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Effects of thermal residual stresses on failure of co-cured lap joints with steel and carbon fiber–epoxy composite adherends under static and fatigue tensile loads

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Abstract

A co-cured joint, which uses excess resin extracted from the composite material (or the polymer material) as the adhesive, has several advantages compared with the adhesively bonded joint. It has no need of the surface treatment of the composite adherend and any adhesive for bonding. In addition, its manufacturing process is very simple because the bonding process is achieved during the curing process of the composite adherend. Thermal residual stresses are important in analyzing failure of the co-cured joint because composite materials are different from metal alloys in thermal and mechanical properties. In general, effects of the thermal residual stresses on failure of the adhesive joint are analyzed through experimental and analytical results.

Therefore in this paper, two design parameters, namely the surface roughness of the steel adherend and the stacking sequence of the composite adherend, are considered for static and fatigue tensile tests of the co-cured single and double lap joints. Stress distribution at the interface between the two adherends is used to analyze failure of the co-cured lap joints through the finite element method. Based on the stress distribution, two failure criteria, namely the three-dimensional Tsai–Wu failure criterion and the Ye-delamination failure criterion, are considered to predict the tensile load bearing capacity of the co-cured lap joints. Finally, effects of thermal residual stresses on failure of the co-cured single and double lap joints with the steel and composite adherends under static and fatigue tensile load conditions are presented through comparing the experimental and analytical results.

Keywords: Co-cured joint; Thermal residual stresses; Static and fatigue tensile loads; Surface roughness; Stacking sequence

1. Introduction

A co-cured joining method is a kind of the adhesively bonded joining method, which uses an adhesive to bond two or more adherends. However, the co-cured joining method is different from the adhesively bonded joining method from a manufacturing process point of view. The co-cured joining method uses excess resin extracted from the composite material during the curing process as the adhesive. Therefore, the bonding process of the co-cured joining method is simpler than that of the adhesively bonded joining method because it requires no surface treatment of the composite adherend and the bonding process can be performed simultaneously during the curing process. Since the adhesive of the co-cured joint is the same material as the resin of the composite adherend, analysis and design of the co-cured joint for composite structures are simpler than those of the adhesively bonded joint [1].

Since the first report on mechanical properties of the co-cured joint was issued in the middle of 1990s, many researchers have introduced some manufacturing processes and mechanical characteristics of the co-cured composite–composite joint [2–6]. However, any papers on manufacturing processes and mechanical characteristics of the co-cured joint with metal and composite adherends have not been reported until the late 1990s [7–13]. The plate type co-cured single and double lap joints subjected to static and fatigue tensile loads were investigated with respect to several design parameters [1,14,15].

Fatigue behavior in joint structures is important because under the alternating load condition the adhesive joint will

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fail at a stress level much lower than what they can withstand under the monotonic load condition. The adhesive joint is generally regarded as possessing good fatigue characteristics compared to the mechanical joint due to its relatively more even stress distribution [16]. In general, static and fatigue joint strength of the adhesive lap joint is dependent on the surface roughness [17–19]. Because the composite adherend has different stiffness with the variation of the stacking angle, it is important to consider the dependence of the joint strength of the co-cured lap joint on the stacking sequence of the composite adherend [2,20].

Thermal residual stresses, which are caused by a difference in temperature originated during the curing process, have much effect on failure of the co-cured joint because composite materials are different from metal alloys in thermal and mechanical properties. Some researchers have studied on thermal residual stresses in the adhesive joint. Lee and Lee presented an optimal condition for the steel–steel tubular single lap joint considering thermal residual stresses [21]. Reedy and Guess discussed the dependence of the temperature on the corner fracture toughness of the butt joint with various bond thickness [22]. Kim et al. investigated stress distribution in the adhesively bonded tubular single lap joint considering thermal residual stresses due to the fabrication and presented a failure model [23,24]. Cho et al. studied the effect of the curing temperature on thermal residual stresses of the polyamideimide–copper joint, which affected significantly the adhesion strength [25]. They have reported that the thermal residual stresses have an important role in failure of the adhesive joint through experimental and analytical results. Therefore, it is important to study the effect of thermal residual stresses on failure of the co-cured lap joint.

In this paper, two design parameters, the surface roughness of the steel adherend and the stacking sequence of the composite adherend, are examined for their effects on failure of co-cured single and double lap joints with steel and carbon fiber–epoxy composite adherends subjected to static and fatigue tensile loads. The effect of the surface roughness is looked upon by experimental results and that of the stacking sequence by experimental and analytical results. Failure mechanism of the co-cured lap joints under the static and fatigue tensile load conditions is investigated from observing many failed surfaces of the specimens and analyzed through the stress distribution of the co-cured lap joints. The stress distribution at the interface between the steel and composite adherends is obtained through the finite element analysis and used to calculate the tensile load bearing capacity of the co-cured lap joints introducing the three-dimensional Tsai–Wu failure criterion and the Ye-delamination criterion. After comparing the analytical and experimental results, an optimal condition to obtain more efficient mechanical characteristics of the co-cured single and double lap joints are presented. An appropriate model for estimating the experimental results is also given for each kind of the co-cured lap joints.

2. Specimen fabrication and experimental procedure

Manufacturing process of the co-cured joint consists of four steps: the machining process and the surface treatment of the steel adherend; the stacking process of the composite adherend and the pre-bonding process of it to the steel adherend; the bonding process (or the curing process) of the pre-bonded co-cured joint; and the finishing process. After machining the steel adherend using machine tools, the surface treatment should be performed carefully to improve the joint strength. In general, as the interface between the two adherends is rougher, the co-cured lap joint has larger joint strength because of the increase of the contact area and the mechanical interlocking effect. The surface treatment should be performed carefully not to contaminate the surface of the steel adherend, not making the joint strength deteriorate. Uncured composite prepregs are stacked and pre-bonded to the steel adherend with a careful alignment and be cured completely in the autoclave under the manufacturer's recommended cure cycle. Fig. 1 shows a cure cycle for the carbon fiber–epoxy composite material. The surface configuration of the steel adherend is transmitted to the composite adherend during the bonding process and determines an interfacial feature between the steel and composite adherends. Subsequent to the bonding process the co-cured lap joint is finished using various abrasive sandpapers to obtain better joint strength by eliminating sharp edges. A resin layer, which plays a role of the adhesive, is formed between the steel and composite adherends with thickness of 5–20 μm. Table 1 shows material properties of the carbon fiber–epoxy composite material (USN 150) produced by SK Chemicals.

Fig. 2 shows a photograph of the co-cured single and double lap joints with the steel and carbon fiber–epoxy composite adherends. The Teflon block surrounded by the steel and composite adherends is used to prevent the two steel adherends from bonding with each other. Fig. 3 shows

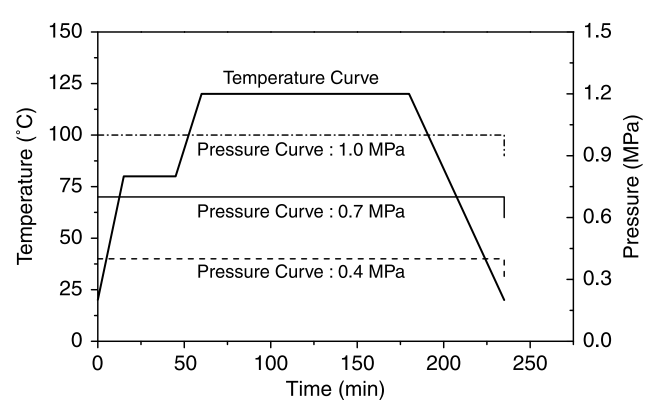

Fig. 1. Cure cycle for the manufacturing process of the co-cured lap joint.