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The Flexible Initiation Test (FIT): A new experimental test to characterize fracture initiation in mode I at the free edge of bonded assemblies

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ABSTRACT

Direct bonding is based on molecular adhesion. This bonding technique consists to join two surfaces into direct contact without the use of any adhesives or additional material. This process requires clean surfaces with a nanometric roughness, sufficiently close together to initiate bonding. Mechanical characterization of this type of assembly with classical mechanical test as for instance wedge test, cleavage test or double shear test present a highly scattering on mechanical results. This paper presents the Flexible Initiation Test (FIT test), an original test designed to characterize fracture initiation in mode I, and to decrease scattering in fracture initiation load measurements, in particular for adhesive with brittle behavior. This new test has to take into account the industrial framework: to be easy to manufacture, easy to execute repeatedly and efficient to provide experimental data for numerical models (stress criteria applications for instance). The paper proceeds first with an explanation of the main initial ideas to introduce the concept of this new test. Next, a numerical analysis is proposed to validate the concept and to determine the optimal geometry of the tests. Then the experimental device is set up and the concept is validated on three different adhesives with the same substrate (a brittle cyanoacrylate adhesive, a ductile and a brittle epoxy adhesives). To conclude, the FIT test is applied on direct bonded samples (an extreme case nanometric interface and very brittle behavior) to determine the fracture initiation load and to compare scattering of measurements.

1. Introduction

Adhesive bonding presents many advantages compared to other joining methods such as riveting, welding or mechanical fastening. These advantages include the ability to bond different materials together, lower structural weight, lower fabrication cost, reduction in stress concentration, design flexibility and easy manufacturing. In fact, adhesive bonding is used in a wide range of industrial applications, such as construction, transportation, automotive, marine, electronics, aeronautics and aerospace. Adhesively bonded joints offer many advantages for the design of structures, but a lack of confidence currently limits the use of this technology [1–3].

Mechanical strength characterization of bonding surfaces is essential to improve integration of bonded assemblies in complex systems [3]. Within the frameworks of fracture mechanics and structure damage evolution tracking, two main issues are addressed: characterization of fracture initiation and fracture propagation in bonded assemblies. In literature many experiments characterizing fracture propagation have been described as in Ripling et al. [4]. These tests are really well known and numerous numerical and experimental results have been reported. There are also a number of tests available to characterize fracture initiation: the standard Single Lap Joint test in ASTM standard, the Thick Adhesive Shear test in ASTM standard, the simple tensile test on a two bonded cylinder assembly as in Berry [5], the three-point bending test as in McDevitt et al. [6], as well as more recent tests such as the ARCAN test [7]. However, all these tests exhibit a non-negligible scattering of results due to a strong sensitivity to defects, in particular for bonding with a brittle behavior. In bonded samples or assemblies, edge effects occur which mainly depend on the Young's moduli and Poison's ratio of both the adhesive and the substrates, as well as on the stiffness and geometries of the substrates. These effects can induce high stress concentrations, which affect the mechanical strength and generally lead to early rupture. The slightest defects in the adhesive or in the substrate can cause the breaking of the assembly, and that's why measurements of ultimate load failure exhibit large scatter. In their interesting and important work, Cognard et al. [8–10] and Davies et al. [11] have developed a process of sample geometry optimization to overcome this problem. The new modified ARCAN test allows better measurement reliability. To reduce the edge effects, a beak, machined with an angle of 45°, a blending radius of 0.8 mm and a convex shape, is imposed on

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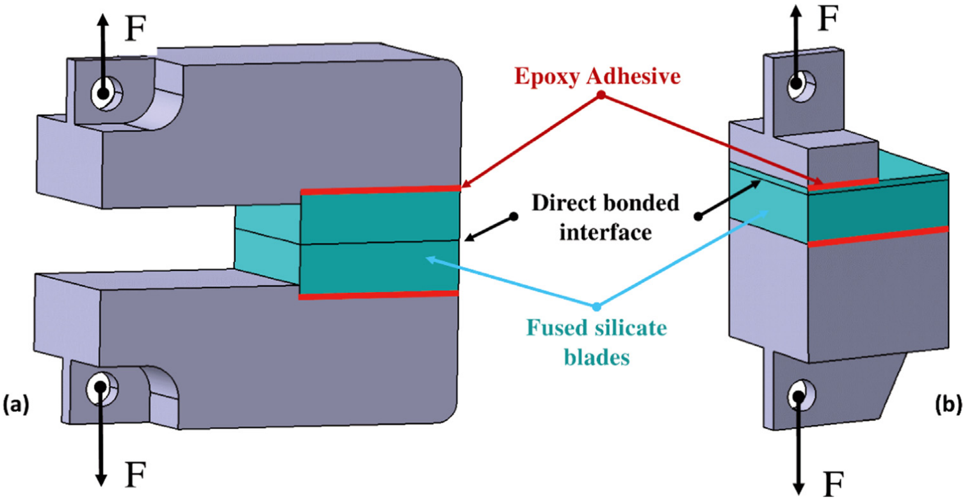

Fig. 1. CAD of modified cleavage test (a) and peel test (b) experimental devices used to characterize direct bonding interface (sample sizes are 40 mm × 40 mm × 12,5 mm in (a) and 40 mm × 40 mm × 12,5 & 1,7 mm in (b)).

the edge part of the adhesive. The introduction of a beak raises manufacturing and handling issues. These specific geometries are very difficult to reproduce in complex industrial structure assemblies, in particular on fused silicate substrate for direct bonding. Furthermore, the experimental results obtained for the epoxy resin Araldite® 420 [12], for example, Cognard et al. [13] in their results still display residual scattering.

This paper reports on the research conducted within the framework of cooperation with the French National Center of Spatial Studies (CNES) concerning fused silica or Zerodur® direct bonding technology. Direct bonding consists in joining two surfaces without the use of any adhesive or additional material as described by Kendall [14]. Usually, by bringing two flats, well-polished surfaces into contact at room temperature, they locally attracted to each other by Van der Walls or hydrogen bonds and adhere or bond. The main applications are on silicon-on-insulator devices. Silicon based sensor and actuators, electronics substrates are other examples of wafer bond classic applications reported by Ventosa et al. [15]. Recently, this process has been used in the manufacturing of high performance optical system for terrestrial application such as Fabry-Perot interferometers, prism assemblies. Nowadays, direct bonding is of particular interest for spatial instrument applications. Indeed, this is a high-precision production process, and direct-bonded assemblies obtained present a dimensional stability (CTE) due to the absence of mechanical parts or glue. In addition, since no adhesive material is used in the process, the risks of contamination associated with degassing are avoided, which is another advantage in a spatial context. A first prototype has successfully passed the space environment tests (mechanical and thermal constraints) where the constraints involved (thermal fatigue, accelerations, vibrations, etc.) are very different from those encountered on Earth.

However, a better understanding of the assemblies' mechanical strength behaviour is required to validate the system life expectancy and to meet the European Space Agency standards. The mechanical strength of direct bonded interfaces depends on the interface defects and on the nature of the bonds involved as described in Cocheteau et al. [16,17]. Indeed, Liao et al. [18] explained that room temperature bonding needs flatness and roughness perfectly controlled, and no particles contaminations on surfaces. Room temperature bonding is usually relatively weak; consequently, for some applications, the bonded assemblies undergo an annealing treatment causing changes in the nature of bonds responsible for adhesion and thus strengthen the bond across the interface as explained in Kissinger et al. [19]. Direct bonding exhibit a brittle behavior and an interface thickness at molecular scale.

This paper presents an original test designed to characterize fracture initiation in mode I, and to decrease scattering in experimental results, in particular for direct bonding. This new test have to take into account the industrial framework: have to be easy to manufacture, easy to execute repeatedly, efficient to confront adhesive performance and to provide experimental data for numerical models. The final aim consist to develop a new experimental test to measure critical initiation load for brittle adhesive considering the extreme case of direct bonding interface (i.e. thickness interface at molecular scale), in order to be able to use these experimental results to apply stress criterion (point stress, average stress, or coupled criteria).

The paper proceeds first with an explanation of the main initial ideas to introduce the concept of this new test named FIT for Flexible Initiation Test. A numerical analysis is proposed to validate the concept of the experimental bench and determine the optimal geometry of the experimental device (Section 3). In Section 4, the design of the new experimental bench is described and the concept is validated experimentally on three different adhesives with the same substrate: the Permabond 910 a brittle cyanoacrylate adhesive with a thickness of 0.01 mm [20]; the Scotch-Weld™ 3M 2216 B/A a ductile epoxy adhesive with a thickness of 0.1 mm [21]; and the Araldite® AV138M-1/Hardener HV998 a brittle epoxy adhesive with a thickness of 0.1 mm [22]. In Section 5, the direct bonding case is considered, the scattering of direct bonding critical initiation load measurement is compared. Finally, conclusions and prospects are drawn in Section 6.

2. New fracture initiation test in mode I

In previous investigation, Cocheteau et al. [16] were performed a peel test and a modified cleavage test in order to determine the influence of the reinforced direct bonding process parameters on the bonding mechanical strength. The experiments were run on five fused silica samples for each experimental tests. In the tensile testing machine, the sample was mounted and bonded between two aluminum mechanical parts, as related in Fig. 1. For each sample, the critical initiation load was measured to characterize the bonding mechanical strength. Then to determine a stress value for the interface mechanical strength, a failure stress criteria is applied.

After the analysis of measurements, the scattering (standard deviation in %) around the critical initiation load average value in both tests is reported in Fig. 2. A lower dispersion is observed for the modified cleavage test than for the peel test. We can see that for this modified cleavage test, the load application point is shifted from the bonding edge. This observation leads to determining the role played by