STUDY OF THE FILAMENT WOUND COMPOSITE PIPES DAMAGE

[J. F. Silva*]: jfs@isep.ipp.pt, S. Correia*, J. Monteiro, P. J. Nunes***, A. T. Marques****

*** Department of Mechanical Engineering, ISEP, Portugal**
**** DEMEGI-INEGI-FEUP, University of Porto, Portugal**
***** Polymer Engineering Department, Minho University, Portugal**

Keywords: *Damage, Fibre Reinforced Thermoplastic, ENF, ESPI*

Abstarct

Reinforced thermoplastic and thermosetting matrix pipes, produced by filament winding or centrifugal casting, may be subjected to different types of loading conditions as well as different environmental conditions. However, they may suffer damage due to unexpected working conditions (low velocity impact, such as stones, tools, etc). This paper describes a methodology based upon fracture mechanics to evaluate possible pipe damages. It reports a set of tests made to characterize materials and pipes. Fracture Mechanics tests were made in filament wound flat samples and tubular specimens were also subjected to low velocity impact tests. The study of damage evolution was done by using the ESPI (Electronic Speckle Pattern Interferometry) technique in order to determine the delamination area.

1 Introduction

The filament winding technology is used in the production of high performance composite structures for aeronautical and aerospace applications and also for more current applications, like pressure vessels or piping systems.

The determination of the critical strain energy release rate (G_{IIc}) is important to evaluate the low velocity impact damage on some filament wound composite structures, such as pipes. The peak impact force, a major key material characteristic used for establishing the damage resistance in composite structures, can, in some cases, be predicted from the elastic and G_{IIc} material properties. In filament wound pipes, interlaminar fracture may occur associated to matrix cracking, leading to significant stiffness losses.

On the other hand, the interlaminar fracture mechanics is not yet well-established for filament wound composites [1, 2].

In glass/polyester structures, the resulting delaminated area can be estimated by visual inspected. In glass/polypropylene pipes this evaluation need the use of more sophisticated NDT testing techniques, such as, C-Scan or ESPI [3].

In this paper, glass/polyester and glass/polypropylene pipes and flat panels were produced and submitted to low velocity drop weight impact and end-notched flexure testing. ESPI was used to assess damage areas.

2. Experimental

2.1 Raw-materials

The raw materials used to produce the flat and tubular specimens are type E glass fibers from Vetrotex, a isophtalic polyester resin (Cristic® 272), commingled glass and polypropylene (GF/PP) fibers, Twintex®, from Vetrotex and polypropylene powder, Icorene 9184 BP from Ico polymers France. The raw-materials relevant properties are summarized in table 1.

Table 1. Raw materials properties

Property	*Units*	GF	PP	Polyester (cured)
Density	Mg/m^3	2.56	0.91	1.20
Tensile strength	MPa	1657	19	75
Poisson ratio	-	0.26	0.21	-
Tensile modulus	GPa	62.5	0.98	3.5
Fiber diameter	µm	13.7	-	-
Particle size	µm	-	398	-

2.2 Test Specimens Production

The filament winding technology was used to produce flat or cylindrical composite structures. The flat panels were produced using a flat mandrel with a 25 µm MELINEX film inserted at half-thickness to generate the starter crack needed for ENF tests. Pipes for low velocity impact tests were produced using a more conventional tubular mandrel. For each of the above mentioned composite structures three types of raw-materials were used: a conventional glass unsaturated polyester system, glass/polypropylene towpreg prepregs, produced using a technique described elsewhere [4, 5], and commercial glass/polypropylene commingled fibres (Twintex).

A filament winding PULTRX 6 axis with a CNC control machine was used in this work. The thermoplastic matrices (towpregs and Twintex fibers) were processed by including an adequate developed set-up system in the mentioned equipment [6].

Table 2 summarizes the filament winding processing conditions used and the lay-up of the employed specimens.

Table 2. Filament winding processing conditions

Parameter	Units	Twintex	Towpreg	GF/polyester
Mandril rotation speed	r.p.m.	15	10	30
Bandwidth	mm	6	6	5
Tow tension	N	10	10	3
Pre-heating temperature	ºC	260	280	-
Consolidation temperature	ºC	280	280	-
Flat specimens lay-up	-	$[\pm 0.8^{o}]_2$		
Pipes lay-up	-	[90º ±55º 90º]		

2.3 Interlaminar Fracture Tests (ENF)

The filament wound pre-cracked flat specimens were submitted to ENF–end notched flexural tests according to the protocol proposed by the ESIS task group [7]. The specimen geometry is schematically represented in figure 1.

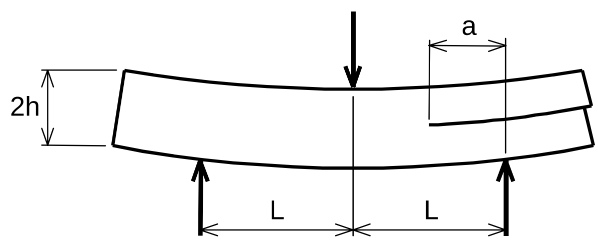

Figure1. Specimen's geometry for the ENF tests

The thickness (2h) was about 3 mm, the distance between supports (2L) and width was 100 and 20 mm, respectively. The relation a/L was always kept constant and equal to 0.5.

The calculation of the mode II strain energy release rate was done using the alternative protocol proposed by the ESIS task group, which stipulates 5% offset from linearity criteria for the determination of the critical point, corresponding to the crack initiation (figure 2). According to this criterion the critical point should be found from the intersection of a line corresponding to a compliance 5% larger than the initial one with the load-displacement curve. Also, an expression that includes the corrected beam theory was considered to calculate G_{IIc}. By this way, it was possible to obtain good results for all different materials.

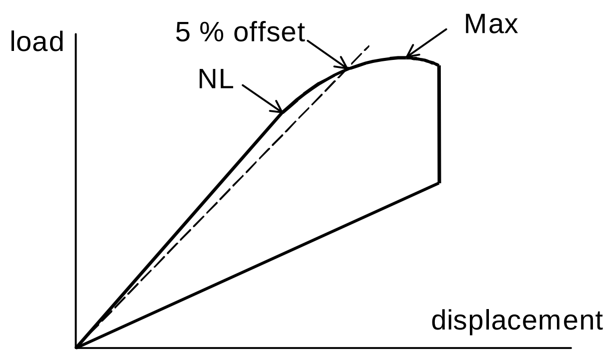

Figure 2 Used crack initiation criteria

2.4 Low Velocity Impact Tests

The low drop weight impact tests were done on the tubular specimens using a Rosand IFW5 instrumented impact test machine. The specimens were simply supported using a V shaped support represented schematically in figure 3.

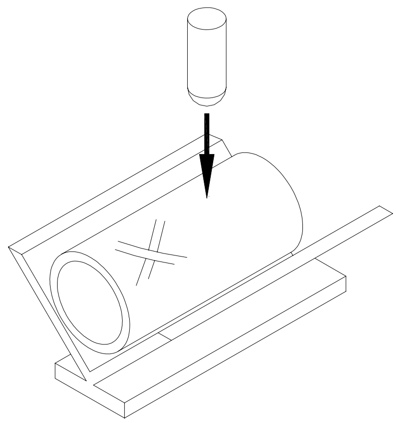

Figure 3. Tubular specimen's support for the impact tests

The used impactor had a weight of 2.853 kg and a hemispherical geometry. All tests were performed at a energy level of 10 J. Figure 4 shows a typical obtained force/time chart.

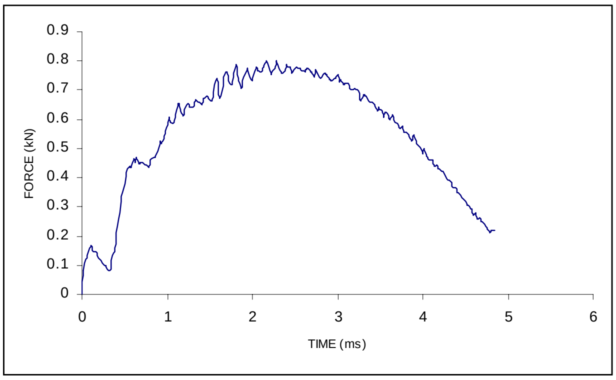

Figure 4. Force time chart from impact tests for a typical glass/polyester pipe

2.5 Electronic Speckle Pattern Interferometry (ESPI) Tests

In order to study the impact zone on pipes an interferometric technique known as ESPI (Electronic Speckle Pattern Interferometry) was used. It is a high sensitive non-contact field technique that makes use of the speckle patterns resulting from a coherent laser light illumination of a rough surface. Micron range deformations over a surface may be easily and accurately detected with ESPI [8]. Such technique is capable of providing three-dimensional displacements and dynamic response characteristics of surfaces. The set-up used in this work is schematically presented in figure 5.

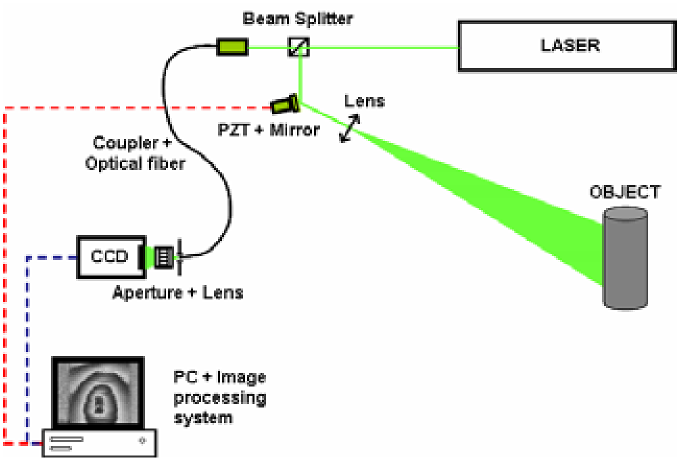

Figure 5. Schematic picture of the ESPI set-up

The interference between the two wave fronts (reference and object beams), allows the recording of the phase of the light diffused by an unloaded object, in the form of a hologram. When the object is loaded and a new hologram recorded, it is possible to obtain the deformed object shape by the correlation of both holograms.

The correlation results in an interferogram, where a set of interferometric fringes is obtained. These fringes represent points of equal displacement in the direction of the sensitivity vector [9]. The displacement difference between two adjacent fringes is half of the wavelength λ of the laser light used in the experiment ($\lambda \approx 532$ nm).

The images resulting from ESPI are then digitally processed.

In this work, temporal phase shift techniques were used to assess the phase maps corresponding to each interferometric pattern. The mirror mounted on a piezoelectric transducer (PZT) is used to modulate the phase of the interferometric patterns that, in combination with image processing techniques, allows the calculation of the spatial phase distribution.

In this work, a special four images phase shift algorithm was used to calculate the phase of each pixel. The continuous phase maps were then obtained by using a special unwrapping algorithm.

In figure 6 we can see the area of the tubular specimen to be inspected.

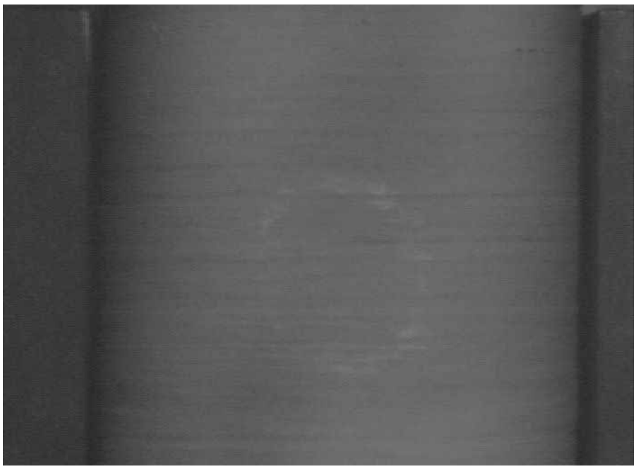

Figure 6. Specimen area to be inspected

The next picture (figure 7) depicts a typical phase map revealing the defect zone.

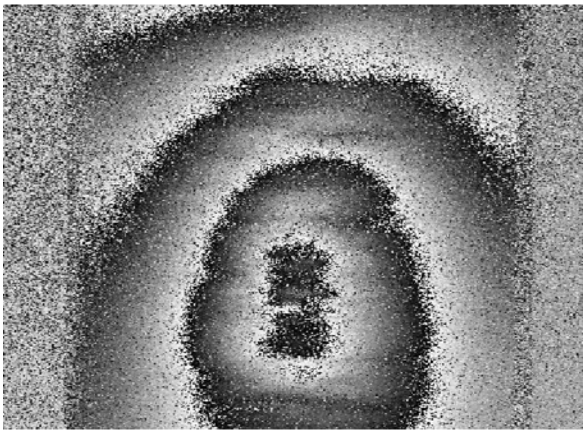

Figure 7. Phase map resulting from the captured raw fringe pattern

These results are then post processed using dedicated algorithms. In figure 8 is shown the defect zone after filtering and rigid body motion removed.

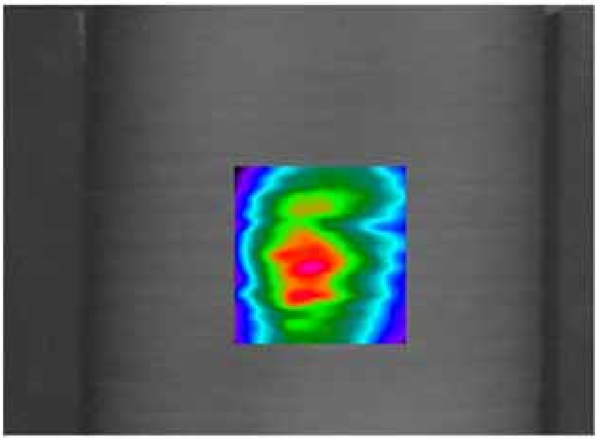

Figure 8. Defect zone after filtering

A 3D representation of the damaged zone is shown in figure 9 for better visualization. From this representation it is possible to estimate the damaged area.

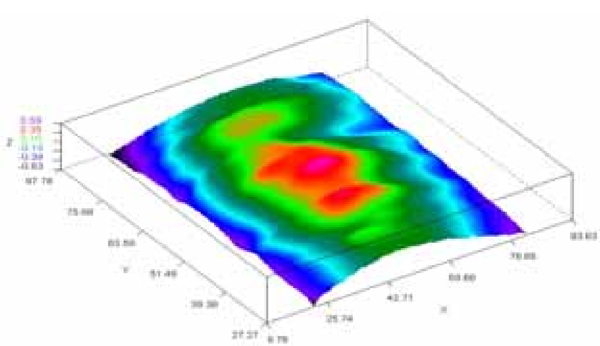

Figure 9. 3D representation of the damaged area

3. Results and Discussion

Table 3 summarizes the results obtained from the ENF tests. As can be seen, the glass polyester composite exhibits the highest value. Probably due to lower fibre impregnation, the GF/PP composites made from towpreg material have much lower G_{IIc} value than those made from commingled Twintex prepreg.

Table 3. Results obtained from ENF testing

Material	**G_{IIc} (kJ/m^2)**
Twintex®	1.00±0.06
Towpreg GF/PP	0.37 ±0.07
GF/ Polyester	2.50±0.1

The results obtained from the low drop weight impact tests made on the produced pipes are shown in Table 4. In this case, the Twintex has the best energy absorption results. Much lower values (not presented) were found for the GF/PP towpregs.

Table 4 Drop weight impact test results

(Impact at 10 J)	Units	Twintex®	GF/polyester
Maximum force	kN	1.05±0.05	0.75±0.1
Energy at max. force	J	8.4±0.8	5.0±0.6
Impact velocity	m/s	2.57±0.006	

The results obtained with ESPI were used to determine the damaged areas for Twintex pipes. For glass/polyester pipes the damage extent was evaluated by simple visual inspection.

Table 5 summarizes all determined results. The calculated values assumed a linear relation for the absorbed energy between the G_{IIc} parameter and the damaged areas [10].

Table 5. Damage areas obtained from ESPI and visual observation

Delaminated area	Units	Twintex®	GF/polyester
Experimental	mm^2	452	1850
Calculated		530	667

As can be seen, in the case of composite pipes produced from Twintex, the estimated value for the delaminated area is in accordance with the experimental obtained values.

For glass/polyester pipes the estimated value for the delaminated area is much lower than the measured values.

4. Conclusions

The following major conclusions were obtained from this work:

- the powder coating equipment allowed producing GF/PP towpregs for being easily processed into flat and tubular composite structures by filament winding;
- critical strain energy release rates (GIIc) were properly determined for the different materials by the employed methods;
- the ESPI technique can be used to determine accurately delamination areas on GF/PP composites;
- composites made from Twintex® exhibited better damage tolerance than traditional GF/polyester ones.

References

[1] Ozdil, F., Carlsson, L.A. and Li, X., 'Characterization of mode II delamination growth in glass/epoxy composite cylinders', Journal of Composite Materials, **34**, pp. 274-298, 2000.

[2] António Torres Marques, Alfredo Balacó de Morais, João Francisco Silva and Paulo Tavares de Castro, ‘Fracture Mechanics Concepts and Structural Integrity of Filament Wound Pipes’, Fracture Mechanics Applications and Challenges, ESIS Publication **26**, pp. 253-260, 2000.

[3] W. -C Wang, C. -H. Day, C. –H. Hwang and T. –B. Chiou. ‘Nondestructive Evaluation of Composite Materials by ESPI’, Research on nondstructive evaluation, **10**, pp. 1-15, 1998.

[4] Nunes, J. P., Silva, J. F., Marques, A. T., Crainic, N., Cabral-Fonseca, S., Production of Powder Coated Towpregs and Composites, Journal of Thermoplastic Composite Materials, **16** (3), 2003.

[5] Nunes, J. P., Silva, J. F., Marques, A. T., van-Hattum F. W. and Bernardo C. A., Advances in Thermoplastic matrix Towpreg Processing, Journal of Thermoplastic Composite Materials, Vol. **17** (6), 2004.

[6] J. P.Nunes, J. F. Silva, F. W. J. Van-Hattum and A. T. Marques, Filament Winding Processing Conditions to Produce Thermoplastic Composites from Towpregs, ANTEC04, Chicago, USA, 2004.

[7] Protocols for interlaminar fracture testing of composites. ESIS-Polymers & Composites Task group. Edited by P. Davies, 1993.

[8] Silva Gomes J, Monteiro J and Vaz M, NDI of interfaces in coating systems using digital interferometry, Mech. Mater. **32** 837–43, 2000.

[9] Burch, J. M.; Holographic Measurement of Displacement and Strain, Journal of Strain Analysis, Vol. **9**, nº 1, 1974.

[10] S. R. Frost and A. Cervenka, Glass fibre Reinforced Epoxy Matrix Filament-wounded Pipes for use in the Oil Industry’, Composites Manufacturing, 5, pp. 73-81, 1994.