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Damage tolerant behaviors of a biomimetic CFRP laminate

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Abstract—The present work examines the damage tolerant behaviors of synthetic composites by using composite architectures observed in biological materials. The static, impact, and compression after impact (CAI) behaviors of biomimetic CFRP laminates with stacking sequences similar to those found in animal hard tissues are compared to those of a standard quasi-isotropic and a cross-ply laminates.

The dependence of the extent of damage in the samples with a hole under tensile loading on the laminate lay-up was analyzed by a finite element analysis. The damage tolerance is then related to the actual damage extension from the hole perpendicularly to the applied load. It is shown that the damage tolerance of biomimetic laminate is more advantageous than the two other laminates. The implications of the findings for the design of damage-tolerant laminates are further discussed.

It is also shown from the results of compression after impact test that the sensitivity of biomimetic laminate to the presence of delamination damage is significantly lower than that of quasi-isotropic and cross-ply laminates.

Keywords: CFRP; damage tolerant; biomimetic laminate; CAI; residual strength.

1. INTRODUCTION

Many biological materials have interesting specific properties. They could provide concepts to improve man-made fiber-reinforced composites [1]. Their microstructure, which is determined to a large extent by the nature of the constituent materials and biosynthesis, is believed to confer on them superior specific properties and resistance to damage [2]. In order to do this, we need to clearly understand the strong as well as weak points of laminates with a biomimetic reinforced structure. Our previous work discussed the damage tolerance of a biomimetic laminate in terms of the extent of an equivalent damage zone, which depends on the architecture of the laminate [3].

This work examines the mechanical properties of a type of biomimetic composite laminate with fiber reinforcement architecture similar to that observed in biological materials such as fish scales or insect cuticles [1, 4]. The static, impact, and compression after impact (CAI) behaviors of a biomimetic CFRP laminate are compared to those of a standard quasi-isotropic and a cross-ply laminate. The sensitivity of a biomimetic laminate to the presence of a damage area, here modeled as an open hole, is investigated and the study compares the residual tensile strength and fracture patterns to those of conventional quasi-isotropic and a cross-ply laminates.

This paper also discusses the compression after impact (CAI) properties of the biomimetic laminate with delaminations of varying damage and compared to that of quasi-isotropic and cross-ply laminates.

2. SPECIMEN PREPARATION AND EXPERIMENTAL METHOD

The fiber or fibril orientation in many biological laminates varies through the thickness of the material in steps that deviate from 90° by a fairly constant angle [2]. As such composite laminates often have a protective or structural function, it was assumed that their damage tolerance must be advantageous. Based on findings in the literature [1–5], a regular angle difference of 78° between successive plies was adopted for the biomimetic laminates in present study (Fig. 1). This angle step gives laminates with a double helical layup and, in multiples of 16 plies, a quasi-isotropic elastic behavior.

The samples were made from unidirectional (UD) AT400/EP carbon fiber-reinforced epoxy prepregs (Asahi Kasei Corporation, Japan). The cured material had a longitudinal modulus of 117 GPa and transverse modulus of about 11 GPa. Laminated plates consisting of 16 plies of prepreg were cured in an autoclave at a pressure of 6 bar and 130°C for 2 h. The heating rate was 2.5°C/min and the

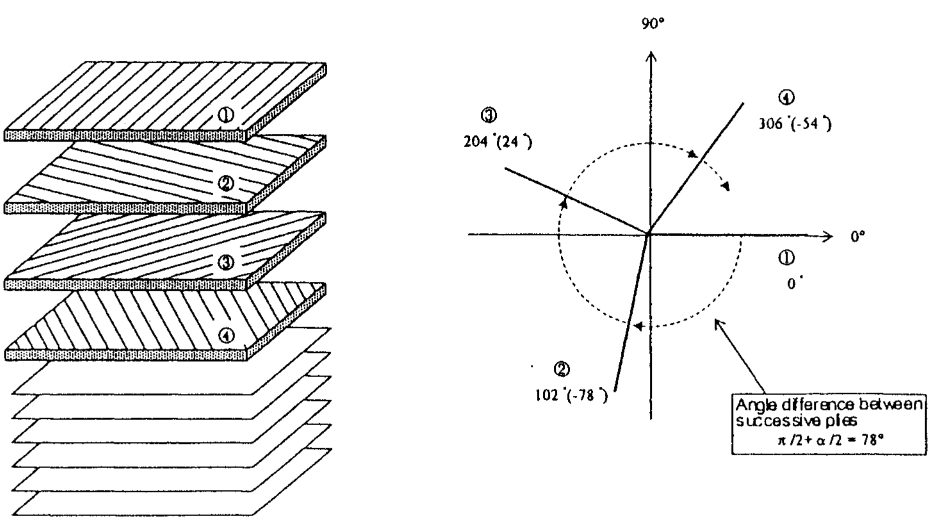

Figure 1. Lay-up definition of the biomimetic CFRP laminate.

Table 1.
Definition of sample types

Designation	ID	Laminate Lay−up	θ^*
Cross−ply	CP	L $[0/90]_{4S}$ T $[90/0]_{4S}$	90° (half plies)
Quasi−isotropic	QI	L $[0/+45/90/-45]_{2S}$ T $[90/-45/0/45]_{2S}$	45° (half plies)
Biomimetic	BM	L $[0/-78/24/-54/48/-30/72/-6//$ $-84/18/-60/42/-36/66/-12/90]_T$ T $[90/12/-66/36/-42/60/-18/84//$ $6/-72/30/-48/54/-24/78/0]_T$	78° (24° for each helix)

θ^*: Angle difference between plies.

samples were slow cooled under pressure by turning off the heat in the autoclave, in order to minimize internal stresses. The resulting laminates had a thickness of 1.98 ± 0.06 mm. The cured plates were cut into 20 mm wide samples with a water-cooled rotary diamond saw. The test pieces were conditioned at room temperature and 65% humidity for two days or more prior to testing. The lay-ups of the samples for this study are given in Table 1.

Tensile tests were performed on the samples without hole and with a central, 2.5 mm, 4 mm or 5 mm diameter hole corresponding to a hole diameter to sample width ratio of 1/8, 1/5 and 1/4. The CFRP samples were clamped between two 5 mm thick acrylic plates during drilling, in order to keep damage around the hole during machining to a minimum. The samples without and with a hole had a gauge length of 120 mm and 80 mm, respectively. Tapered GFRP tabs were bonded to the sample ends to reduce the likelihood of damage or slippage in the grips. The samples were tested in tension up to failure at crosshead speed of 1 mm/min. The extension of plain samples was measured by strain gauges bonded to each side of the samples. The stress was calculated for the sample net cross-section. Failure loads were accepted only for samples which failed in the free gauge length.

The dimensions of the test specimens used for four-point bending were 15 mm in width, 120 mm in length and 2 mm in thickness. The supporting span length was 80 mm, while the loading span length was 40 mm. The samples were tested at the constant speed of 2.5 mm/min in four-point bending of a beam.

The static bending and tensile samples were cut out from two different direction of each laminate, longitudinal (L) and transverse (T) directions.

The impact tests were conducted at a speed of 4.4 m/s on a closed-loop electro-hydraulic impact testing machine. The impact load was applied with a 12.7 mm diameter rod on the central portion of the 75 mm × 75 mm CFRP plates, in which the outside of 60 mm diameter was clamped between steel plates by using four springs to give a constant force (Fig. 2).

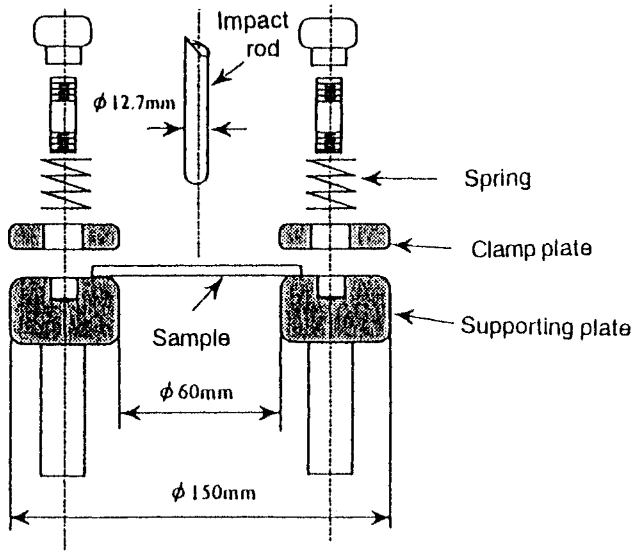

Figure 2. Penetration impact test equipment.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The biomimetic and the standard quasi-isotropic laminates had nearly the same fracture strength and elastic modulus in tension, while the cross-ply laminate was much stronger and stiffer [6]. The symmetric quasi-isotropic and cross-ply laminates had no extension/flexural coupling. All samples failed on the free length, away from the grips. The cross-ply samples broke along a straight line, perpendicular to the loading axis, and damage was localized in the vicinity of the fracture. On the other hand, the damaged area in the quasi-isotropic and biomimetic laminates extended over a length corresponding to more than twice the width of the tensile sample, with extensive delamination and splitting.

Table 2 compares the four-point bending properties among cross-ply (CP), conventional quasi-isotropic (QI) and biomimetic (BM) laminates. The bending strength and rigidity of the quasi-isotropic laminate are influenced remarkably by the directions of laminate, longitudinal (L) and transverse (T) directions. On the other hand, those of biomimetic laminate did not differ significantly, even if the sample was cut in the different direction from the laminate. This is more clearly observed in the load-deflection curves for three different laminates [6]. This indicates that the biomimetic laminate has an improved isotropic characteristic when compared with conventional quasi-isotropic laminate.

The static tensile strength of the biomimetic laminate with holes of varying diameter is compared to that of quasi-isotropic and cross-ply laminates. The first two have similar elastic moduli and strengths without a hole. The change of the strength ratio with an increase of hole diameter is compared in Fig. 3 between quasi-isotropic and biomimetic laminates.

Table 2.
Four-point bending properties of the laminates compared

ID	Bending strength σ_b (GPa)	Flexural rigidity EI (N m^2)
CPL	1.21	1.77
CPT	0.88	1.44
QIL	0.91	1.35
QIT	0.68	0.74
BML	0.76	1.13
BMT	0.82	1.02

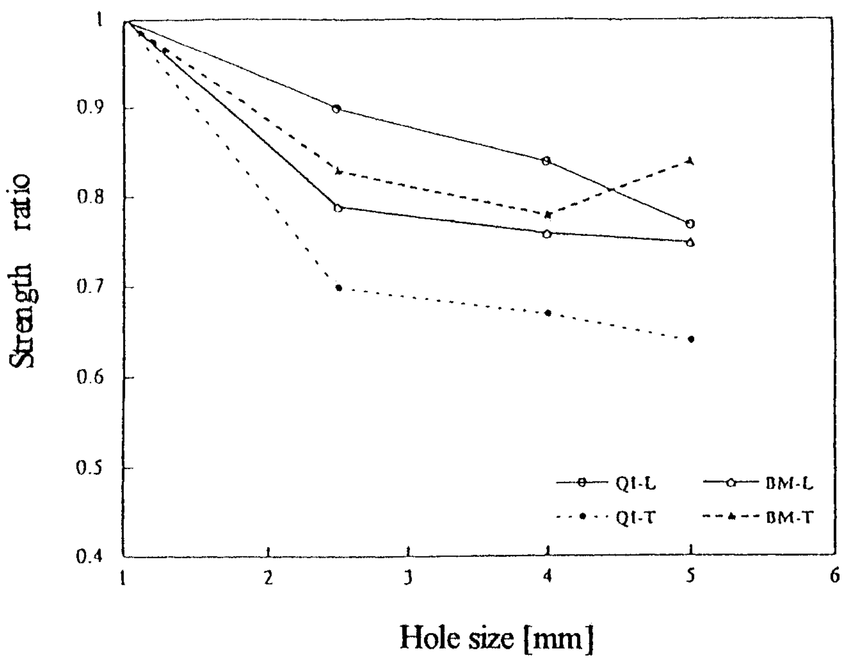

Figure 3. The change of the strength ration with hole diameter.

The strength ratio of quasi-isotropic sample is monotonically decreasing as the hole diameter increases within the present work, while the strength ratio of biomimetic sample becomes almost constant for the hole diameters beyond 2.5 mm, independently of loading direction. The change of strength ratio with hole diameter in the longitudinal direction of quasi-isotropic sample is quite different from that in the transverse direction. The sensitivity of biomimetic laminate to the presence of a hole is significantly lower than that of quasi-isotropic laminate. The biomimetic laminate has a higher resistance to the notch for the larger hole diameters than the quasi-isotropic and cross-ply laminates. The damage tolerance of the laminate depends apparently on the architecture of the laminate.

Table 3.
Absorbed energy during impact and calculated ductility index

ID	Impact rate (m/s)	Maximum load (kN)	U_{total} (J)	U_{peak} (J)	Ductility index
CP	4.4	1.78	124	39	2.16
OI	4.4	1.95	152	58	1.63
BM	4.4	1.83	155	49	2.19

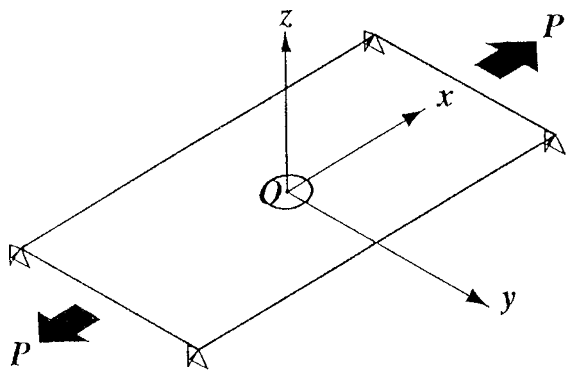

Figure 4. Finite element analysis.

The features of fracture in laminates with a central 4 mm diameter hole were compared in the previous paper [6]. The failed zones had different appearances. The notched cross-ply samples broke along a straight line, and the damage, involving mainly fiber breakage, was very localized in the vicinity of the fracture. In the quasi-isotropic samples, the fracture ran at 45° from the hole, leading to a 90° V shape. This was accompanied by delamination exposing mainly 45° and some loose debris of pulled-out delaminated layers. On the other hand, the angle of the V-shaped fracture in the biomimetic laminate was larger than in the quasi-isotropic laminate, and much less splitting was observed in the surface layer with longitudinal fibers.

As a result of penetration impact test, the peak load and energy until peak load, U_{peak}, as well for quasi-isotropic sample are slightly higher than those for biomimetic sample, while the cross-ply laminate has the lowest values (Table 3). The total energy until failure, U_{total}, for biomimetic sample is almost the same as that for quasi-isotropic sample. Here, if a ductility index is defined as the ratio of energy after peak load, $(U_{total} - U_{peak})$, to energy until peak load, U_{peak}, the ductility index value for biomimetic sample is the highest of all laminates investigated. It is very interesting to note that the load–deflection behavior of biomimetic laminate is more ductile than those of the two other laminates, while undergoing impact loading.

The dependence of the extent of damage in the samples with a hole under tensile loading on the laminate lay-up was analyzed by a finite element analysis using a commercial FE code (see Fig. 4). The damage tolerance is related to the actual

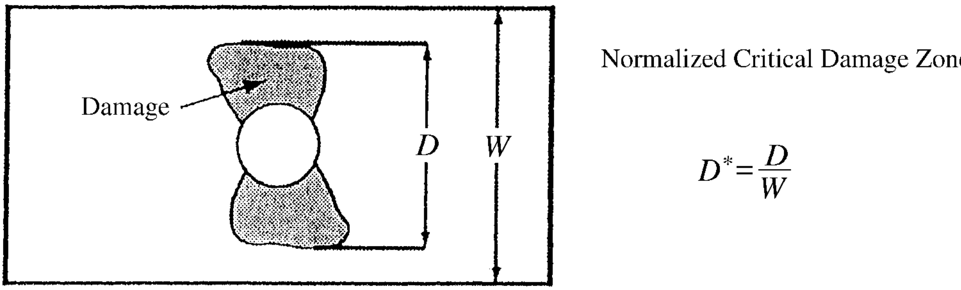

Figure 5. Critical damage zone D^*.

Table 4.
The calculated critical damage zone value

ID	D^*
Cross-ply (CP)	0.500
Quasi-isotropic (QI)	0.571
Biomimetic (BM)	0.843

damage extension from the hole perpendicularly to the applied load. The critical damage zone width D^* was calculated as the ratio of damage zone size to the specimen width size, D/W at the ultimate load of the sample with a hole, as shown in Fig. 5. This critical damage zone value is taken as an indicator of the damage tolerance of the laminate. A larger critical damage zone at failure means a higher damage tolerance. As can be compared in Table 4, the calculated critical damage zone D^* at failure load level for the samples with the 4 mm diameter hole was about 47% larger in the biomimetic laminate than in the standard quasi-isotropic laminate. The value of D^* for the cross-ply laminate was the lowest, at less than 60% of the value for the biomimetic laminate. The higher value of D^* indicates a more extensive lateral propagation of the damage before failure of the sample. Whereas the cross-ply laminate fails catastrophically, the biomimetic laminate had a more extensive spatial distribution of the damage before final failure. The broader distribution of angles between plies and the loading direction is expected to lead to a wider range of interlaminar shear stresses near edges and hole, and thus to a more progressive evolution of damage.

The compression after impact (CAI) properties of the biomimetic laminate with delaminations of varying damage is compared to that of quasi-isotropic and cross-ply T800H/3631 laminates. The change of the residual compressive strength with an increase of damage area is compared in Fig. 6. The residual compressive strength for quasi-isotropic laminate and cross-ply laminate are monotonically decreasing as the damage area increases within the present work, and the rate of decrease in the residual strength for the biomimetic sample is apparently lower than that for the quasi-isotropic sample. In addition, the compressive strength of biomimetic laminate becomes almost constant for the damage area beyond 500 mm^2. The

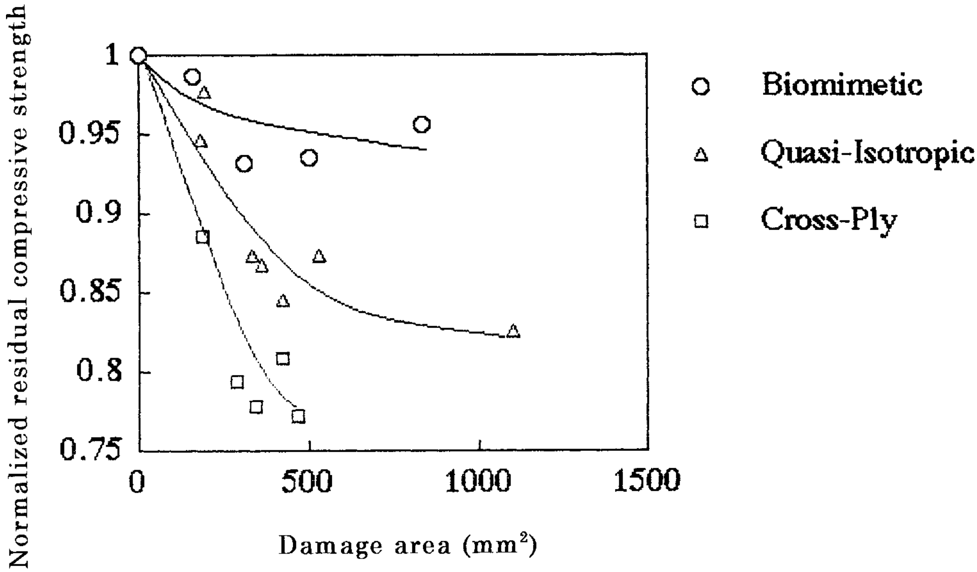

Figure 6. The change of residual compressive strengh with damage area.

sensitivity of biomimetic laminate to the presence of delamination damage is significantly lower than that of quasi-isotropic laminate. The biomimetic laminate has a higher resistance to the impact damage than the quasi-isotropic and cross-ply laminates, particularly for the larger damage area. The damage tolerance of the laminate depends apparently on the architecture of the laminate.

As the biomimetic laminates have a more complex layup, an optimized design involves a tradeoff between performance and manufacturability.

4. CONCLUDING REMARKS

This paper presents results on the residual compressive strength properties of a biomimetic laminate after it has been impact damaged. It examines the sensitivity of a biomimetic laminate to the presence of a damage area, here modeled as a delaminated area. The sensitivity of biomimetic laminate to the presence of delamination damage is significantly lower than those of conventional quasi-isotropic and cross-ply laminates. It is quite an important conclusion that the biomimetic laminate has a higher resistance to the impact damage, particularly for the larger damage area than the quasi-isotropic and cross-ply laminates. The damage tolerance of the laminate depends apparently on the architecture of the laminate.

Judging from the results of both the notched strength in tension and impact energy after reaching peak load, it is reasonable to consider that the damage tolerance of biomimetic laminate is better than that of the standard quasi-isotropic laminate.

The above-mentioned results obtained in the present work seem important issues for the actual design of damage-tolerant laminates in application to structures. As the biomimetic laminates have a more complex layup, an optimized design involves a tradeoff between performance and manufacturability.

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