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Experimental and numerical investigation of shear strain along an elasto-plastic bonded lap joint

Sylvain Chataigner [a,b,*], Jean-Francois Caron [a], Van Anh Duong [a], Alberto Diaz Diaz [c]

[a] Université Paris-Est, UR Navier, UMR CNRS-LCPC, Ecole des Ponts Paristech, 6-8 Avenue Blaise Pascal, 77455 Marne La Vallée Cedex 2, France
[b] LRPC d'Autun, Boulevard de l'Industrie, BP 141, 71 405 Autun, France
[c] CIMAV, Miguel de Cervantes 120, Complejo Industrial Chihuahua, 31109 Chihuahua, Chihuahua, Mexico

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ABSTRACT

This study investigates the use of an elasto-plastic adhesive in a bonded double lap joint to increase its ultimate capacity. The first section describes the experimental work we performed to characterize the materials and measure the shear strain along the joint. A comparison between an elastic adhesive and a highly plastic adhesive is made and the effect of the type of behaviour on both the capacity and the characteristic anchorage length is studied. The second section then compares the experimental results with a classical 3D finite element model. Good correlation was found between numerical expectations and experimental measurements, and the modelling allowed us to highlight typical phenomena linked to the use of an elasto-plastic adhesive. In addition, a parameter based on a microscopic measurement has been defined which allows us to describe the onset of plasticity and predict maximum capacity.

1. Introduction

The technology of adhesive bonding is currently under close investigation in order to obtain a good understanding of the mechanisms at work in this kind of assembly and identify the key parameters for proper design, high quality manufacture and long service life.

In view of the fact that different kinds of adhesion forces exist [1,2], and that these are highly influenced by the surface preparation, it is easy to see the importance of the manufacturing stage with regard to optimizing joint capacity. The quality of manufacture is mainly determined by the surface preparation and the curing conditions of the adhesive. Similarly, the service life will be determined by the exposure of the adhesive, which is an organic material, to extremes of humidity, solar radiation, and temperature. In the case of structural adhesive bonding, the quality of manufacture and service life are thus closely linked to the characteristics of the material and the adhesion forces.

Proper design is achieved more by reducing stress concentrations and studying the stress distribution within the joint. This aspect has been investigated by a large number of researchers who have highlighted the importance of detailing geometries and choosing materials with suitable characteristics when designing the bonding technology so as to reduce the concentration of both shear and peel stresses. As adhesive joints work best in shear, most of the studies have focused on determining the shear stress, which is nonlinear along the lap length [3–5]. The following approach was thus adopted to reduce the observed shear concentrations on the edges of the lap length. First, some researchers worked on the geometry of the adhesive fillets [6,7] or the adherends at the ends of the joint [8]. Others then studied the use of adherends with variable thickness [9] or variable modulus [10]. The geometry and the flexibility of the adherends has therefore been thoroughly investigated. As far as the adhesive is concerned, some studies have analyzed the use of two adhesives with different moduli [11] or graded modulus adhesive [12].

The considerable number of difficulties associated with adhesively bonded joints mean their design is a difficult process. For civil engineering applications, the design process has to be both simple and reliable. The authors of this study have conducted a large number of investigations to obtain a better understanding of the way adhesively bonded joints work either in the case of concrete reinforcement using a composite material [13] or the assembly of composite structures [14]. This understanding means that simplified modelling procedures often based on analytical methods can be applied for adhesively bonded joints. One such approach, which has recently been patented, has been used to design an optimized adhesively bonded anchorage [15].

This study focuses on the identification of conveniently and accurately measurable macroscopic values to characterize a bonded joint for the design of an anchorage for a pultruded carbon

* Corresponding author at: LRPC d'Autun, Boulevard de l'Industrie, BP 141, 71 405 Autun, France.
E-mail address: sylvain.chataigner@developpement-durable.gouv.fr (S. Chataigner).

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plate on a pedestrian footbridge [16]. More particularly, we have investigated the role of the plasticity of the adhesive in bonded lap joints. This topic was first considered by Hart-Smith [17]. Another analytical study which has examined the influence of plasticity on the anchorage length considers multilinear behaviour of the adhesive and is described in [14]. Both these studies were concerned only with determining stress profiles. Shear strain along the lap length is dictated by the plastic flow rule which these analytical procedures do not consider.

In order to compare the experimentally measured strain to the theoretically expected values it is necessary to use numerical modelling, for example finite element techniques. Among the first to conduct such modelling were Bigwood and Crocombe in [18]. The importance of the use of nonlinear models for some of the adhesives used in the industry has been highlighted in [19]. These authors described the inadequacy of the simple Von Mises yield criterion. However, in the modelling presented below, this criterion has been adopted to make an approximate comparison between different models. Further work will address the issue of the most suitable criterion, taking account of the sensitivity of the adhesive to hydrostatic stress and using a Drucker–Prager yield criterion as described in [15,20].

In the first part of this paper, we have shown that plasticity changes in the adhesive drastically modify the behaviour of the bonded joints. In particular, they affect the characteristic anchorage length, and hence the maximum capacity. With regard to the design procedure, our work concentrated on understanding the adhesive behaviour of the adhesive. Combining experimental results obtained from characterization tests and the observation of strain along bonded double lap joints with theoretical modelling enabled us to represent the effect of nonlinear behaviour of this type. The modelling was shown to closely match the strain measurement based on microscopic study of the adhesive in shear.

We shall begin by presenting the experimental investigations. These involved several steps: the characterization of the different materials, bonded joint failure tests, and measurement of shear strain along the lap lengths for both elastic and elasto-plastic adhesives. A global quantity related to the 3D shear strain, the slip, was identified, rigorously defined and chosen as a potential global macroscopic parameter for characterizing a joint. The second section then describes the use of finite element modelling to analyze these experimental results and investigates the usefulness of slip as a design parameter. This finite element modelling took account of the nonlinear behaviour of the adhesive in order to determine the shear strain along the lap length. Finally, a comparison has been made between the experimental results and those obtained from this numerical modelling. Some of our observations have also been tied in with other theoretical results.

2. Experimental investigations

The first stage of the study was experimental and consisted of using an elastic and an elasto-plastic adhesive with unidirectional pultruded carbon plates as adherends in a bonded lap joint. Tensile tests were conducted to observe the behaviour of the adhesive. Obviously, its shear behaviour may differ from its tensile behaviour, particularly in the case of thin adhesive layers. However, the adhesive joints used in civil engineering are relatively thick and the anisotropy of the adhesive material observed in some studies [21] is certainly less likely to occur. For this reason it was decided that it would be acceptable to adopt the hypothesis of isotropy in this study to simplify calculations. After the characterization of the materials alone, several series of bonded joints were tested to find the differences in terms of maximum capacities and to study the strain profiles along the lap lengths. The procedure used to manufacture the bonded joints was very similar to that applied in [14] and will be described more precisely at the end of this section.

2.1. The used materials

The adherends and the two adhesives were subjected to tensile tests. The tensile tests were conducted at low speed to limit the impact of viscosity effects on the results. Although viscosity effects may be relatively large for this kind of polymer, it was decided not to include them in the initial modelling. More details about viscosity may be found in [22]. The strain was measured using conventional strain gauges.

For bonding, two-component epoxy adhesives were used in both cases. The first, which exhibits elastic behaviour is more commonly used for reinforcing concrete structures with carbon plates. Its tensile Young's modulus was found to be 4940 MPa (Fig. 1). The second, exhibits elasto-plastic behaviour, and is a commercial industrial adhesive. Its tensile behaviour breaks down into two parts: an elastic part and a plastic plateau. The elastic tensile modulus was found to be 2500 MPa, and the plateau was reached at 37 MPa (Fig. 1). The shear properties were obtained from the tensile properties, assuming the materials were isotropic. Although we shall not consider it in depth in this study, readers should bear in mind that the question of whether adhesives have isotropic behaviour or not in bonded joints is still unresolved, as mentioned in [21]. As the same study [21] has found the differences in shear modulus between bulk material and joint material to be fairly small, the isotropic hypothesis seemed to be a reasonable starting point. Besides, in the special case of civil engineering applications, adhesive joint thicknesses are usually relatively large reducing the danger of the alignment of internal loads which may be responsible for anisotropic behaviour. Poisson's ratio was considered to be 0.3 for both adhesives. In the manufactured bonded joints, the adhesive thickness was 0.6 mm for the elastic adhesive, and 0.25 mm for the elasto-plastic adhesive, fulfilling the recommendations in the technical data sheet.

The orthotropic behaviour of the pultruded carbon plate was determined using two tensile tests, and the "rule of mixture" theory. The tensile Young's modulus in the fibre direction was 162,000 MPa, and in the transverse direction 10,600 MPa. The Poisson's ratio was found to be 0.325. The rule of mixture gave then an out-of-plane shear modulus of 4077 MPa. The used pultruded plate was 1.2 mm thick and 20-mm wide.

2.2. Bonded joints

Double lap bonded joints were chosen in order to minimize peel stresses and obtain shear stresses in the adhesive joint. A careful manufacturing procedure was applied to ensure good alignment of the adherends. The bond thickness was controlled by embedding two nylon wires within the joint, far from the edges to avoid disturbing these critical zones. In order to investigate the behaviour of the bonds thoroughly, a first series of tests was conducted to find the optimum surface preparation for achieving cohesive rather than adhesive failure of the joint. The results were different for the two adhesives. While simple degreasing appeared to be sufficient for the elasto-plastic adhesive, additional mechanical abrasion was necessary in the case of the elastic adhesive to obtain cohesive failure, which actually occurred as a result of interlaminar failure of the pultruded plate. The failure mode was checked using microscopic observation of the bonded joints after failure (Fig. 2).

Once the surface preparation was determined, several series of tests where the bonded length was varied were conducted. These series provided a good idea of the typical anchorage length of the assembly for each of the two adhesives. For the elastic adhesive,