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Crack stopping in composite adhesively bonded joints through corrugation

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ABSTRACT

In the present paper, the effectiveness of corrugation as a crack stopper in composite adhesively bonded joints was investigated by mechanical testing and numerical simulation. Two different joint configurations were studied: the double-cantilever beam (DCB) and the crack-lap shear (CLS) configuration. For simulating crack growth at the adhesive and damage at the composite adherents, the cohesive zone modeling and the progressive damage modeling methods were implemented, respectively, by means of a FE model developed using the LS-DYNA FE code. On the DCB specimen, quasi-static tests and simulations were conducted by applying a normal load. For this case, both the tests and model showed that the crack stopped at the corrugation. On the CLS specimen, tension–tension fatigue tests and quasi-static simulations were conducted. In the fatigue test, the composite adherents failed early at the area of corrugation with only half of the specimen disbonded. On the contrary, the numerical model predicted complete disbonding without crack stopping and without failure at the composite adherents. This contradiction between the test and the model reveals that the specimen subjected to fatigue was failed due to interaction of cyclic loading with layup irregularities created at the area of corrugation during manufacturing. Using the numerical model, additional parametric studies on the effect of corrugation's diameter and height on the crack growth behavior of both specimens subjected to quasi-static loading were performed. The results reveal no major deviation from the reference geometry of corrugation.

1. Introduction

State-of-the-art design rules and standards for joining primary composite aircraft structures usually lead to local thickening of the fastener area and to a large number of fasteners. Consequently, compared to their counterparts in metallic structures, the interfaces in composite thin-walled structures induce a significant weight and cost penalty, thus mitigating the technical and economic benefits expected from the massive use of composite materials in aircrafts. Adhesive bonding of thin-walled composite structures is a very promising method for reducing aircraft cost and weight, while it brings several technical advantages compared to mechanical fastening such as the uniform distribution of transferred load over the bonded area, which reduces detrimental stress concentrations, the avoidance of fiber cuts associated with drilling of holes for introducing fasteners [1–5]. For secondary structures, adhesive bonding is a common practice but until today the certification rules that are applicable for primary bonded structures prevent the use of bolt-free bonded joints for primary structures, as a result of earlier experiences, where the interpretation of the rules led to in-service premature failure incidents on adhesively bonded joints [6].

The first among the three Means of Comply, defined by the international airworthiness authorities (EASA and FAA) to demonstrate that a bonded joint exhibits the required load bearing capacity, states that "The maximum disbond of each bonded joint consistent with the capability to withstand the required loads must be determined by analysis, tests or both. Disbonds of each bonded joint greater than this must be prevented by design features" [7]. In this item it is stated that "Design features can be proposed to prevent cracks or disbonds larger than the larger size for ensuring the load bearing capacity in a damage tolerance manner". Based on this statement, it emerges that the design of primary composite structures containing crack stopping features (CSFs) that will prevent disbond from growing beyond a critical size maybe the way toward certification.

The design of CSFs is not a new technological area as a great deal of experimental and numerical work was already accomplished on metallic structures e.g. [8–12]. Although the findings

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from the work on metallic structures do not apply directly to adhesively bonded joints some of the existing features maybe used as a base of the investigation. In the literature, there is no published work on crack stopping in adhesively bonded joints. The research on this area started very recently on 2012 in the frame of the European project BOPACS (Boltless Assembling of Primary Aerospace Composite Structures). The CSFs that are currently under investigation in BOPACS were categorized as following:

- Through thickness reinforcements.
- Surface and geometry modification.
- Surface interfacing features.
- Adhesive bondline architecturing.
- Supporting adhesive modification.

A schematic description of examples of CSFs can be seen in Fig. 1.

In the present work, the role of corrugation as a CSF in adhesively bonded composite joints was experimentally and numerically investigated. The paper is structured as follows. After the introduction, the geometries, materials and loading conditions of the corrugated bonded joints are presented in Section 2. In Section 3, a short description of fatigue testing follows. In Section 4, the cohesive zone modeling and the progressive damage modeling modules of the numerical model are described. Finally, in Section 5 the experimental and numerical results on DCB and CLS specimens are presented and discussed in terms of the effectiveness of corrugation as a CSF.

2. Experimental

2.1. Geometries and loading conditions

Two different configurations of bonded specimens were considered in the present study: the double-cantilever beam (DCB) specimen and the cracked lap shear (CLS) specimen. The DCB was loaded by a normal tensile load which develops a pure mode-I load at the bondline away from the corrugation while the CLS was loaded by an axial tensile load which develops a mixed-mode I + II load at the entire bondline. Schematic representations and basic dimensions of the CLS specimen are shown in Fig. 1. The dimensions of the DCB specimen are the same with the dimensions of the long plate of CLS (see Fig. 2).

2.2. Materials and manufacturing

The adherents were made from the R-367-2 resin reinforced by Structil T2TE2 20 fibers in 2 × 2 twill fabric architecture. The layup

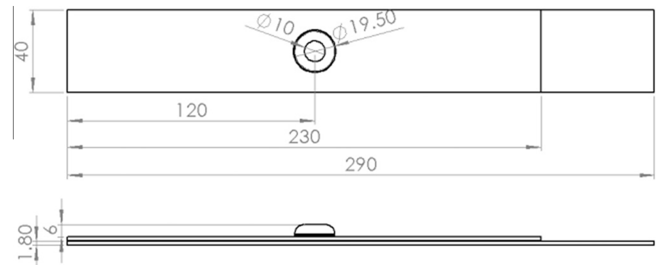

Fig. 2. Schematic representation and basic dimensions (in mm) of the CLS specimen.

of the composite adherents is $(0/90)_8$. The adhesive was a mixture of EA 9395 (80%) and EA 9396 (20%) adhesives.

For the manufacturing of the adherents, two different tools were produced. The tools include the contour of corrugation. In order to achieve a good fit of the two contours, one tool was made as a negative (aluminum plate with machined cavities) and one as a positive (tooling material with added steel corrugations). The prepreg layers were draped on the tool, yet in the corrugation area it had to be cut in order to follow the small radii of the corrugation. Cut areas were filled with additional layers. Every fourth layer was debulked at full vacuum. The prepreg was cured out-of-autoclave following the material supplier's recommendations. Prior to bonding the surfaces of the adherents were polished using sandpaper. For the bonding operation, a 0.2 mm spacer was applied to control the bondline thickness. The adhesive mixture was cured at 0.2 bar at room temperature for 5 days. The two sides of corrugation are illustrated in the photos of Fig. 3.

3. Mechanical testing

The CLS specimen was subjected to axial tension–tension fatigue ($R = 0.1$, 1 Hz, 60% of initial crack static load). The DCB specimen was subjected to a quasi-static normal load using a loading rate of 0.5 mm/min. Both tests were conducted using the electromechanic testing machine Zwick Z 250 with a loading capacity of 250 kN.

4. Numerical simulation

4.1. The Cohesive Zone Modeling (CZM) method

Disbond initiation and propagation at the joints were simulated using the Cohesive Zone Modeling (CZM) method, which was implemented using the LS-DYNA explicit FE code [13]. For the

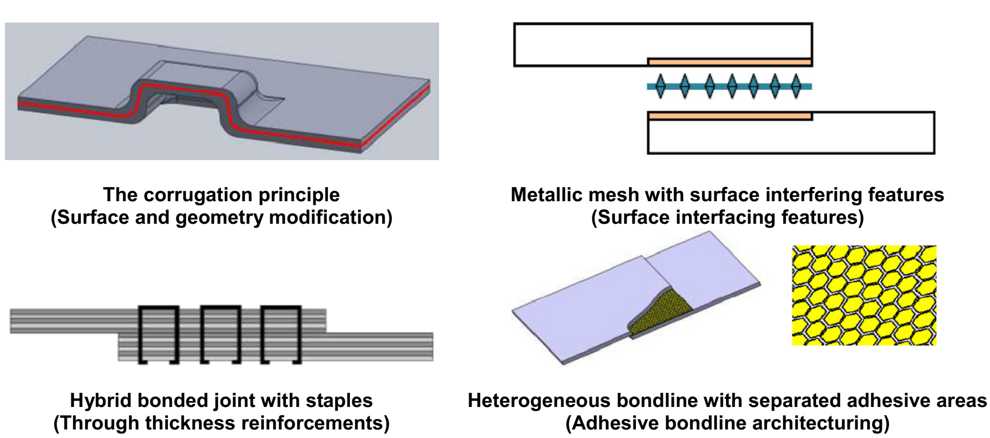

Fig. 1. Schematic representation of CSFs [6].