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Experimental & numerical study of the Tensile/Compression-Shear Arcan test under dynamic loading

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ABSTRACT

The characterization of the adhesive of bonded assemblies under combined and dynamic loading cases appears to be crucial for the development of the future structures dedicated to the transport industry. To date, most of the tests on adhesive joints are dedicated to comparative studies and only a few ones to characterization. Among these, the stress concentration-free bonded Arcan Tensile/Compression-Shear test specimen (Arcan TCS) developed by Créac'hcadec *et al.* allows to characterize the adhesive of bonded joints under combined quasi-static loading cases while minimizing the edge effects. This paper deals with an extension of the use of this specimen under dynamic loadings.

In a first part, an experimental study of the Arcan TCS device under drop weight conditions is made. The mechanical behaviour of the adhesive appears to be non-linear and clearly dependent of the strain rate. Also, stress-strain curves highlight a significant influence of tests conditions. In particular, the way the kinetic energy is transmitted by the falling mass to the testing device plays a significant role on the vibrational behaviour and the loading rate of the specimen.

In a second part, a dedicated finite element model is built under the plane stress and elastic assumptions. Results extracted from this numerical study are in agreement with several experimental observations. Moreover, they allow a better understanding of the loading seen by the adhesive.

1. Introduction

With a global aim of mass reduction of structures, the main transport industries, aeronautics, aerospace and automotive for instance, have increased the use of structural adhesive as a mean of multi materials assembly [1–3]. Regardless of the sector, the integration of bonded joints requires a fine knowledge of the mechanical behaviour under complex impact conditions (*e.g.* during a car accident for automotive or a bird strike for aeronautics) in order to ensure the safety of users. Experimental tests and analysis on structures are complex and expensive. It appears therefore essential to develop modeling strategies relying on reliable experimental data and suitable material laws.

Nowadays, several test methods exist to determine the impact properties of some kind of joints with different geometries. One can cite the Izod and Charpy pendulums, split Hopkinson pressure bar (SHPB) techniques, drop weight methods and servo hydraulic systems. Goglio in [4], da Silva *et al.* in [5] and Sato in [6] provide excellent reviews of these experimental test methods. Although many standardized tests are available for the evaluation of mechanical properties of adhesives under quasi-static loadings, to our knowledge there are only two methods for dynamic conditions: the ISO 11343 Wedge Impact Peel Test [7] and the ASTM D950-03 Block Impact Test [8]. This last one has been for years the most usual and popular test used for the evaluation of adhesive joints under impact conditions. In the test, a small block bonded to a larger one which is clamped to the base of the testing machine is impacted on its side by a pendulum hammer. Depending on the instrumentation of the device, impact energy absorbed and load-displacement curve can be extracted. However, Adams and Harris in [9] presented a critical assessment of this test due to the fact that the stress distribution in the adhesive layer is mainly dependent on the positional uncertainties of the specimen and that the way the loading is applied can produce complex dynamic effects. In addition, it was shown in [10] that the geometry of this specimen generates high stress concentrations at the ends of the overlap, usually called 'edge effects' [2,11–13], that can initiate cracks and the final failure of the specimen.

Since then, the Single-Lap Joint (SLJ) geometry commonly used

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under quasi-static loading is increasingly used in dynamic [14–21]. This last is defined by the standard test method for apparent shear strength of single-lap joint adhesively bonded metal specimens by tension loading according to the ASTM D1002-10 [22]. The specimen is composed of two thin plates bonded together. The tensile loading applied to these plates generates, as for the block impact test, a 'shear' loading inside the adhesive. Nevertheless, this test leads to several difficulties particularly in regards with the distribution of stresses in the adhesive layer [1,11,13,23,24]: (1) the bending of the thin plates generates a complex mix of shear and normal stresses in the adhesive. (2) The high rigidity gradient between the adhesive and the substrates generates 'edge effects'. Therefore, this test specimen is interesting for comparative studies but not for material characterization.

The Tensile/Compression-Shear Arcan test specimen developed by Créac'hcadec et al. [25] seems to be a promising alternative for the dynamic characterization of adhesively bonded joints. The global geometry of this specimen is based on the work of Arcan et al. [26] and allows to test the adhesive layer under different loading directions. Its local geometry (i.e. near the adhesive joint) is inspired by the test specimen used by Cognard et al. [27,28] and limits the stress singularities near the free edges. A previous in depth numerical study was conducted on the evaluation of the use of this specimen under dynamic conditions [10]. Conclusions drawn from this study are mainly positive but an experimental campaign appears to be essential to confirm or infirm the observations made. This paper complements the work done in that previous numerical study and is focused on the extension of the use of the Arcan TCS specimen under dynamic loadings.

In a first part, a global description of the specimen is made. Then, the mechanical behaviour of the Arcan TCS device is investigated through an experimental drop weight tests campaign. The non-linear and strain rate dependent mechanical behaviour of the adhesive is clearly highlighted. A parametric study is thereafter performed to investigate the influence of test parameters on the way the kinetic energy is transmitted by the falling mass to the testing device. A strong influence of the loading conditions is highlighted on the vibrational behaviour of the device.

Finally, a dedicated dynamic finite element analysis model of the specimen under elastic and 2D plane stress assumptions is proposed. A comparative analysis of experimental and numerical results provides a better understanding of the physical phenomena involved in the loading of the Arcan TCS specimen and on the consequences of this loading upon the quality of the test.

2. Description of the Arcan TCS specimen

The experimental Arcan Tensile/Compression-Shear (TCS) test shown in Fig. 1 has been developed by Créac'hcadec et al. [25]. It aims at providing a reusable and easy to implement specimen dedicated to the characterization of adhesive bonds under combined loadings while minimizing the edge effects occurring in the joint.

This specimen is an assembly composed of three parts: two metal substrates and an adhesive between them (resp. named A, B and C on Fig. 1b & c). In order to test the bonded assembly under various loading cases, four holes are machined on each substrates. Boundary conditions are applied on two opposite holes defined by their orientation compared with the loading direction which is designated γ. Thus, if $\gamma = 0°$ (resp. 45°, 90° and 135°), *i.e.* the mechanical loading is applied on the holes noted 0° in Fig. 1a (resp. 45°, 90° and 135°), the loading case is a tensile test (resp. a tensile-shear test, a shear test and a compression-shear test).

Edge effects are reduced through (1) the use of a low ratio $\beta = E_s/E_a \lesssim 50$, corresponding to the ratio between the Young's moduli of the substrates and the adhesive, and (2) the use of two filleted beaks (see Fig. 1b) [10]. These latter are precision machined on each substrates and form an angle $\alpha = 30°$ with the lap joint (see Fig. 1c).

The bonded area measures 25 (length)×10 (width) ×0.2mm (thickness). During the manufacturing, the two substrates can be fixed together with two shoulder screws allowing to control their relative orientations and the thickness of the adhesive. Also, these latter protect the adhesive from unwanted loading during the handling of the specimen.

3. Experimental analysis of the Arcan TCS specimen under drop weight conditions

3.1. Specimen and bonding process

Experimental tests presented in this section were made using EN 2017 Aluminium (AU4G, measured Young's modulus & Poisson's ratio: $E_s = 73$GPa, $\nu_s = 0.37$) substrates and an Huntsman™ Araldite 420 A/B Adhesive (Young's modulus & Poisson's ratio given by the manufacturer [29,30]: $E_a = 1.495$GPa, $\nu_a = 0.34$). The latter is a bi-component epoxy-based, room temperature curing paste adhesive of high strength and toughness. The choice of the material for the substrates is derived from the choice of the adhesive in order to have a low ratio $\beta = E_s/E_a$ and satisfactory adhesion conditions.

Before assembling the two substrates, the bonded surfaces are sandpapered down with a grade of 120, degreased with acetone and cleaned with dry air. After laying the adhesive, the two positioning screws are placed. Cotton swab are used to clean the edges and the beaks. The curing cycle followed for all the specimens is $T = 40$°C during $t = 16$h.

In order to follow the displacements of the substrates as close as possible to the adhesive, a speckle is painted on both substrates near the beaks (see Figs. 2b and 3b).

3.2. Experimental setups

The experimental campaign presented here was conducted under quasi-static and dynamic testing means. For all tests, the specimen is mounted on a 'double' frame test rig shown in Fig. 2b and illustrated in Fig. 3a. This device is composed of two frames: one static, the other one moving. The specimen is fixed between them thanks to pivot links. Finally, this test rig allows to move away the two pivots axis by bringing

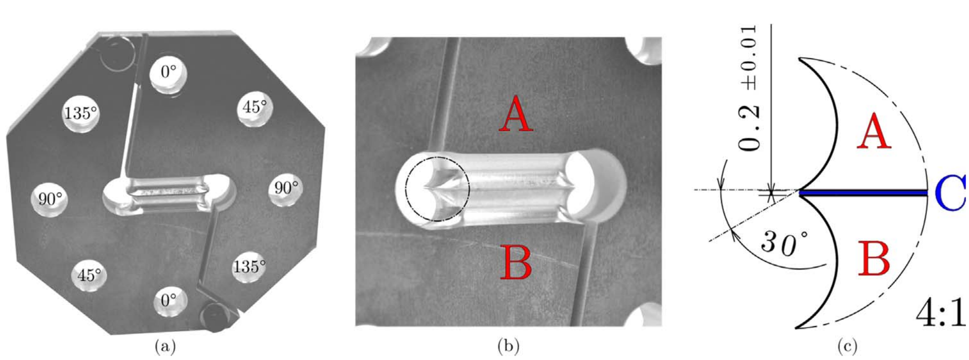

Fig. 1. Tensile/Compression-Shear Arcan Test. (a) General view of the test specimen. (b) Zoom on the local geometry of beaks. (c) Local geometries all around the adhesive in order to reduce the 'edge effects'.