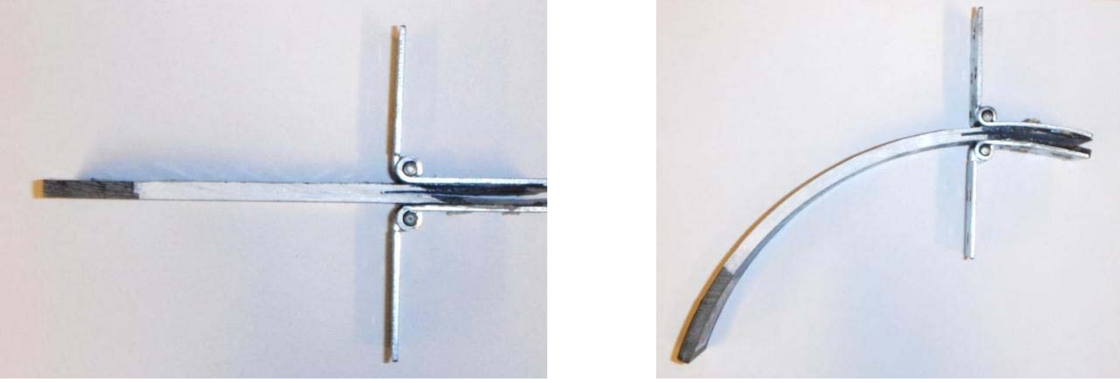


**Figure 5:** Longitudinal and transverse DCB samples

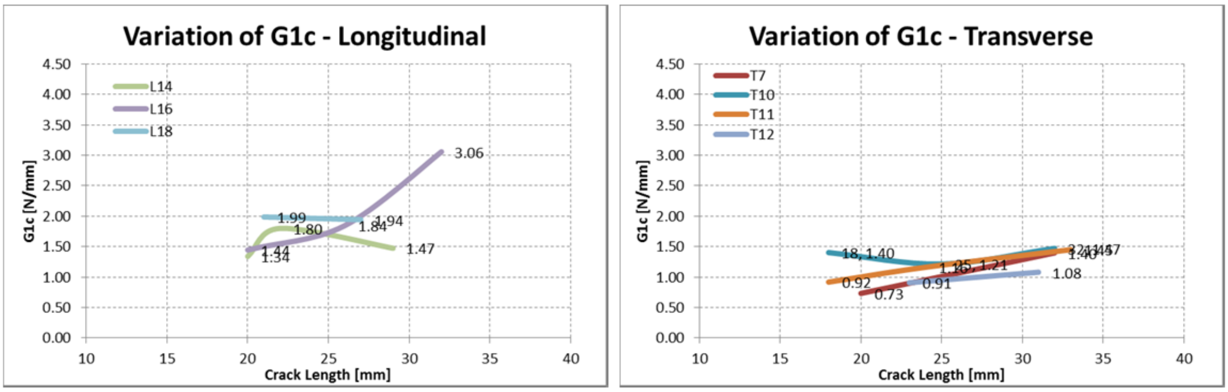
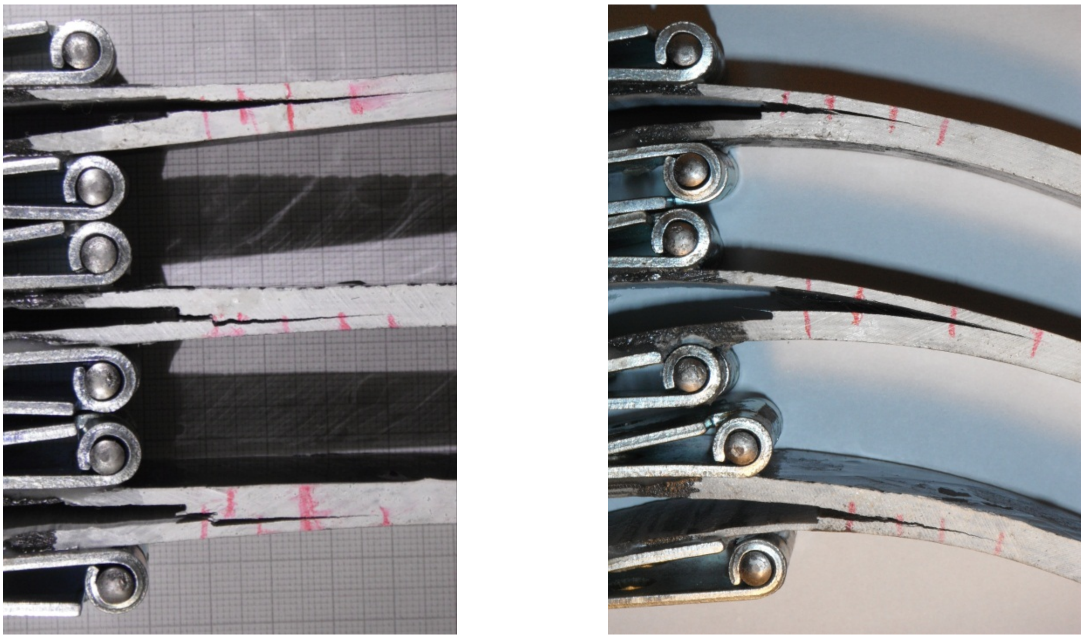


**Figure 6:** $G_{Ic}$ evaluation at different crack length for transverse and longitudinal samples

The results for transverse and longitudinal samples are reported in Figure 6. For all the tests, the first load/unload cycle has not been considered for the evaluation of $G_{Ic}$. Due to the thick initial crack made by the band saw, the first crack initiation is not representative for a natural crack. For both sample geometries, the crack propagates mostly stably. The value of $G_{Ic}$, for the different crack length, is more stable in the transverse samples than the longitudinal ones. Moreover, during the crack evolution, the transverse samples present a more stable crack growth that propagates on the middle plane (Figure 7). For longitudinal samples, instead, the crack plane tends to move from the middle surface, jumping between the different layers. This is the reason that the fibre bridging, viewed for both samples, is more pronounced in the longitudinal ones, with a consequent decrease of the result accuracy.

Due to these considerations, only the results calculated with the transverse sample can be used. The average $G_{Ic}$ value, evaluated on the transverse samples, from real produced filament wound material is: $G_{Ic} = 1.22[N/mm]$ or $1220\ [J/m^2]$

The value of $G_{Ic}$ was also measured using completely flat unidirectional specimens made from the same constituent materials as the pipe. Samples were made in a filament-winding machine wrapping the fibres around a plate. This process tries to be representative of the pipe production. However, fibre content is difficult to control and typically lower than in the real pipe. Furthermore the void content was fairly high. The measured $G_{Ic}$ value was about $0.33\ [N/mm]$ or $330\ [J/m^2]$ [13]. Even though the test based on the methods from ASTM D5528 [5] and ISO 15024 [6] should give the best possible $G_{Ic}$ values with pure stress states, the value is much lower than what is tested on the real pipe. It shows that the material was not representative and a non-perfect test on a curved specimen gives better results, than a good test on a wrong material.



Longitudinal samples

Transverse samples

**Figure 7:** Crack path for longitudinal and transverse samples

## 3. Conclusion

Methods to measure the critical energy release rate $G_{Ic}$ of the interface between layers of filament wound cylindrical composite pipe have been evaluated. Two different DCB test samples (longitudinal and transverse), machined from a real composite pipe, have been numerically analysed and experimentally tested.

The numerical simulations show that both test geometries present a mixed mode stress field at the crack tip. Mode II and mode III stresses can be up to 1.5% and 10.2% respectively of the mode I component. They cannot be reduced by changing the specimen geometry. The transverse specimen was clearly better suited for testing from an experimental point of view, because the crack propagated nicely within the same interface. The longitudinal specimens did not show stable crack growth.

Flat specimens were made using the same constituent materials as used in the pipe. However, making flat specimens from materials used for filament winding is difficult and the fibre volume fraction was lower and the void content higher than in the pipe. These specimens were tested according to the ISO/ASTM standards. These unidirectional specimens were well suited for the standardized $G_{Ic}$ testing. Even though the stress state is fairly close to pure mode I in these specimens, the measured $G_{Ic}$ was only about 1/4 of the values obtained for samples taken from the pipe itself. This shows that measuring on the real material with a non-ideal test gives more meaningful results than testing perfect specimens made of a non-representative material.

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## References

[1] Peters,S.T., *Composite Filament Winding.* 2011. ASM International.

[2] Ozdil, F. and L.A. Carlsson, *Characterization of Mode I Delamination Growth in Glass/Epoxy Composite Cylinders.* Journal of Composite Materials, 2000 34: p. 398.

[3] Hutchinson, J., *Mixed mode cracking in layered materials.* 1992 Advances in applied mechanics.

[4] Sundararaman, S. and Davidson. B.D., *New test methods for determinning fracture toughness as a function of mode mix for bimaterial interfaces.* Application of fracture mechanics in electronic packaging and materials, 1995.

[5] ASTM Standard, *D5528: Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites.*

[6] ISO Standard, *ISO 15024: Fibre-reinforced plastic composites -- Determination of mode I interlaminar fracture toughness, GIC, for unidirectionally reinforced materials.*

[7] Lauke,B. and Friedrich. K., *Evaluation of processing parameters of thermoplastic composites fabricated by filament winding.* Composite manuafacturing, 1993. **4**: p. 93-101.

[8] Foral, F.R., *Delamination failures in curved composite laminates.* Key Engineering material, 1989. **37**: p. 197-148.

[9] Lauke, B. and K. Friedrich, *Evaluation of processing parameters of thermoplastic composites fabricated by filament winding.* Composites Manufacturing, 1993. **4**(2): p. 93-101.

[10] Ozdil, F. and L.A. Carlsson, *Characterization of Mixed Mode Delamination Growth in Glass/Epoxy Composite Cylinders.* Journal of Composite Materials, 2000 **34**: p. 420-441.

[11] Tsai, S.W. and H.T. Hahn, *Introduction to composite material.* 1980.

[12] Anderson, T.L., *Fracture Mechanics - Fundamentals and applications.* 2005.

[13] Perillo, G. and A.T. Echtermeyer, *Fracture toughness testing on interfaces of composite pipes.* To be published.