Composites: Part A 48 (2013) 1–8

Contents lists available at SciVerse ScienceDirect

Composites: Part A

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

Surface modification of carbon fiber/epoxy composites with randomly oriented aramid fiber felt for adhesion strength enhancement

Ilbeom Choi, Dai Gil Lee *

School of Mechanical Aerospace & Systems Engineering, KAIST (Korea Advanced Institute of Science and Technology), ME3221, 291 Daehak-ro, Yuseong-gu, Daejeon-shi 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 16 October 2012
Received in revised form 17 December 2012
Accepted 14 January 2013
Available online 26 January 2013

Keywords:
A. Aramid fiber
A. Carbon fiber
B. Adhesion
E. Autoclave

ABSTRACT

To increase the strength of an adhesive joint whose adherend is composed of a carbon fiber/epoxy composite, the surface of the adherend is reinforced with randomly oriented aramid fiber felt before the full cure of the adherend. With this smart cure cycle, the aramid fibers are exposed from the adherend, promoting a bridging effect between the fibers and the adhesive. The cured carbon fiber/epoxy composite material, on which the aramid fiber felt is placed, is co-cure bonded with a smart cure cycle developed in this work. The improvement of the adhesive bonding strength due to the aramid fiber felt is measured with the single-lap shear test of adhesively bonded joints. Additionally, the flexural strength of the carbon fiber/epoxy composite adherend with the co-cure bonded aramid fiber felt is measured.

1. Introduction

Composite materials have been widely used in aerospace, machine tool structures, robot constructions and automotive components [1]. Carbon fiber/epoxy composites are applied more extensively for structural applications than other high performance fiber composites due to their overall high specific stiffness and strength properties [2].

Adhesive joining technologies requiring treatment of the composite surface have been used when the composite structures are to be joined to other structures [3–5]. Conventionally, the mechanical abrasion method has been used for improving the adhesively bonding performance of the composites [6]. Additionally, chemical treatments such as the plasma treatment, flame treatment and coupling agents for the secondary surface treatment improve the adhesive bonding strength of the composite materials [7–9].

Because the strength and toughness of adhesives are improved by reinforcing the adhesive layer with fibers, the aramid fiber, which has high strength and low coefficient of thermal expansion (CTE), thereby decreasing residual thermal stresses generated during the curing process, was employed to improve the bonding performance of the adhesive layer in addition to modifying the surface of composites [10–12]. Also, the interfacial adhesion strength between the reinforcing fibers and the epoxy resin is important to determine the material properties of the composite materials or the adhesive layer [13–15]. Not only aramid fiber was used to improve the adhesion performance but also the low density aramid fiber felts were adopted to improve the interlaminar strength of the carbon/epoxy composite as inserting between the composite plies [16,17].

The carbon black was embedded to increase the adhesion strength of the composite material and the co-cure bonding method was used to increase the material properties and to embed the sensors for the smart composites [18–23]. Additionally, a smart cure cycle was used during the fabrication process of the composite material to improve the mechanical properties of the composites as well as the strength of adhesive joints with reduction of thermal residual stress [24–26]. The smart cure cycle was based on the autoclave vacuum bag degassing method, in which the temperature is controlled [26].

In this work, the surfaces of the carbon fiber/epoxy composites were reinforced with the randomly oriented aramid fiber felt by the co-cure bonding method to increase the adhesive bonding strength. This fabrication method was efficient for the adhesive bonding application because the surface treatment process was not only reduced, but it also provided reinforcement to the adhesive. The surface modification of the carbon fiber/epoxy composite using the aramid fiber felt was fabricated by controlling the cure cycle. Then, the improvement of the adhesive bonding performance of the carbon fiber/epoxy composites due to the aramid fiber felt was measured by the single-lap shear test of the composite adhesive joints. Finally, the flexural strength of the surface modified carbon fiber/epoxy composite using the randomly oriented aramid fiber felt was compared with that of the carbon fiber/epoxy composite without the surface modification.

* Corresponding author. Tel.: +82 42 350 3221; fax: +82 42 350 5221.
E-mail address: dglee@kaist.ac.kr (D.G. Lee).

1359-835X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesa.2013.01.003

2. Fabrication of the carbon fiber/epoxy composite with the aramid fiber felt

High performance composite structures are usually cured with the autoclave vacuum bag degassing method to maximize their mechanical properties [1]. The general autoclave vacuum bag degassing cure cycle for the composite material is shown in Fig. 1, where the cure cycle may be divided into five steps (A, B, C, D and E): In step A, the temperature is increased from the room temperature to 80 °C. In step B, which is a dwelling process for the consolidation of the composites, the temperature is maintained at 80 °C. In step C, the temperature is increased from 80 °C to 125 °C. The duration of all three steps (A, B and C) is approximately 30 min. In step D, which is the main curing step, 125 °C is maintained for 2 h to ensure the complete cure of the epoxy resin. In the final step E, the temperature is cooled down to the room temperature for 30 min. In all the steps, the applied pressure outside the vacuum bag is 0.6 MPa, while the vacuum state is maintained inside the vacuum bag from the beginning. However, the vacuum might be applied after some time to retard void generation from the epoxy resin.

In this work, the unidirectional carbon fiber/epoxy composite specimens were fabricated using prepregs (URN 300, SK Chemicals, Korea), whose mechanical properties are shown in Table 1 [26]. The measured fiber volume fraction of the cured carbon fiber/epoxy composite was 0.64.

2.1. Smart cure cycles for composite to bond the aramid fiber felt

The smart cure cycle was used to co-cure bond the aramid fiber felt on the outer surface of the carbon fiber/epoxy composite, exposing bare aramid fibers on the felt surface by partially wetting the aramid fiber felt as shown in Fig. 2a. If the aramid fiber felt was co-cure bonded to the composite materials using the conventional cure cycle in Fig. 1, the aramid fibers would be fully wetted with the excess epoxy resin in the prepregs as shown in Fig. 2b.

Therefore, the cure cycle was controlled to achieve partial wetting of the aramid fiber felt on the carbon fiber/epoxy composite. Several different cooling times in step D (Fig. 1) were used to cure the specimens, where the notations of SC10, SC20, SC30 and SC40 were used to represent cooling times of 10, 20, 30 and 40 min from the start of the step D.

The fabrication process of the smart cure cycles may be divided into a pre-cure process, control process and post-cure process. In the pre-cure process, the carbon fiber/epoxy prepregs were stacked only on a flat mold and cured through the cure cycle steps of A, B and C under the outside vacuum bag pressure of 0.6 MPa. In the control process, the cooling of the laminates was performed by

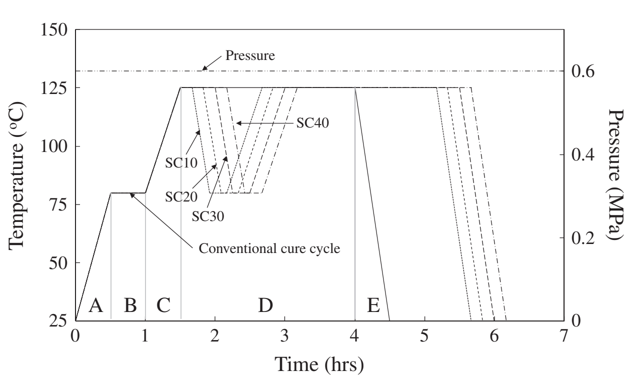

Fig. 1. Conventional cure cycle (solid line) and smart cure cycles (dotted and chain lines) of the composite material.

Table 1
Mechanical properties of the unidirectional carbon fiber/epoxy composite (URN 300).

Density, ρ (kg/m^3)	Longitudinal stiffness, E (GPa)	Tensile strength, σ (MPa)	Ply thickness, t_{ply} (mm)
1550	380	710	0.25

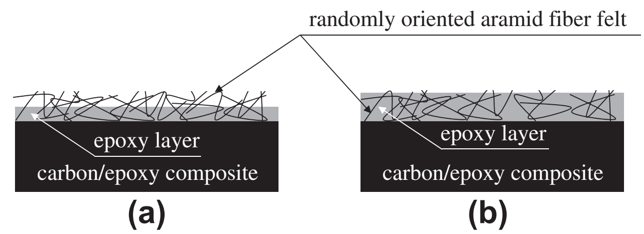

Fig. 2. Schematic drawings of the surface modified carbon fiber/epoxy composites by the co-cure bonding of randomly oriented aramid fiber felt: (a) aramid fibers exposed due to the partial wetting of epoxy resin; (b) aramid fibers barely exposed due to full epoxy resin wetting.

turning off the autoclave's electrical power and releasing the pressure inside the autoclave at the start of cooling. In the post cure process, after the vacuum bag was removed, the aramid fiber felt was placed on the surface of the partially cured composite laminates. After the specimen was sealed again with a new vacuum bag, the cure cycle started at the end of step C (the start of step D) under the outside vacuum bag pressure of 0.6 MPa, while maintaining vacuum state inside the vacuum bag. The mold size was 150 × 150 mm and the areal density of aramid fiber felt was 98 g/m^2. The process diagram of the total fabrication process is shown in Fig. 3.

2.2. Surface and cross section analysis of the composite

Figs. 4 and 5 show the photographs of the surface and cross section of the composites with the aramid fiber felt cured by the smart cure cycles of SC10, SC20, SC30 and SC40. In Fig. 4, the aramid fiber felt was fully wetted with the excess epoxy resin during the SC10 cure cycle, while the aramid fiber felts were partially wetted during the SC20 and the SC30 cure cycles. When the SC40 cure cycle was applied, the aramid fiber felt was not bonded to the composite surface due to the almost full curing of the epoxy resin. From observations of the cross section in Fig. 5, the aramid fibers protruded little from the outer surface of the composite cured with the SC10 cure cycle, while bare aramid fibers were exposed and protruded from the outer surface of composites cured with the SC20 and the SC30 cure cycles. However, the epoxy layer thicknesses, including the aramid fiber felt, cured with the SC20 and SC30 cure cycles were 170 μm and 110 μm, respectively. A gap existed between the aramid fiber felt and the composite cured with the SC40 cure cycle.

3. Bonding performance of the surface modified composite

3.1. Lap shear strength

The lap shear bonding strengths of the adhesive joints whose adherends were made of carbon fiber/epoxy composite were measured by the single-lap shear test with respect to aramid fiber felt surface modification. Fig. 6 shows the configuration of a single-lap joint specimen, which was bonded with the epoxy adhesive (Araldite®, Huntsman, England) and cured with the cycle shown in Fig. 7. The adhesive properties are listed in Table 2. The lap shear