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Mechanical behavior of polyurethane adhesive joints used in laminated materials for marine structures

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ABSTRACT

One of the most relevant applications of adhesives in shipbuilding is the manufacturing of structural laminated materials. In this study, a new sandwich structure with a polyurethane adhesive joint, composite material and steel is evaluated. The use of this material in a marine environment for long periods of time and under adverse environmental conditions leads to accelerated degradation of the polyurethane adhesive. Therefore, to guarantee suitable functioning of the adhesive joint over a long period of time under adverse conditions and variable stress modes, a specific experimental procedure is required. For this purpose, we report a new experimental procedure for investigating the mechanical behavior of polyurethane adhesive joints.

Test results have led to the conclusion that steel–polyurethane–steel adhesive joints immersed in sea water exhibit the best behavior in service when subjected to shear stress. In addition, the comparative analysis of the results obtained for the fracture energy and cohesive laws indicated that immersion in distilled water has a favorable effect on the behavior of the joint when subjected to peel stress and shear stress. Similarly, the low values of tangential and normal stress in the joints that were immersed in seawater indicate that this joint undergoes a progressive degradation process.

1. Introduction

Adhesive joints are increasingly used in industry because they offer many advantages compared to other traditional bonding methods, such as welding or riveting.

The advantages of adhesives include the capacity to join different materials and irregular geometries as well as a lower weight, more uniform stress distribution, resistance to galvanic corrosion and tightness. Therefore, the marine industry is one of the fields where adhesives are widely used. In particular, one of the most relevant applications of adhesives in shipbuilding involves the manufacture of structural laminated materials. For example, in the Malecon© hybrid material (Herreros et al., 2008), adhesives play a very important role. This material has a sandwich structure that is composed of an adhesive steel joint, composite material (fiberglass and vinylester resin) and steel. Therefore, the structural adhesive is present both in the composite material (vinylester resin) and in the joints between this adhesive with the steel (polyurethane adhesive).

The use of this material in a marine environment over a long period of time and under adverse environmental conditions (i.e., humidity, temperature, and concentration of ions chloride) results in accelerated degradation of the polyurethane adhesive (Alía et al., 2013). This degradation leads to a decrease in the mechanical performance, which can result in failure of the adhesive joint (Davis, 2011; Ashcroft and Comyn, 2011).

A great deal of research has focused on the effects of temperature and humidity on adhesive joints. Most of these studies independently assess the influence of both factors (Sargent, 2005; Doyle and Rethick, 2009; Bowditch, 1996). However, the simultaneous and combined action of humidity and temperature has a synergistic effect on the evolution of the mechanical behavior of the adhesive. Therefore, Datla et al. (2011) studied the combined effect of both temperature and humidity on the fatigue of aluminum bondings. Under dry conditions, an increase in temperature to 80 °C had an insignificant effect, and at 40 °C, the fatigue behavior was not influenced by humidity. However, humidity and temperature did influence the growth patterns of the crack. Therefore, a shift towards the adhesive/adherend interface was observed under saturated humidity. In addition, Loh et al. (2005) studied the effect of mass adhesive samples under different humidity conditions, and at 50 °C, an increase in the level of saturation was due to the relative humidity. A two-stage model

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was proposed for absorption, which provided excellent adjustment results, and this model was easily modeled with finite elements.

The mechanical properties of the adhesive polyurethane changed over time, especially when the sample was subjected to a variable load over a long period of time (Anderson and Stigh, 2004; Feng et al., 2005; Sen et al., 2002). In addition, adhesive bondings rarely work by traction or pure shear stress (mode I or mode II). However, these bondings are typically loaded in a mixed mode (mode between peel and shear) (Chai and Chiang, 1996; Chai, 2003; Högberg and Stigh, 2006).

Therefore, to guarantee suitable functioning of the adhesive joint over a long period of time under adverse conditions (i.e., temperature and humidity) and with variable stress modes, a specifically designed test must be developed to obtain experimental data from the evolution of the deformations in the bond line to determine the cohesive behavior of the adhesive (Sørensen, 2002; De Moura et al., 2008).

For this purpose, we report an experimental procedure to investigate the mechanical behavior of substrate–adhesive bonding under load for an extended period of time, which is subjected to variable environmental conditions and mixed mode requests. In these tests, a specimen called a mixed cantilever beam (MCB) should be used. This specimen, which was designed by Högberg and Stigh (2006), exhibits flexibility, variety and stability and offers a suitable geometry for studying the cohesive behavior of the adhesive and the energy of the adhesive fracture. In addition, using special tools (Suárez et al., 2010), the sample can be subjected to stress in a mixed mode between modes I and II. In addition, the testing under different environmental conditions and stress modes required the design and construction of a specific test unit that allowed us to obtain experimental data from the evolution of the deformations in the bond line to determine the cohesive behavior laws.

To demonstrate its suitability, the developed experimental method was applied to a steel–polyurethane–steel joint. Therefore, the mechanical behavior of this adhesive joint has been experimentally investigated when subjected to long-term tests, adverse environmental conditions (i.e., immersion in seawater and different temperature) and stress in different mixed modes between peel (mode I) and shear (mode II). The obtained experimental data for the evolution of the deformations in the bond line allows us to determine the cohesive behavior of polyurethane.

2. Adhesive fracture in mixed mode and cohesive laws

The stress that is applied to an adhesive joint under service conditions and the determination of the maximum force applicable to the bond are complex when typical defects occur in the adhesive joints. In this case, it is appropriate to apply fracture mechanics where the maximum stress in a material is due to the defects it contains. Although the use of these fracture mechanisms is more complex compared to other methods, they are more reliable and efficient for studying adhesive bonds (Suárez et al., 2010; Ashby and Jones, 2008).

Adhesive joints typically work in mixed mode (i.e., a relationship between peel stress (mode I) and shear stress (mode II)). However, the fracture energy (J_C) and morphology of the adhesive bond changes with the thickness of the adhesive layer (Anderson and Stigh, 2004).

Simplified analysis of adhesive bonds based on stress and strain measurements are satisfactory, and the basic variables produced in the adhesive layer are normal stress (σ), shear stress (τ), normal strain (w) and shear strain (v) (Högberg and Stigh, 2006; Suárez et al., 2010; Ashby and Jones, 2008). Fig. 1 shows the stress distribution in a thin layer of adhesive.

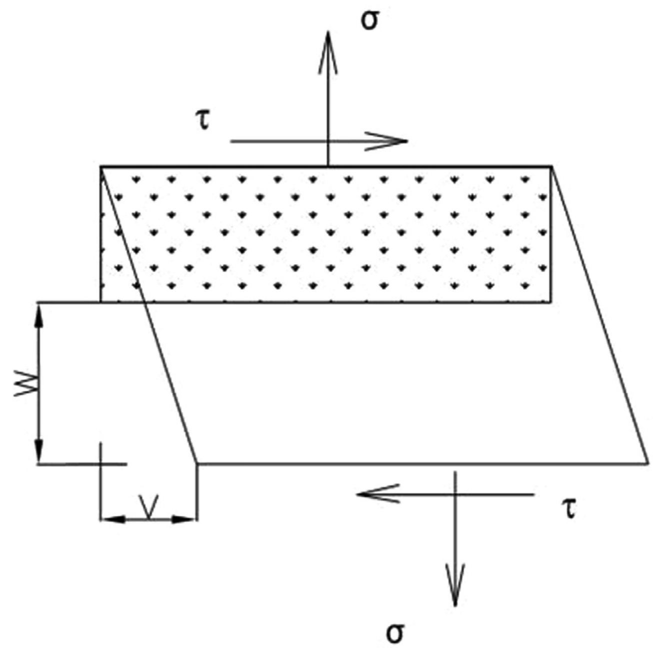

Fig. 1. Stress and strain distribution in a thin layer of adhesive.

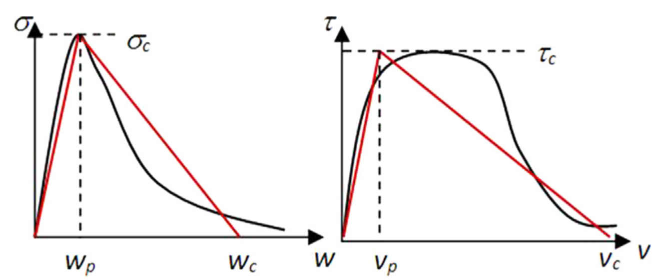

Fig. 2. Simplified model of the cohesive law for adhesive loaded with pure modes I and II.

In these simplified studies, the theory of the adhesive layer (Suárez et al., 2011) is applied. Therefore, the area of the process must be large compared to the thickness of the layer for these studies to be suitable. Under these conditions, fractures mechanisms can be used via a load parameter (i.e., fracture energy (J_C)). However, the gradients along this thickness should be taken into account.

By applying the theory of the adhesive layer, the mechanical macroscopic properties of an adhesive layer can be described by constitutive relations (i.e., by expressing the stress status according to the adhesive layer deformation (in addition to the material and the properties of the adherends)). Under a constant load increase, the stress increases up to a certain value when plastifying starts and damage occurs. Later, the stress decreases down to zero. At this point, the strain increased to a critical value (w_c), and the dissipation energy in the fracture process zone (FPZ) has reached a critical value. This fracture energy (J_C) is identified as the area under the curve (Fig. 2). After this critical point, crack propagation occurs, and new surfaces are formed.

For adhesive joints, the essential relationship represents the mechanical behavior of the entire adhesive layer (either before or after the crack). Mathematically, the essential relationship can be represented by traction–separation models, which are also known as “Cohesive Laws”. These laws have been used to model the initiation and propagation of cracks in the adhesive layer (Schmidt,