Experimental and numerical study of adhesively bonded tubular specimens under uniaxial loading

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Abstract

The aim of this paper is the study experimentally and numericaly the mechanical behavior of E glass fiber/ Vinylester resin adhesively bonded tube using Araldite adhesive. The tensile tests have shown that, the mechanical behavior can be described by two phases. The first phase concerns the linaire elastic behavior. The second phase, is observed by a non lineaire behavior accompanied by the apparition and propagation of cracks in the bonding zone leading to the failure of the bonding interface. The damage mechanisms have been investigated thanks to scanning electron microscopy. In order to predict the mechanical behavior and the damage propagation of joined composite tube observed during the tensile tests, a numerical model is proposed. Mainly a good agreement between experimental and numerical results has been obtained.

1. Introduction

Filament-wound composites tubes are being increasly used for several industrial applications owing to their high strength, light weight, high stiffness in addition to their good corrosion resistance [1-2-3].
The manufacturing phase of these structures is usually followed by the assembling step. For composite structures, adhesive bonding technique appears to be the most suitable solution since materials are highly anisotropic and inhomogeneous causing stress concentration in the holes used for bolting or riveting.
The necessity to reduce the cost of the adhesive bonding technique and the growing demand to get light structures were the main cause to ameliorate the joining process. In this context, and with the collaboration of "Chaudronnerie Tuyauterie Resine Anticorrosion" CTRA Company composites tubes have been manufactured for a potential application in the chemical industries.

The mechanical behavior of adhesively bonded specimens has been the subject of servel studies [4-5]. A.Parashar et al [6] have studied the failure mechanisms of joined tubes. P.Mertiny et al [7] focused their research on the evolution of damage mechanisms under fatigue loading of adhesively bonded tube. A comparison between the mechanical behavior of bolted and bonded joint tube was conducted by T. Vallée et al [8].

In the present study, the mechanical behavior of glass fiber reinforced Vinylester resin adhesively bonded tubes under tensile loading was investigated. To better understand the different mechanisms of damage which manifest during loading SEM postmortem observation have been conducted. A finite element model based on the concept of the meso-model [9] has been formulated. The meso-model is

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defined by two meso-constituents: layer and interface. This model is used for studing composite failure mechanisms and replace the classical damage model (micro and macro).

2. Experimental procedure

2.1. Composite material

Composite tubes were produced by CTRA Company (Tunisia) using a filament winding technique. The tubes were formed by the superposition of two types of layer. The first layer named anti-corrosion (AC) which is made glass fiber mat. The second layer called mechanical layer (RM) was formed by a bundle of E-glass fiber impregnated Vinylester resin (VE). After the manufacturing phase, the specimens were adhesively bonded using Araldite 2014-1 adhesive. The dimensions of the joined tube are illustrated in Fig. 1.
Mechanical properties of the VE matrix, E-glass fiber are summarized in table 1.

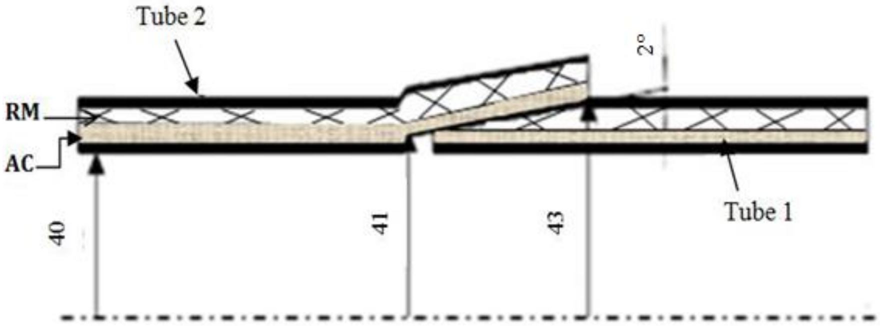

Figure 1. Dimension of adhesively bonded tube

Table 1. Mechanical properties of VE resin and glass fiber

Specimen Type	*Tensile strength* (MPa)	*Tensile modulus* (GPa)	*Tensile elongation (%)*
Resin	86	3.2	5-6
Glass Fiber	1970	78.8	-

2.2. Tensile tests and characterization of damages

Tensile tests have been conducted according to ASTM-D 2105-01[10] standard using SHIMADZU UH-F30A machine. A customized fixture was designed to hold the specimens in the tensile testing machine as shown in Fig. 2. The tests have been carried out with an imposed velocity of 10 mm/min. In order to better understand the damage mechanisms of adhesively bonded tubes, scanning electron microscope (SEM) observations have been conducted after the uniaxial tensile test.

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Figure 2. Experimental device developed for joined specimen for tensile test

2.3. Microscopie analysis

3. Results and discussion

A series of tensile tests have been performed on E glass/Vinylester resin adhesively bonded tubes, in order to predict their mechanical behavior. The results of these tests are shown in Fig. 3. From this curve, it can be observed that the mechanical behavior curve can be divided into 2 zones. For the first zone, a quasi-linear behavior can be noticed up to 2.3 mm. This linear behavior is associated to undamaged state. The second zone is characterized by decreasing slope which indicated the non-linear behavior. This zone is distinguished by the apparition and propagation of some cracks located in the bonding area. With the increasing load, several macro damages, namely transverse cracking of the matrix, matrix/fiber debonding and delamination are observed. At a displacement of about 7.2 mm, a pronounced peak was recorded, which correspond to the failure of the bonding interface.

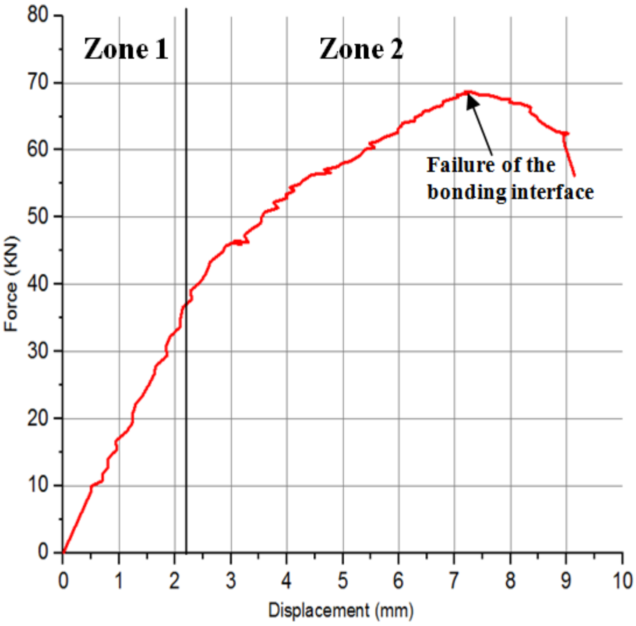

Figure 3. Mechanical behavior of E glass/ Vinylester resin adhesively bonded tubes under tensile load

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Matrix failure, fiber failure and fiber/matrix debonding are the damage mechanisms observed in the bonding area during the tensile test.

It was shown from the analysis of these microscopic images that, cracks are dispersed in the bonding zone. Figure 4 (a) show the failure of the matrix and fiber. The fiber/matrix debonding as illustrated in Fig 4(b) is also caused by external solicitations.

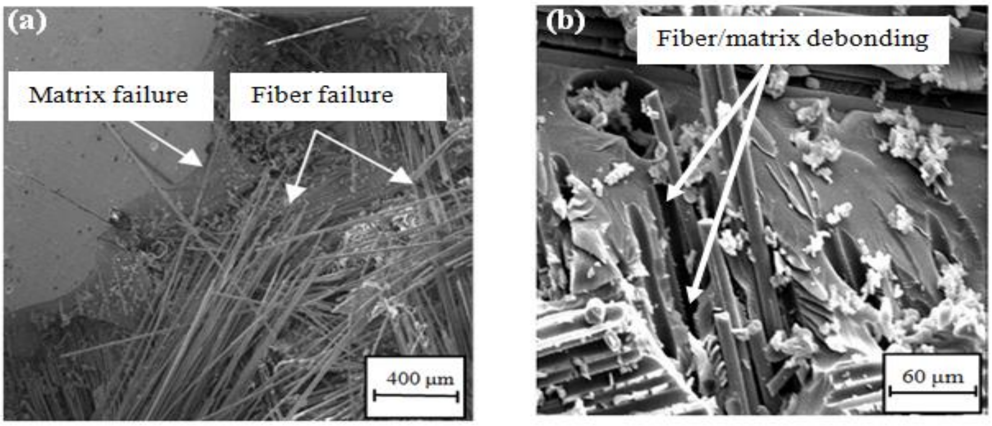

Figure 4. Microscopic observation of bonded area of glass fiber/VE resin tube (a) fiber and matrix failure (b) fiber/matrix debonding

4. Numerical model

In order to predict the mechanical behavior of joined specimens, a FE model was performed based on the concept of the meso-model [9]. A non linear analysis were conducted using SAMCEF software and volume composite elements. The adhesive was modeled with a two dimensional damageable entity. The anti-corrosion layer is modeled with elastic behavior. The mechanical layer is considered as a plastic damageable material with two ply degradation mechanisms i) matrix microcraking and (ii) fibre/matrix debonding. Figure 5 presents the meshed with boundery conditions of the proposed model. The tube 1 was constrained from translation and rotation. A displacement was imposed on the rigid node which is connected to the tube by different rigid elements on the upper face of the tube 2.

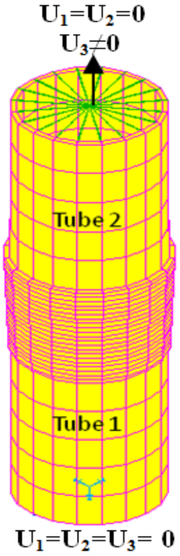

Figure 5. Mesh of the proposed numerical model of joined specimen with boundary conditions

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4.1. Damage Kinematics of the interface

The strain energy of the interface is given by the following equation

$$E_D = \frac{1}{2}[\frac{\sigma^2{}_{33}}{k_3(1-[\sigma_3]d_1)} + \frac{\sigma_{13}{}^2}{k_1(1-d_2)} + \frac{\sigma_{23}{}^2}{k_2(1-d_3)}] \qquad (1)$$

where: d$_1$, d$_2$, d$_3$ are the damage variables,
K$_1$, K$_2$, K$_3$: elastic properties of the interface.
The damage is piloted by an equivalent force

$$Y = [(Y_{d3})^{\alpha} + (\delta_1 Y_{d1})^{\alpha} + (\delta_2 Y_{d2})^{\alpha}]^{\frac{1}{\alpha}} \qquad (2)$$

α: material parameter,
δ_1, δ_2 : coupling parameters.
The damage evolution law is written in the following form:

$$W = (\frac{n}{1+n}\frac{<Y-Y_0>}{Y_c - Y_0})^n \qquad (3)$$

$$\left| \begin{array}{ll} d_1 = d_2 = d_3 = W(Y) & \text{if } d<1 \\ d_1 = d_2 = d_3 = 1 & \text{otherwise} \end{array} \right.$$

where: Y_c represents the critical value,

Y_0 represents the threshold value.

4.2. Damage Kinematics of the ply

The strain energy of the ply is written in the following form

$$E_D = \frac{1}{2}[\frac{<\sigma_{11}^2>}{E_1^0} + \frac{\varphi(<\sigma_{11}>)}{E_1^0} - \frac{2\upsilon_{12}^0\sigma_{11}\sigma_{22}}{E_1^0} + \frac{<\sigma_{22}>^2}{E_2^0(1-d^{'})} + \frac{<\sigma_{22}>^2}{E_2^0} + \frac{\sigma_{12}^2}{G_{12}^0(1-d)}] \qquad (4)$$

d, d': damage variables.
The damage evolution law of the ply is defined following the thermodynamic force

$$Y(t) = \sup_{\tau \le t}(\sqrt{Y_d(\tau) + bY_{d'}(\tau)}) \qquad (5)$$

where

$$Y_d = \frac{\partial E_D}{\partial d} = \frac{1}{2}\frac{\sigma_{12}^2}{G_{12}^0(1-d)^2} \qquad (6) \qquad\qquad Y_{d'} = \frac{\partial E_D}{\partial d'} = \frac{1}{2}\frac{\sigma_{22}^2}{E_2^0(1-d')} \qquad (7)$$

b: coupling parameter

In summary, the interface model depends on damage parameters $G_I, G_{II}, G_{III}, \alpha$ and on elastic parameters K_1, K_2, K_3.

The ply model depends on several material parameters:

Elastic parameters: $E_1^0, E_2^0, E_3^0, G_1^0, G_2^0, G_3^0, u_{12}^0, u_{13}^0, u_{23}^0$

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Damage parameters: $Y_0, Y_0^{'}, Y_c, Y_c^{'}$ and b

Plasticity parameters: a^2, K, γ and R_0

The different parameters are listed in table 2,3 and 4.

Table 2. Summaryse of the parameters of the mechanical layer

Elastic parameters	E_1 (MPa)	E_2=E_3 (MPa)	G_{12}=G_{13} (MPa)	G_{23} (MPa)	$\upsilon_{12}= \upsilon_{13}$	υ_{23}
	7010	5296	1200	2037	0.28	0.3
Damage parameters	Y_0 (MPa)	Y_c (MPa)	$Y_0^{'}$ (MPa)	$Y_c^{'}$ (MPa)	b	
	0.01	3.24	0.014	1	4.4	
Plasticity parameters	R_0 (MPa)	K (MPa)	a	ɣ		
	11.6	1194	0.9	0.57		

Table 3. Elastic paramaters of anti-corrosion layer

Elastic parameters	E_1 (MPa)	E_2=E_3 (MPa)	G_{12}=G_{13} (MPa)	G_{23} (MPa)	$\upsilon_{12}= \upsilon_{13}$	υ_{23}
	8800	5250	3180	1590	0.3149	0.2280

Table 4. Summaryse of the parameters of the bonded interface

K_1^0 (MPa/mm)	K_2^0 (MPa/mm)	K_3^0 (MPa/mm)	n	α	G_I (KJ/m^2)	G_{II} (KJ/m^2)	G_{III} (KJ/m^2)
2400	4074	5296	0.5	0.9	3	6	1

4.3 Numerical result

The comparison between experimental and numerical results of adhesively bonded tube are shown in Fig. 6. It was found that numerical curve was linear up to 2 mm and became non linear up on increasing the force level. This non linearity can be explained by the crack initiation and propagation in the bonding area. This result was confirmed by the damage cartography as shown in Fig. 6. A good agreement between experimental and numerical results has been obtained. However, an error of about 11% has been observed.

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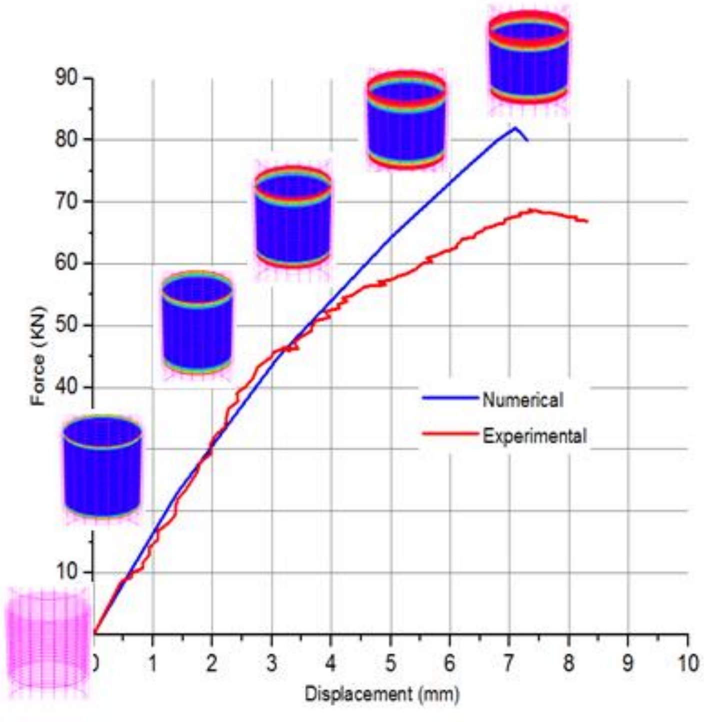

Figure 6. Numerical and experimental results of tensile test of adhesively bonded tube

This may be explained by the fact that, the behavior of anti-corrosion layer was considered as elastic. Furthermore, matrix microcraking and matrix/fiber debonding were the only two damage mechanisms considered for mechanical layer in the numerical model. However, during the experimental study, several damage mechanisms were noticed either in mechanical or in anti-corrosion layer.

5. Conclusions

Mechanical behavior of joined composite tubular specimens was investigated experimentally and numerically under uniaxial loading. The following conclusion can be drawn:

- From the experimental study, it was observed that the mechanical behavior of adhesively bonded tube has 2 distinct phases: linear elastic behavior and nolinaire behavior followed by the apparition and propagation of cracks in the bonding area.
- The SEM analysis reveal that damage mechanisms observed are mainly fiber/matrix debonding, matrix failure, transverse failure of the interior of ply followed by fiber failure.
- The numerical study based on the concept of the meso-model has been investigated. The composite tube has been modeled by two constituents: the layer and the interface. A good agreement has been obtained between experimental and numerical results with a small diffrence noticed from a displacement of 4.5 mm. This difference can be explained by the fact that the anti-corrosion layer was considered as elastic material and only two damage mechanisms namely matrix microcracking and fiber/matrix debonding were considered in the model for mechanical layer.

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