Composite Structures 100 (2013) 154–162

Contents lists available at SciVerse ScienceDirect

Composite Structures

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

Letter to the editor

Effects of curing thermal residual stresses on fatigue crack propagation of aluminum plates repaired by FML patches

Hossein Hosseini-Toudeshky [a,*], Mojtaba Sadighi [b], Ali Vojdani [b]

[a] Aerospace Engineering Department, Amirkabir University of Technology, 424 Hafez Ave, Tehran, Iran
[b] Mechanical Engineering Department, Amirkabir University of Technology, 424 Hafez Ave, Tehran, Iran

ARTICLE INFO

Article history:
Available online 11 January 2013

Keywords:
FML
Fatigue
Repair
Thermal residual stress
Composite
Aluminum

ABSTRACT

One of the main disadvantages of using composite patches in repair of metallic panels is development of thermal residual stresses due to the curing cycles of the bonded repairs. Fiber Metal Laminates (FMLs) have the overall larger thermal expansion coefficients when compared with the fully composite patches. In this study, the thermal residual stresses that occur due to the thermal expansion coefficient mismatch between the FML patch and underlying cracked aluminum panel are investigated using both numerical and experimental studies. The fatigue crack growth behaviors of centrally cracked aluminum panels in mode-I condition with single-side repairs of FML patches that are made by alternating layers of aluminum and glass fiber-epoxy are carried out. Sensitivity of the curing temperature on fatigue crack-growth life extension and crack-front shape of the repaired panels is also investigated. It is shown that implementing of various curing temperatures do not significantly affect the thermal residual stresses, crack-growth lives and crack-front shapes of the repaired panels by FML patches.

1. Introduction

A structurally efficient method for life extension of aging aircraft is the use of adhesively bonded composite patches for repair of damages such as fatigue cracks or corrosion and/or strengthening the aircraft structures. Comparing with the mechanically fasteners repairs, high performance adhesively bonded composite patches such as graphite/epoxy and boron/epoxy are most advantageous. This is due to the high directional stiffness, high failure strain, good fatigue performance, and durability under cyclic loading that improve the original function of damaged structure by retardation of crack re-initiation and propagation in the parent metal. Furthermore, bonded composite patches have low density and excellent formability that conform more easily to complex geometries [1]. Also adhesively bonded repairs do not create an additional source of damages such as fasteners holes.

Adhesively bonded repairs using boron/epoxy and graphite/epoxy patches have also some drawbacks. One of the main disadvantages of these patch materials results from their relatively low thermal expansion coefficient compared to the metallic substrate [2]. When the adhesives curing are employed at elevated temperature for patch bonding and when the operating temperatures are very low, residual tensile and/or compression stresses are introduced into the metallic component that may affect the opening of the cracks.

Numerical studies were performed by Hosseini-Toudeshky and Mohammadi [3] to evaluate the thermal residual stress effects on fatigue crack growth of single-side repaired panels bonded with various composite materials in mode-I condition. It was shown that low curing temperatures with long curing cycles have not a considerable effect on fatigue crack-growth life of the aluminum panels repaired with glass/epoxy patches and have minor effects for repaired panels with graphite/epoxy and boron/epoxy composite patches. But, it is considerable when high curing temperatures were employed. Albat [4] carried out analytical and experimental studies to investigate thermal residual stresses effects in bonded composite repairs on cracked metal structures. It was found that high thermal residual strains (reaching 15% of the yield strain) presented in the bonded repair specimen at ambient temperature. Modeling and measurement of residual stresses due to the composite repair bonding process have been also performed by Djokic et al. [5]. In this study, an experimental technique was presented for monitoring of residual stresses occurred by the curing process. It was found that it is possible to achieve significant (>20%) reductions in patch lay-up and at the same time, minimize the processing time and obtaining a high final adhesive degree of curing. The focus of a research performed by Crooks [6] was the use of a high strength composite patch technique to repair a fatigue crack on an aluminum aircraft structure. The research concluded that reducing the curing cycle temperature could decrease the thermal residual

* Corresponding author. Tel.: +98 21 6454 3224; fax: +98 21 6695 9020.
E-mail address: Hosseini@aut.ac.ir (H. Hosseini-Toudeshky).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2012.12.052

strains by as much as 26.5% between the graphite/epoxy composite patch and aluminum structure when FM-73M adhesive was used to bond them together. The research also concluded that a lower curing cycle temperature did not significantly affect the panels' fatigue crack growth rates. A numerical study carried out by Aminallah et al. [7] to evaluate the distribution of the thermal residual stresses due to the adhesive curing in bonded composite repair by means of finite element method. The obtained results of their work show that the normal thermal stresses in the plate and the patch are important and the shear stresses are less significant. The level of the adhesive thermal stresses is relatively high and the presence of the thermal stresses increases the stress intensity factor at the crack-tip, which reduces the repair performance.

Therefore, thermal expansion coefficient of patch material can be an important parameter in determining the overall repair efficiency. Although the CTE mismatch problems due to the curing temperature are minimal in thick structures, thermal considerations become paramount during the repair process of cracked fuselage structures [8]. So it is expected that in cases with single-side bonded repairs to cracked thin aluminum sheets, moderate-modulus, relatively high-CTE patch materials such as fiber metal laminate GLARE-2 are more effective than typical composite patch materials such as boron/epoxy. The Fiber Metal Laminate (FML) GLARE is a hybrid material of moderate modulus, combining aluminum with high strength s-glass/epoxy composite. It is known for its excellent fatigue resistance due to the "crack bridging" effect of the fibers and its high residual strength [8].

It has been shown by Fredell [9] that the relative effective coefficients of thermal expansion of the patch and the fuselage play the largest roles in determining the performance of the repair. The GLARE 2 proved more effective than high modulus composites in reducing the stress intensity factor of a crack in a fuselage. The application of GLARE repairs to a USAF C-5A transport has been described in [10]. It is indicated that the repair is a technically viable solution for the Crown-Cracking problem of the C-5A. Daverschot et al. [11] performed numerical, experimental and analytical studies to investigate thermal residual stresses in bonded repair. In this work, two analytical models, i.e., the Wang–Rose model and the Van Barneveld–Fredell model were used to determine residual stresses. They also applied experiments based on two configurations, i.e., test specimen (free expansion of the repaired skin) and in-field specimen (restrained expansion of the repaired skin), to measure thermal residual stresses in bonded repairs produced with GLARE 2 and boron/epoxy patches. The obtained results were compared with FEM results. It is indicated that a GLARE 2 repair introduced detrimental tensile stress in the plate for a test specimen and favorable compressive stress in the plate of an in-field specimen. A study carried out by Vlot et al. [12] to evaluate several in-service effects such as variable amplitude fatigue loading and realistic operating temperature, for bonded GLARE and boron/epoxy repairs. Bonded repair specimens were tested under fatigue loading at −40 °C and smaller crack growth rate were observed for the GLARE repairs than the boron/epoxy repairs. Also, finite element analyses revealed that the higher crack growth rates for boron/epoxy repairs are caused by the larger thermal stresses induced by the curing of adhesive.

It should be noted that out-of-plate bending occurs in single-side repaired panels, results from the shift in the neutral axis of the panel under tension loading. This causes stress intensity factor variations over the thickness of the cracked panel at crack-front. Therefore, a curved crack-front shape is produced due to the non-uniform crack-propagation along the panel's thickness [3,13–16].

This study investigates the effects of thermal residual stresses that occur as a result of thermal expansion coefficient mismatch between the patch, adhesive and metallic parent material. Numerical (FEM) and experimental studies are performed to investigate the effects of curing temperature on fatigue crack-growth behavior of centrally cracked aluminum panels in mode-I condition repaired with FML patches that are manufactured using alternating layers of aluminum and glass fiber-epoxy. The obtained life extension, crack-front shape and fatigue crack-growth behavior of the single-side repaired panels are discussed for the cracked panels repaired with two categories of FML patches, at various curing temperatures. The obtained numerical fatigue lives are compared with experimental fatigue tests results.

2. Finite element modeling and analysis

3-D finite element analyses based on the modified crack closure method or single step Virtual Crack Closure Technique (VCCT) are carried out in this study for crack growth behavior analysis of single-side repaired panels considering thermal residual stresses effects. These analyses are performed considering the real crack-front shape (non-uniform crack growth along the thickness) due to the stress variations along the panel thickness.

Fig. 1 shows typical geometry and loading of the cracked aluminum panels repaired with two classes of FML composite patch. The panels with centrally crack in mode-I condition were made of 2024-T3 aluminum alloy and the patch materials were FML composites that consisting of a laminate of one (or two) thin 2024-T3 aluminum alloy layer(s) bonded with layers of glass fiber-epoxy composite (Fig. 1). Dimensions and material properties of the aluminum cracked panel, adhesive and FML patch are given in Tables 1 and 2, respectively. The lay-up configurations in glass fiber-epoxy layers of FML patches were unidirectional perpendicular to the crack length for all models. The applied remote stress of 116 MPa with a load ratio of $R = 0.05$ are considered for all models. Five different curing temperatures of room temperature, 50 °C, 80 °C, 100 °C and 120 °C are considered for thermal residual stress analysis of the repaired panels.

ANSYS finite element code is used to investigate fatigue behavior of cracked aluminum panels repaired with FML patches. In these 3-D elastic analyses, isotropic 8-node solid elements are used to model the aluminum layers and adhesive. Furthermore a layered 8-node solid element is used to model the glass/epoxy layers in FML patches. Ten elements in the thickness of plate, one element in the thickness of each material in FML patch and one element in the adhesive thickness are used and a fine mesh is generated for the region close to the crack-front at each increment. A typical finite element mesh of the repaired panels has been shown in Fig. 2.

Performed numerical analysis of the thermal residual stresses is based on the experimental facts that during the heat-up phase of curing process, both parts of panel and patch are allowed to expand or contract freely because the adhesive has not yet cured and locked to the structure. When the adhesive is sufficiently cured, structural constraints are introduced between the repair and parent structure. Therefore, when the repair has been cooled to the ambient temperature, thermal residual stresses occurred due to the thermal expansion coefficient mismatch between the panel and patch material.

In this finite element modeling it is assumed that the structural constraints are exerted in the interface of aluminum panel and FML patch at evaluated temperature. Then the temperature cools down to the ambient temperature of 20 °C. Following that the residual stress and strain fields are obtained from a linear solution. The obtained residual stresses in this stage accumulate with the stress values obtained from linear elastic solution considering the applied external tension loads and constraints at each crack propagation increment. It is also noted that after curing process the initial crack