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Crack propagation in flat panels stiffened by bonded pads

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ABSTRACT

This paper presents the results of an experimental and numerical investigation about crack growth in metallic flat panels stiffened by means of multilayered bonded pads.

An experimental program was performed to assess the fatigue crack growth and the residual strength of a number of selected configurations of stiffened panels, within the framework of a collaboration between Piaggio Aero Industries (PAI) and the University of Pisa.

In the paper, the test procedures and equipments used for the experimental test campaign are described and the main results of the fatigue crack growth and of the residual strength tests are reported and analysed.

Finite Element analyses were performed to further investigate the crack propagation phenomena. The numerical model was validated by comparing the strains measured, at different crack lengths, by a set of strain gauges bonded on the tested panels, with those provided by FEM.

Two possible scenarios are accounted for: crack propagates only in the skin, while pads remain uncracked, or crack propagates simultaneously in the skin and in the pad layers.

The values of the stress intensity factor numerically evaluated well compare with the values obtained from the experiments.

1. Introduction

Aircraft manufacturers identified some decades ago that the joining of aircraft structural elements with adhesive bonding is a key technology to provide low weight, high fatigue resistance and cost saving. Among the bonding applications in aircraft structures, a particular interest has been devoted to skin-stringers joints, due to their promising performances in terms of damage tolerance behaviour. According to the *crack arrest* design concept, the ability of bonded stiffeners to reduce the skin crack growth rate was investigated since end of 70s, early 80s, [1–4]. The study of adhesively bonded joints further spread with the increasing diffusion of innovative materials, such as composites and Fiber Metal Laminates. However, even for metals, the interest has been maintained until now [5,6] and grew in developing panels made of thin metal skins stiffened with bonded reinforcements. Such a configuration is able to delay or inhibit crack propagation and to withstand large damages, combined with a low structural weight.

Damage tolerance of bonded stiffened metallic structures is a widely studied problem in the aeronautical fatigue literature; many papers have been published over the years addressing the problem from an experimental point of view [2,5,7–11], or proposing analysis methods, all founded on the stress intensity factor (SIF) concept, based either on numerical, mainly FEM [2,5,11,13,14], or analytical, derived from compatibility of displacements [1,3,4,10,12], approaches to calculate SIF.

The results of tests on metallic panels with bonded stiffeners highlight that their main limit is the premature fatigue failure of the reinforcements caused by the high load transfer from the skin to the stiffeners when the crack runs underneath them. Consistently with such observation, to improve Damage Tolerance, the reinforcements should be preferably made of material characterised by high values of fatigue resistance, stiffness and static strength [7,8]. If the crack propagates only in the skin and the intact stiffeners can control the defect evolution during the propagation, an effective *crack arrest* design is obtained. Actually, the beneficial effects of the bonded pads may be reduced, until the presence of a prematurely broken pad (due to fatigue loads) may become detrimental for the structure.

Furthermore, particular attention must be devoted to debonding at the interface between skin and pads around the area of

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Nomenclature

a	half-crack length (mm)
E	Young's modulus (MPa)
J	value of J-integral (N/mm)
K	stress intensity factor for skin panel (MPa mm$^{1/2}$)
N	Number of fatigue cycles
R	fatigue stress ratio (= Smin/Smax)
Smax	maximum cyclic stress (MPa) (constant amplitude fatigue loading)
Smin	minimum cyclic stress (MPa) (constant amplitude fatigue loading)
t	skin thickness (mm)
W_{bay}	bay width (mm) (distance between the axis of two consecutive pads)
β	ratio of stiffened and unstiffened skin panel stress intensity factors
σ	stress (MPa)
ν	Poisson's ratio

nucleation and propagation of the crack. Such a phenomenon, represents a negative event since it compromises the stiffening effectiveness. Nevertheless, the occurrence of debonding limits the peak stress in the stringer.

The complexity of the behaviour of bonded stiffened panels is further increased by secondary effects, such as residual stresses introduced by the bonding process, when components made of different materials are joined, and bending produced by the loss of symmetry of the panel cross-section, enhanced by the presence of cracks. Due to mechanisms mentioned previously, reliable predictions, numerical or analytical, of crack growth and residual strength in bonded structures are not straightforward to obtain. In particular, the damage tolerance assessments of integral reinforced structures is relatively easy [7,8] following the slow crack growth approach; the same estimation is not so straightforward in structures with bonded stiffeners [10] where different materials are involved, with load transfer through the adhesive layer, which can alter its behaviour due to damage and degradation.

In the present paper the authors devoted their attention to metal to metal bonded stiffened panels. In particular, the fatigue crack growth and the residual strength of a number of selected configurations of stiffened panels were assessed thanks to an experimental program performed at the former Department of Aerospace Engineering of the University of Pisa (now part of the Dipartimento di Ingegneria Civile e Industriale), in the framework of a collaboration with Piaggio Aero Industries (PAI). In all the tested panels the skin is stiffened by double layered pads; such configuration is the result of a preliminary optimization activity performed by Piaggio Aero Industries, aimed at providing damage tolerance capabilities, for circumferential cracks, to a stringer-less fuselage architecture. The experimental activities described in this paper give a first positive assessment of the proposed configurations. A possible evolution of this solution may lead to introduce glass fibre layers between metal layers in a Glare® like confi guration.

In order to further understand the damage tolerance behaviour of such panels, numerical analyses were carried out. Two possible extreme scenarios were simulated: crack propagates only in the skin, while pads remain un-cracked, or crack propagates simultaneously in the skin and in both the pad layers.

The actual behaviour of a stiffened bonded panel can be in-bet ween the two considered cases, depending on the effectiveness of the bonding and, mainly, on the static and fatigue resistance of the pads.

The numerical model was developed with the aim of evaluating the stress intensity factor (SIF) at different crack lengths. SIF calculated via FEM were compared with those deducible from the experimental data. The numerical model was preliminarily validated by comparing FEM predictions with the strains measured, at different crack lengths, by a set of strain gauges bonded on one of the tested specimens.

2. Experimental activities

2.1. Specimens description and preparation

The specimens were flat panels having a width of 1500 mm and a length of 1200 mm. Their design was originally tailored for a different laboratory which had constraint in the maximum length of the test panels, resulting in a very low aspect ratio of the specimen. The test program is summarized in Table 1: two different stiffening configurations, with six or seven pads, were tested, in order to have the initial crack starting either from a pad or from the skin at the centre of the central bay (distance between the pads axis). Panels of types 1 and 2, which have six pads with 210 mm spacing, had a through artificial crack in the skin, located in the middle of the central bay, while panels of types 3 and 4, which have seven pads with 210 mm spacing, had a through artificial crack in the central pad (cutting the skin and both layers). In Fig. 1 a sketch of a seven pads panel is shown, together with a detail of the bonded pads.

For each configuration, two specimens were defined, obtained by bonding pads of different thickness to the flat skin. The bonding process was executed according to Piaggio Aero Industries specification detailing the methods for surfaces preparation (anodizing and primer application) and the curing cycle for the selected epoxy adhesive (3 M™ Scotch-Weld™ Structural Adhesive Film AF 163–2 K). Both the skin and the pads were made of 2024-T3 aluminium alloy. The double layer configuration for pads, selected for the experimental tests, was considered by PAI as the most promising solution for an application in a stringerless fuselage of a new aircraft program. Due to the preliminary nature of the test program, only one panel per type was built and tested.

In all the tested panels, the manufacturer introduced an artificial defect by means of a precision saw cutting; characteristic dimensions of the initial defect are reported in Table 1. In order to evaluate the importance of a completely broken pad, on panel type 3, central pads were severed at midsection by precision saw cutting, thus obtaining a configuration with an artificially cracked skin and a completely broken pad.

All the panels were instrumented with strain gauges to perform strain surveys at different crack lengths.

2.2. Equipment description

The geometry of the test articles, flat panels with very low height-to-width ratio, required the use of special grips, developed in a previous activity for similar situations.

In particular, the low height-to-width ratio of the panels causes a non-uniform stress distribution in the panel, which tends to be overloaded in its central part. A possible solution to the problem consists in locally reducing the stiffness of the grip head plates by introducing a slot in their central part and, consequently, reducing the amount of load transmitted in the central part of the panel.