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Characterisation of composite bonded single-strap repairs under fatigue loading

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ABSTRACT

High cycle fatigue behaviour of single-strap repairs of carbon–epoxy laminates was analysed experimentally and numerically. Static and fatigue tests were performed under three-point bending loading. The specimens revealing cohesive failure were selected for the sake of numerical model validation. The numerical approach is based on a mixed-mode I+II cohesive zone modelling accounting for quasi-static and fatigue degradation through a unique damage parameter. It was verified that numerical fatigue life prediction is in the range of the fatigue life observed experimentally. In addition to the validation of the numerical model, several numerical analyses were performed in order to assess the influence of loading, geometry and material properties on the fatigue behaviour of single-strap repairs and important conclusions were drawn.

1. Introduction

Composite materials have been used increasingly for structural transportation applications such as aerospace, aeronautical, automotive and others, where low weight is a crucial aspect. However, these materials are susceptible to internal damage, as is the case of delaminations between layers which are considered dangerous under compressive loads [1,2]. The premature replacement of structural components made of thermoset based composites is economic and ecological inadvisable, which makes the development of adequate and suitable repair procedures a fundamental issue. In this context, adhesively bonded repairs are particularly appealing relative to the mechanical fastening method owing to more uniform stress distribution, better fatigue behaviour and reduced corrosion effects. Since frequently only one face of the structure is accessible and sometimes there is only one side of a structure allowed to be patched for other reasons, one-sided repairs are often adopted in practical applications. The procedure consists of removing the damaged material and bonding one (single-lap repair) patch over the damaged region.

Fatigue is a typical type of loading in transportation structures, which means that characterisation of repair bonded joints under high-cycle fatigue is a fundamental research topic. Failure due to fatigue occurs in the elastic regime and far from the static limit strength of the structure, thus being very dangerous in the context of aeronautical applications for example.

Several works have been dedicated to study the fatigue life of repairs involving composites. The majority of the studies are dedicated to repairs of metallic structures with composite patches [1–3]. Baker [1] studied repairs based on adhesively bonded fibre-composite patches or reinforcements on defective or degraded metallic aircraft components. The author concludes that the ability to predict the patch system fatigue behaviour and to assure its environmental durability is crucial for certification. In addition, a smart patch concept in which the patch system monitors its own health is also important to detect patch loss. Meniconi et al. [2] performed experimental and numerical fatigue analysis of a composite repair that was applied to the metallic hull of a floating, storage and offloading platform. The experimental strain data, together with a specific fatigue curve experimentally defined provided the input of a finite element model of the repaired structure and resulted in the expected fatigue life of the repair metal-composite. Clark and Romilly [3] performed experimental and finite element studies of a bonded composite repair on metallic aircraft structure. They concluded that bending and composite failure modes play an important role on the fatigue lifetime.

The majority of the studies involving composite adherends are focussed on fatigue analysis of bonded joints [4–7]. Only few works have been dedicated to fatigue analysis of repaired

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composite structures. Charalambides et al. [8] analysed the performance of carbon fibre/epoxy repair joints bonded under static and fatigue loading. The authors found that repair joints have fatigue performance similar to structural repair panels, as well as similar failure modes, which was found appealing since the smaller repair joints are easier and more economical to manufacture and test relative to large repair panels. They have concluded that the fatigue behaviour of the repair joints was significantly inferior to that of the parent material. Tenchev and Falzon [9] carried out experimental fatigue tests on composite adhesively bonded stepped joints. They showed that this type of adhesive joint, widely used in repairs, significantly reduced the static strength as well as the fatigue life of the composite. Botelho et al. [10] evaluated the effects of the fatigue behaviour on repaired aramid fibre/epoxy composites and verified a decrease of 10% in the low cycle fatigue resistance values and 18% for high-cycle fatigue relatively to the non-repaired structure. They concluded that the repair procedure can be used in aerospace applications.

In the present work, experimental and numerical analyses of the high-cycle fatigue behaviour under three-point bending of single-strap repairs of carbon–epoxy composite laminates were performed. The experimental fatigue life and normalised compliance versus number of cycles relationships were used to assess the performance of the previously developed cohesive mixed-mode I+II damage model appropriate for high-cycle fatigue [11]. One of the advantages of the proposed model is the use of a sole damage parameter mimicking material degradation under quasi-static and fatigue loading. Subsequently, the model was used to study the influence of loading, geometrical and material properties on the fatigue behaviour of single-strap repairs. Important conclusions were drawn about relevant aspects influencing the fatigue behaviour of these joints, thus providing design guidelines concerning the behaviour of composite single-strap repairs under high-cycle fatigue loading.

2. Experimental work

The single-strap repair specimen consists on bonding a repair patch over the removed damaged material of a structure. A single-strap bonded joint geometry was assumed to allow a simpler two-dimensional analysis. Hence, the adopted repair configuration consists of two composite beams separated by the removed damage length (L_R), over which a composite patch repair was bonded (see Fig. 1). The adherends and repair patch were prepared with 16 plies of unidirectional prepreg (CFRP – Carbon Fibre Reinforced Plastic), which provided a thickness of 2.2 mm. The surfaces were polished with sandpaper and cleaned with acetone in order to avoid premature and unwanted adhesive failures characterized by adhesive/adherend debonding. A two part component ductile epoxy adhesive, Araldite® 2015 manufactured by Huntsman, was used in this work. The manufacturer instructions were followed to assure an optimal cure process. The mechanical properties of the adherends (Table 1) and of the bulk adhesive (E=1850 MPa and ν=0.3) were defined in [12].

A nominal adhesive thickness of 0.2 mm was assured using calibrated steel strips during the curing process of the adhesive. Excesses of adhesive were carefully removed in order to avoid unwanted filleting effects that would make results incomparable.

The experimental tests were performed under three point bending loading condition (Fig. 2). Three preliminary static tests were performed under displacement control (1 mm/min) to determine the static failure load whose average value pointed to 640 ± 43 N. The cyclic fatigue loading tests were made in a MTS 810 servo hydraulic machine (Fig. 2), with a FlexTest 40 digital servo controller MTS and a software MTS MultiPurpose TestWare allowing to register the signals corresponding to applied load, displacement, time and number of cycles. The tests were performed under load control (load cell 5 kN), frequency of 1.5 Hz and load ratio $R=P_{min}/P_{max}$ equal to 0.1. The maximum load was taken equal to 50% of the static failure load.

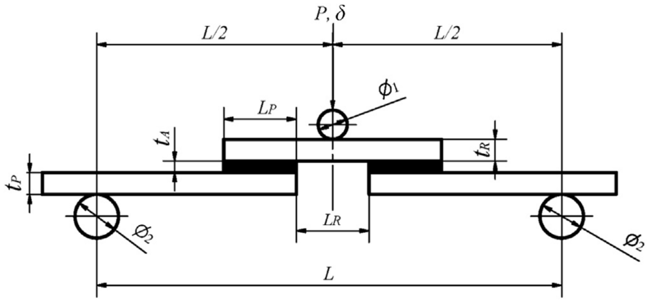

Fig. 1. Single-strap repair geometry under three-point bending: L=80, L_R=10, L_P=10, t_P=t_R=2.2, t_A=0.2, width B=30 and $Ø_1$=8, $Ø_2$=12.5; all dimensions in mm.

Table 1
Typical elastic properties of carbon–epoxy [12].

E_1=109 GPa	ν_{12}=0.34	G_{12}=4315 MPa
E_2=8819 MPa	ν_{13}=0.34	G_{13}=4315 MPa
E_3=8819 MPa	ν_{23}=0.38	G_{23}=3200 MPa

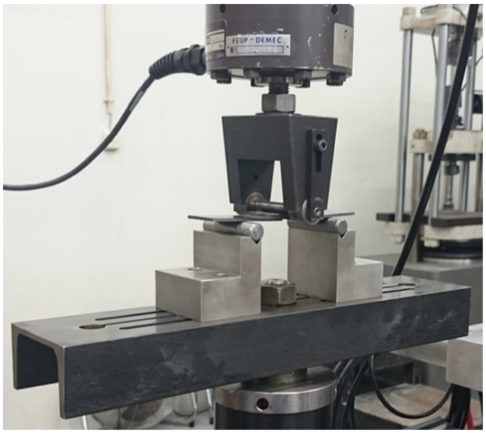

Fig. 2. Experimental setup of the single-strap repairs under three point bending.

3. Review of cohesive zone model

A cohesive zone mixed-mode I+II damage model accounting for static and fatigue damage was used to predict the fatigue behaviour of single-strap repairs. The static damage is directly related to applied load and in the fatigue case material degrades as a function of time. The simplest triangular cohesive law (Fig. 3) is constituted by two branches: up to the local strength in mixed-mode (σ_{um}) a constant cohesive stiffness k=1E7 N/mm^3 is considered; after that a softening relationship takes place as a function of a damage parameter. In the present case it was assumed that both, static and fatigue damages, follow the same softening law. The global damage parameter (e) writes

$$e = e_s + e_f \tag{1}$$

where e_s and e_f represent the static and fatigue damage parameters, respectively. The static damage parameter is given by [13]