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Effects of adhesive disbond and thermal residual stresses on the fatigue life of cracked 2024-T3 aluminum panels repaired with a composite patch

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ABSTRACT

The technology of bonded composite repair has displayed its effectiveness in increasing the residual fatigue life of cracked aeronautical structures. However, two major phenomena reduce the performance of this technique; the adhesive disbond by the fatigue load and the thermal residual stresses due to the adhesive curing. In this study, the effects of the adhesive disbond and the thermal residual stresses on the fatigue life of repaired cracked aluminum plate were analyzed experimentally and numerically. Fatigue tests were performed on cracked 2024-T3 aluminum alloy specimens repaired using carbon/epoxy patches that have artificial disbonds, to highlight the adhesive disbond effect. Fatigue tests were performed on repaired specimen bonded with elevated temperature cure and ambient temperature cure adhesives to evaluate the effect of the thermal residual stresses. To analyze the effects of the two phenomena, the finite element method was used to compute the stress intensity factor at the front of repaired cracks. The experimental results indicate that fatigue life is significantly reduced by the presence of an initial adhesive disbond and thermal residual stresses. The numerical results are consistent with the experimental observations, and reveal that the stress intensity factor increases with an increase in the disbond width. Moreover, it also increases in the presence of thermal residual stresses.

1. Introduction

The bonded composite patch repair of damaged aircraft structures is a highly effective technique when compared with the method that uses mechanical fastening [1–4]. This is because an adhesive joint avoids the concentration of stresses, and this leads to better stress bridging between the damaged structure and the composite patch. However, the weak resistances of the adhesive materials may lead to a disbond of the adhesive layer under fatigue loads. Eventually, the adhesive failure causes the detachment of the composite patch. Consequently, the stress transfer is significantly reduced. In the case of repaired cracked structures, the crack propagates under fatigue loading and is affected by the size of adhesive disbond [5–8]. This effect is a major factor in determining the efficiency and durability of the bonded composite repair. Several numerical and experimental studies focused on the analysis of the effect of adhesive failure on the bonded composite repair [9–11]. The fore-mentioned studies confirmed that an adhesive disbond reduces repair performances. Denny and Mall [12] conducted fatigue tests on a 2024 alloy repaired using a boron/epoxy composite. They studied different partially bonded configurations and compared the same with a fully bonded configuration. They concluded that size and location of disbond affects both the fatigue life and crack growth characteristics. Schubbe and Mall [13] experimentally investigated the crack growth behavior of 2024-T3 repaired using a single side boron/epoxy composite patch. They considered the disbond characteristics and radii of curvature of repaired specimens. Naboulsi and Mall [14] developed an analytical procedure to characterize the crack growth rate of both completely bonded and partially bonded specimens. Bachir Bouiadjra et al. [15] investigated the effect of the adhesive failure on the variation of the stress intensity factor (SIF) at the tip of a repaired crack. Their results clearly indicated that the disbond of the adhesive layer significantly increased the mode I SIF at the crack tip when the disbond propagated perpendicularly to the direction of the applied load, vice versa. The study also showed that the disbond in the adhesive layer on both sides of a double symmetric patch has a higher negative effect. In another study, Bouiadjra et al. [9] confirmed that in the case of mixed mode loading, in both mode I and mode II, the SIF increased due to the failure of the adhesive layer. Ouinas et al. [16] concluded that the SIF is

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effectively reduced if and only if the disbond length exceeds the crack length.

Adhesives cured at elevated temperatures have been widely used to characterize the repair performance of metallic aircraft structure. The heating causes a thermal expansion of the repaired metallic structure. The bonding of the patch during cooling prevents the heated metallic structure from returning to its initial state (without deformation). The difference between the thermal expansion coefficients of the cracked material and the composite generates thermal residual stresses (TRS) in the two materials. The metallic structure is subjected to residual tensile stresses and the composite patch is subjected to residual compressive stresses. The presence of TRS reduces the fatigue life of repaired aircraft structures and the repair efficiency is therefore negatively affected by the thermal residual stresses. Several authors tried to estimate the effects of the TRS on the repair performance [17–22]. Aminallah et al. [20] showed that the presence of TRS leads to an increase of the SIF at the tip of the repaired crack, which reduces the fatigue life. Albedah et al. [21] recommended the optimization of the repair parameters to attenuate the negative effects of the TRS. Benyahia et al. [22] showed that the TRS depends on the patch shape. The use of a circular shape can reduce the levels of these stresses.

In this study, experimental and numerical investigations were performed to examine the effect of the adhesive disbond and the TRS on the fatigue life of the cracked 2024-T3 aluminum alloy repaired using a bonded carbon/epoxy patch. Fatigue tests were performed on cracked 2024-T3 aluminum alloy specimens that were repaired using bonded composite patches that have artificial disbonds. To highlight the effect of the TRS on the repair performances, the fatigue lives of specimens repaired using adhesives cured at room and at elevated temperatures were compared. In the numerical part, the repaired structures with adhesive disbond were modeled, and the SIF was calculated at the crack tip to evaluate the effect of the adhesive disbond size on the behavior of the repaired crack. To evaluate the effect of the TRS on the repair efficiency, the values of the SIF in specimens repaired using an elevated temperature cure adhesive were compared with those of specimens repaired using ambient temperature cure adhesives.

2. Experiments

2.1. Materials and specimens

The specimens with dimensions 150 mm × 50 mm × 2 mm were cut along the L-T direction from Al 2024-T3 plates as shown in Fig. 1. A “V” notch with a length of 6 mm and an included angle of 60° was cut at an edge midway of the substrate to facilitate mode I crack propagation (as shown in Fig. 1) during the fatigue test. The fatigue tests were conducted in accordance with ASTM E647 standards [23]. The specimens were machined using an abrasive water jet machine to avoid the formation of residual stresses due to machining. The material used for crack repair was the cured pre-impregnated carbon/epoxy system provided by Zoltek. Eight plies with dimensions of 250 mm × 250 mm (corresponding thickness of 1.44 mm) were aligned unidirectionally and cured at 120 °C for 90 min under a constant pressure of 50 kPa as suggested by the prepreg manufacturer. Square specimens with a length of 50 mm (full width of the substrate) were cut from the composite plates and used as patch material.

2.2. Adhesive disbond

To highlight the effect of the adhesive disbond on the repair performance, the composite patches were bonded to the aluminum specimen using an epoxy adhesive (Araldite 2015) after preparing the surface based on the Bell Process Specification method [24]. The surface was prepared for the region along which the patch was bonded. Initially, the surface was cleaned using acetone to remove grease, which can lead to a weak bond. The bonding area was then polished using

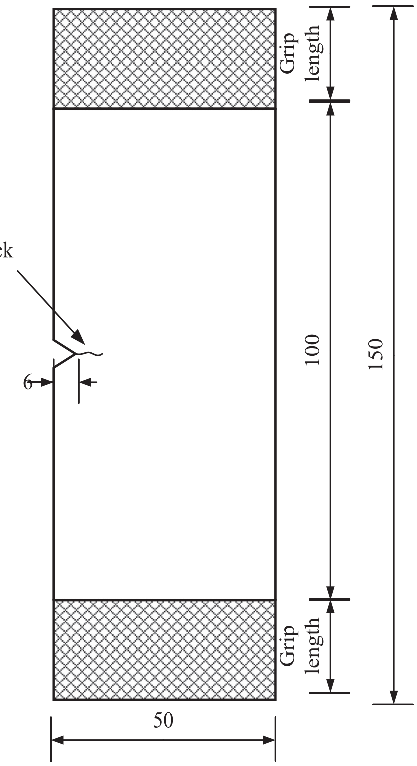

Fig. 1. Specimen geometry (in mm).

1200 grit sand paper along the loading direction only. Thereafter, the surface was cleaned using ethanol and air-dried followed by the application of a bi-component adhesive. The adhesive was cured for 48 hours at room temperature (RT) to obtain the full handling strength. The assembly of the substrate, adhesive, and patch was cured without any external heat for Permabond and Araldite adhesives. Thus, thermal residual stresses were not formed during the curing. However, Redux 312 was cured at its curing temperature of 120 °C, which leads to the formation of thermal residual stresses. Rectangular defects (disbonds) were deliberately introduced into the adhesive layer to simulate the adhesive disbond. A thin film of an anti-adhesive material (Teflon) with a thickness of 0.1 mm was used to avoid adhesion in the region considered as a disbond area (as shown in Fig. 2).

2.3. Thermal stresses evaluation

To study the effect of the TRS on the patch repair performance, three different adhesives were selected:

1. *Permabond ET515* is a bi-component structural adhesive cured at RT without thermal residual stresses.
2. *Araldite 2015* is also bi-component structural adhesive cured at RT without thermal residual stresses.
3. *Redux 312* adhesive comes in the form of thin film cured at an elevated temperature of 120 °C. The elevated temperature curing in this case generates thermal residual stresses.

The material properties of the three adhesives and other details are presented in Table 1. The aim of this part of the study is to compare the repair performances using the elevated temperature cure and ambient temperature cure adhesives.

2.4. Fatigue tests

Fatigue tests were conducted under a constant amplitude loading on a servo-hydraulic fatigue testing system (model 8801, Instron) with a