Composite Structures 160 (2017) 89–99

Contents lists available at ScienceDirect

Composite Structures

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

A comparative study of the mechanical properties and failure behavior of carbon fiber/epoxy and carbon fiber/polyamide 6 unidirectional composites

Yan Ma [a], Masahito Ueda [b], Tomohiro Yokozeki [c], Toshi Sugahara [d], Yuqiu Yang [e,*], Hiroyuki Hamada [a]

[a] Advanced Fibro-Science, Kyoto Institute of Technology, Kyoto 606-8585, Japan
[b] Department of Mechanical Engineering, College of Science and Technology, Nihon University, Tokyo 101-8308, Japan
[c] Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo 113-8656, Japan
[d] Maruhachi Corporation, Fukui 910-0276, Japan
[e] Key Laboratory of Textile Science & Technology, Ministry of Education, College of Textiles, Donghua University, Shanghai 201620, PR China

ARTICLE INFO

Article history:
Received 10 September 2016
Revised 13 October 2016
Accepted 15 October 2016
Available online 18 October 2016

Keywords:
Polymer matrix composite
Failure behavior
Damage mechanics
Prepreg

ABSTRACT

Two types of unidirectional carbon fiber reinforced plastic were fabricated using identical carbon fibers but different matrix systems. Thermoplastic polyamide 6 and thermosetting epoxy were used as matrices. A large number of on-axis tensile tests of unidirectional carbon fiber reinforced polyamide 6 (CF/PA6) and the unidirectional carbon fiber reinforced epoxy (CF/Epoxy) laminates were performed. Mechanical properties and failure behaviors are discussed based on fiber distribution, impregnation conditions and interfacial shear strength. Tensile strengths were predicted by means of a modified global load sharing model and compared with experimental results. Step-by-step tensile tests revealed the fracture process of 0-degree unidirectional CF/PA6 laminates.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been used in an extensive range of engineering applications because of their outstanding mechanical properties, which enable lightweight and extended service-life structures [1–5]. Metallic materials have gradually been replaced by CFRP [6–9]. It is well known that the mechanical properties of a CFRP are affected by various factors such as the properties of the fiber and matrix, the fiber volume fraction, fiber distribution, impregnation of the matrix, and compatibility between the fiber and the resin (interface and interphase). Manufacturing processes such as temperature, pressure, and process time also affect the mechanical properties. Therefore, many methods to improve the mechanical properties of CFRPs such as fiber treatment [10–12], post-treatment [7,9], structure optimization [7,9,13–15], and micro- or nano-scale filler doping [16–21] have been investigated. One of the most efficient ways to ameliorate the capability of CFRPs is to choose an appropriate surface treatment to improve interfacial strength between the fibers and the matrix.

During loading of a unidirectional (UD) CFRP, mesoscopic events, such as matrix cracking and fiber breakage, initiate and propagate progressively. Such damage accumulates with increased loading. Fiber breakage and matrix cracking often cause interfacial de-bonding [22]. A firm adhesive interface (ideal impregnation of matrix and strong bonding between fibers and matrix) is necessary for the efficient transfer of stress throughout the interface [23]. Modification of the interface could affect fracture modes of a UD CFRP, resulting in disparate mechanical properties [24–28]. The fracture process of a UD CFRP is not currently well understood because the process is extremely rapid (>500 m/s [29]). Ultimate failure of a UD CFRP always occurs abruptly after initiation of mesoscopic events, without any symptoms or visible signs of damage serving as an alarm.

Analytical modeling of tensile failure of a UD CFRP, followed by fiber fragmentation is well established. A useful baseline is obtained by assuming that stress re-distribution around broken fiber follows global load sharing (GLS) [30,31]. This approach assumes that the load from a broken fiber is shared uniformly and equally to all remaining intact fibers across the cross-section of the break point [30–44]. Curtin [30,31] was the first to develop an analysis of the stress–strain response of a fragmenting bundle,

* Corresponding author.
E-mail addresses: stonemayan0416@gmail.com (Y. Ma), ueda.masahito@nihon-u.ac.jp (M. Ueda), yokozeki@aastr.t.u-tokyo.ac.jp (T. Yokozeki), toshi@maruhati.co.jp (T. Sugahara), amy_yuqiu_yang@dhu.edu.cn (Y. Yang), hhamada@kit.ac.jp (H. Hamada).

http://dx.doi.org/10.1016/j.compstruct.2016.10.037
0263-8223/

based on the Cox's [32] shear lag model, Rosen's [33] chain of bundle concept and the Kelly–Tyson [34] approximation model for inefficient length. Curtin's model was later extended by Neumeister [35,36] to account in an approximate way for the overlap of influence zones adjacent to fiber breaks, and subsequently an exact solution to the fragmentation problem was developed. Further research using the GLS model has mainly focused on investigating mechanical behavior, the influencing factors and mechanisms [37–44].

In the present study, a typical thermoplastic resin, polyamide 6 (PA6) and a thermosetting epoxy resin were used as matrices to fabricate UD carbon fiber reinforced PA6 laminates (CF/PA6) and epoxy laminates (CF/Epoxy) through hot compression molding. Their failure behaviors and mechanical properties were investigated based on the fiber distribution, impregnation conditions and interfacial shear strength (IFSS). The modified GLS model was used to predict tensile strengths, which were then compared with experimental results.

2. Experimental methods

2.1. Materials

2.1.1. Production of unidirectional composites

Two types of UC CFRP were fabricated using one type of carbon fiber and different matrix systems. Two UD prepreg sheets were prepared from carbon fibers (T700SC 12K, Toray, Tokyo, Japan) with PA6 (MXD-PA, Mitsubishi Gas Chemical, Tokyo, Japan), and carbon fibers (T700SC 12K, Toray) with epoxy (MCP939, Maruhachi Corporation, Fukui, Japan). The mechanical properties of the raw materials are shown in Table 1. The thickness of a single ply lamina was about 0.1 mm. CFRP laminates with a thickness of 1 mm were fabricated by laminating 10 plies of prepreg sheets with stacking sequences of $[0]_{10}$ for 0-degree longitudinal tensile tests. Molding conditions were 280 °C for 3.5 min under a compression pressure of 4 kg/cm^2 for CF/PA6 laminates and 130 °C for 50 min under a compression pressure of 25 kg/cm^2 for CF/Epoxy laminates. Similarly, laminates with thickness of 2 mm and stacking sequences of $[0]_{20}$ were prepared for transverse tensile tests. Specimens of both CF/PA6 and CF/Epoxy laminates were cut with a size of 15 × 250 × 1 and 25 × 15 × 02 (Width × Length × Thickness: *mm*) for longitudinal and transverse tensile tests, respectively. Rectangular-shaped aluminum-alloy tabs were bonded on both ends of the specimens using an epoxy adhesive (Araldite™), as shown in Fig. 1.

2.1.2. Sample preparation for microindentation tests

From the UD composites, specimens of about 2 mm × 25 mm were cut out and embedded standing upright in a PMMA tube filled with liquid epoxy resin. In this way, an epoxy resin cylinder, containing a sample of CFRPs at the center with fibers in longitudinal direction, is produced. 2 mm thick plate is cut off in order to get a plane perpendicular to the fiber direction.

After cutting, the previously cut face side of the cylinder is grinded and polished by using SiC abrasive paper with grain size from 400, 600, 800, 1200, 1500–2000 step-by-step, then use the aluminum powder with grain size from 1 mm, 0.1 mm to 0.05 mm progressively. For this procedure, the cylinder is clamped in an adapter holding the cylinder perpendicular to the polishing plane. After finishing the first side, the last step in the sample preparation procedure is to grind and polish the second side of the specimen in a similar manner as describe above, till a slice of composite with a thickness of about 100 μm.

2.2. Experimental procedures

2.2.1. Tensile tests

About 60 pieces of 0-degree specimens and more than 10 pieces of 90-degree specimens were prepared. The tensile tests were carried out on a computer-controlled, screw-driven universal testing machine (55R4206, Instron, Kanagawa, Japan) equipped with a 100-kN load cell at a speed of 1 mm/min on the basis of testing standard ASTM D3039 [45]. The tensile tests were performed at room temperature in a relative humidity (RH)-controlled laboratory (23 ± 0.5 °C, 48 ± 2% RH).

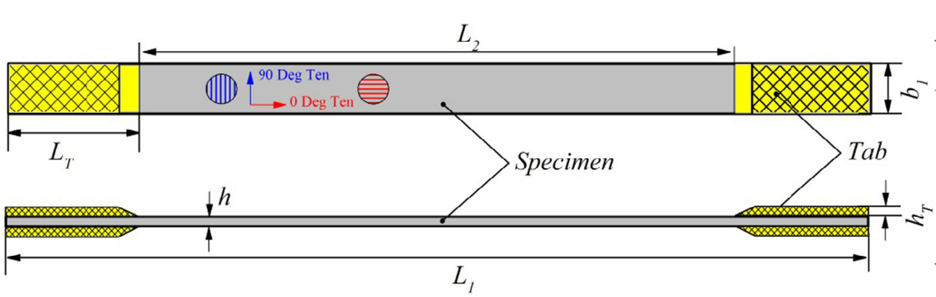
2.2.2. Single-fiber push-out tests

Single-fiber push-out tests were performed using a Berkovich Indenter with pyramid geometry (Nano Indenter G200, Agilent Technologies, Oak Ridge, TN, USA), as shown in Fig. 2. The load was applied at a constant rate of 0.2 μm/s. For single-fiber push-out tests, the specimen is required to be thin, to allow fracture over

Table 1
Mechanical properties of materials.

Material	Manufacturer	Type	E(GPa)	σ(MPa)	δ.(%)	ρ.(g·cm^{-3})
CF	Toray	T700SC 12 k	230	4900	2.1	1.8
PA6	Mitsubishi Gas Chemical Company	MXD-PA	2.4	82*/48$	4.0*/136$	1.1
Epoxy	Maruhachi Corp.	MCP1110	3.2	80.6	5.4	1.2

E: Tensile modulus;σ: Tensile strength;δ:.Elongation;ρ: Density.
* Yield point.
$ Break point.



Parameters	Size of 0° /mm	Size of 90° /mm
L_1	250	200
L_2	150±1	100±1
b_1	15±0.5	25±0.5
h	1±0.2	2±0.2
L_T	50	50
h_T	1	1

Fig. 1. Schematic of specimens used for tensile tests, based on the ASTM D3039 standard.