Engineering Failure Analysis 56 (2015) 2–13

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Failure analysis of adhesively-bonded skin-to-stiffener joints: Metal–metal vs. composite–metal

Sofia Teixeira de Freitas *, Jos Sinke

Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

ARTICLE INFO

Article history:
Received 19 September 2014
Received in revised form 30 May 2015
Accepted 31 May 2015
Available online 16 June 2015

Keywords:
Adhesive bonding
Skin-to-stiffener connection
Composite-to-aluminium joints

ABSTRACT

The purpose of this research is to evaluate the performance of two adhesively bonded skin-to-stiffener connections: composite stiffener bonded to a Fiber Metal Laminate (FML) skin, representing a hybrid joint, and an Aluminium stiffener bonded to a FML skin, representative for a metal joint. The bonded joints were tested using Stiffener Pull-Off Tests (SPOT), which is a typical set-up used to simulate the structural behavior of full-scale components subject to out-of-plane loading, such as internal pressure of a fuselage or leading edge low pressure zone. In the hybrid joint, the damage initiates at the central noodle of the composite stiffener. Unstable delamination then propagates from the noodle to the tip of the stiffener foot, preferably through the stiffener foot plies (>90% of inter/intra-laminar failure) and, in limited areas, through the adhesive bond line (<10% of cohesive failure). In the metal joint, the failure starts at the tip of the stiffener foot at the adhesive bond line. Unstable debonding then propagates along the stiffeners foot. The complete failure occurs in the adhesive bond line (100% cohesive failure). The loads associated with >90% of inter/intra laminar failure of the composite stiffener (hybrid joint) are 40–60% lower than the ones associated with 100% cohesive failure (metal joint). This research identifies that in order to use the full capacity of adhesively bonded hybrid joints, the adhesion between carbon fibers of the composite laminate, ie intralaminar strength, must be improved. Otherwise, Aluminium stringers are still very competitive.

1. Introduction

Due to their superior specific strength and stiffness when compared to the traditional metals, composite laminates are becoming the first choice in aircraft applications. A true testimony of this fact is the newest civil aircraft Boeing 787 applying materials of which are 50% composites and 50% metals. With such hybrid structures, composite parts often need to be joined with metal parts. Adhesive bonding offers major advantages for joining different materials when compared to traditional mechanical riveting. Moreover, adhesively bonded joints are the most suitable technology for joining composite materials, since it avoids drilling, stress concentrations and fiber-cutting which can significantly decrease the performance of the composite laminate. Therefore, the application of adhesive bonded joints has been developed in parallel with composites [1].

Most of the research in composite-to-metal bonded joints is limited to coupon tests. Single- and double-lap joints (SLJ and DLJ) have been used to evaluate the shear strength of bonded composite-to-aluminium joints [2–4]. Double cantilever beam (DCB) hybrid specimens are used to characterize the crack propagation behavior and giving input data for fracture mechanics

* Corresponding author. Tel.: +31 15 28 82287; fax: +31 15 278 1151.
E-mail addresses: S.TeixeiraDeFreitas@tudelft.nl (S. Teixeira de Freitas), J.Sinke@tudelft.nl (J. Sinke).

http://dx.doi.org/10.1016/j.engfailanal.2015.05.023
1350-6307/

[5,6]. Since adhesion is one of the key components for guarantying the integrity of bonded joints, new peel tests have been developed in order to assess the adhesion quality of composite-to-metal bonded joints [7].

However in order to succeed, composite-to-metal bonded joints also need to prove their performance in structural applications and not only at the coupon level. In aircraft applications, skin-to-stiffener joints are very common in fuselage panels and wings. Due to the impossibility to test different design concepts and materials at a full-scale, sub-components test simulate the loading and boundary conditions of the full-scale components. Stiffener Pull-Off Tests (SPOT) is one of the sub component tests that simulates out-of-plane loading in skin-to-stiffener joints, such as internal pressure of the fuselage skin and low pressure zone of leading edges [8–10].

Stiffener Pull-Off Tests have been extensively used to evaluate the performance of different design concepts and structural features in skin-to-stiffener joints. The aim of these new features is to try to identify the ones that offer more load capacity or higher toughness [10–12]. SPOT are also used to identify the failure sequence and failure modes in order to help designers to predict the behavior of these complex joints [13]. However, most of the research is performed in either co-cured composite-skin to composite-stiffener or bonded metal-skin to metal-stiffener [13,14]. Few research is available in skin-to-stiffener hybrid joints.

With the increasing use of composites over metals, attention should be paid on how this material replacement influences the structure's behavior. In this research, the aim is to compare the performance of two adhesively bonded skin-to-stiffener joints; metal skin to metal stiffener and metal skin to composite stiffener (hybrid). Stiffener-Pull-Off Tests (SPOT) were conducted in order to characterize the failure mechanism and the load carrying capacity of both types of joint. The conventional metal solution is compared with the new solution for hybrid structures.

2. Materials and specimens

Stiffener Pull-Off Test specimens were manufactured by bonding the stiffener to the skin. For the metal joint an Aluminium stiffener was bonded to a Fiber Metal Laminate (FML) skin. For the composite-to-metal hybrid joint, a Carbon Fiber Reinforced Polymer (CFRP) stiffener was bonded to a FML skin.

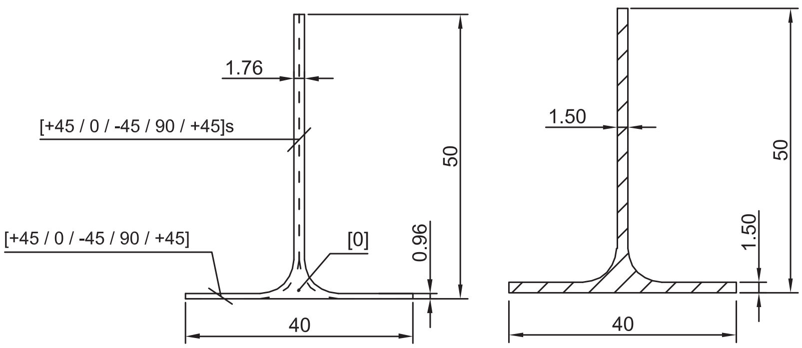
2.1. Materials

The Fiber Metal Laminate (FML) skin was Glare 5–3/2–0.3, which consists of three 2024-T3 aluminium alloy layers 0.3 mm thick, bonded together with glass prepregs S2-glass/FM-94 with the layup $[0^\circ/90^\circ/90^\circ/0^\circ]$. The skin layup is therefore $[Al/[0^\circ/90^\circ/90^\circ/0^\circ]/Al/[0^\circ/90^\circ/90^\circ/0^\circ]/Al]$. The outer faces of the skin are Aluminium layers (metal). The skin was cured in the autoclave according to the standard procedure for Glare (4 bars, 60 min at 120 °C). The aluminium surfaces were pre-treated with chromic acid anodizing and primed with BR 127 (Cytec Engineered Materials, Tempe, Arizona, USA).

The Aluminium stiffener was an extruded inverted T-shape stiffener of 2024-T3 aluminium allow. The surface pre-treatment was identical to the FML skin aluminium surfaces.

The CFRP stiffeners were prepared from unidirectional pre-preg consisting of HexPly 8552 epoxy matrix in combination with AS4 carbon fiber (Hexcel Corporation, Stamford, Connecticut, USA). The CFRP stiffener was an inverted T-shape stiffener. It was manufactured from two laminates, each with layup $[+45^\circ/0^\circ/-45^\circ/90^\circ/+45^\circ]_S$, which were put back to back in a L-shape. The noodle region was filled with 0° fibers. The stiffener was cured at 180 °C for 120 min in the autoclave. Prior to bonding, the CFRP-stiffener-foot surfaces were abraded with sand paper and then wiped clean with an acetone-soaked cloth. Fig. 1 shows the configuration of both stiffeners.

Two adhesives were used on both configurations; AF 163–2 K.06 (3 M, Minnesota, USA) and EA9696.060 PSF K (Henkel, Düsseldorf, Germany). Both are epoxy film adhesives with a curing temperature of 120 °C for 90 min in the autoclave. The



(a) CFRP stiffener (b) Aluminium stiffener

Fig. 1. Stiffeners' configuration (dimension in mm).