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Improved impact response of hygrothermally conditioned carbon/epoxy woven composites

Abstract: The effects of hygrothermal conditioning and moisture on the impact resistance of carbon fiber/epoxy composite laminates were investigated. Specimens were fabricated from carbon fiber/epoxy woven prepreg materials. The fabricated specimens were either immersed in water at 80°C or subjected to hot/wet (at 80°C in water for 12 h) to cold/dry (at -30°C in a freezer for 12 h) cyclic hygrothermal conditions, which resulted in different moisture contents inside the laminates. It was found that the absorbed moisture did not migrate out from composite materials at -30°C. Neither of the hygrothermal conditions in this study had detrimental effects on the microstructure of the laminates. Low-velocity impact testing was subsequently conducted on the conditioned specimens. When attacked by the same level of impact energy, laminates with different moisture levels experienced different levels of impact damage. Moisture significantly alleviated the extent of damage in carbon fiber/epoxy woven laminates. The elastic response of the laminate under impact was improved after hygrothermal conditioning. The mechanism behind the improved impact resistance after absorbing moisture was proposed and deliberated.

Keywords: composites; damage characteristics; hygrothermal; impact resistance; moisture.

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Nomenclature

D_i	Projectile deflection corresponding to incipient damage point, mm
D_{max}	Maximum projectile deflection, mm
D_p	Projectile deflection corresponding to the peak load point, mm
D_Z	Through-the-thickness diffusivity constant, mm²/s
DI	Damping index
E_d	Impact energy dissipated through damage creation and propagation, J
E_{d1}	Damage generation energy before the peak load point, J
E_{d2}	Damage generation energy after the peak load point, J
E_{el}	Impact energy absorbed through elastic deformation, J
E_p	Total energy absorbed corresponding to the peak load point, J
E_{total}	Total impact energy or actual impact energy exerted on specimens, J
F_i	Incipient damage load or load corresponding to the incipient damage point, kN
F_p	Peak contact force between the impactor and the specimen, kN
h	Thickness of a plate, mm
M_f	Final moisture content of specimens, %
M_m	Effective equilibrium moisture content, %
M_1	Moisture content at time t_1, %
M_2	Moisture content at time t_2, %
W_i	Initial weight of laminates (measured after curing), g
W_f	Final weight of specimens or weight before impact testing, g

1 Introduction

Laminated composites are generally fabricated by incorporating high-strength endless fibers (e.g., carbon fiber, glass fiber, etc.) into a polymer matrix. They exhibit light weight but high strength compared to some metals, making them an ideal material for weight-critical applications. Because of their high strength/stiffness-to-weight ratios, laminated composite materials are now widely used in aerospace structures [1, 2], automobiles [3, 4], sports equipment [5, 6], marine applications [7, 8], etc.

Most polymer matrix composites (PMCs) are vulnerable to hygrothermal environments. Much effort has been devoted to the investigation of the behavior of laminated composites under combined hygrothermal environments. Hygroscopic aging causes matrix swelling because of moisture absorption, while thermal treatment might promote additional curing of the matrix causing matrix shrinkage [9]. Both fiber- and matrix-dominated properties of PMCs have been reported to be degraded after hygrothermal conditioning [10, 11]. Wosu [12] studied the effects of moisture and temperature on the dynamic compressive properties of graphite/epoxy composites by conducting high strain rate penetration experiments. The decrease in the compressive strength, elastic modulus and energy absorbed was observed when the composites were loaded under extreme temperature, moisture and combined moisture and temperature conditions. Chen [13] conducted a compression test under a hygrothermal environment and found that this environment degraded the compression properties of both stitched and unstitched laminates (with a hole). Aniskevich [14] conducted mechanical testing on moistened glass fiber-reinforced polyester composites and found that specimens moistened up to the saturation level suffered from a decrease of 8% and 16.5% in both flexural modulus and strength, respectively. However, the tensile modulus and strength of the material were not affected by the sorbed moisture.

The impact properties of polymer matrix composite materials have attracted special attention in both academic field and the industry. The two components of a composite material, fibers and matrix resin, do not impart much plastic deformation to the composites. Even a strike by a relatively light impact load can result in permanent failure of either the reinforcement or the matrix resin, endangering the structural integrity of the composite parts. In many cases, these damages are initiated inside the structure and therefore usually go unnoticed. Process parameters such as contact force, energy and projectile deflection, values of which are normally gathered during an impact testing event, are useful for the comparison of the impact properties of laminated composites [15–17]. The influence of hygrothermal conditioning on the capacity of PMCs to resist impact loading, however, has not received enough investigation. It was, however, reported that moisture and temperature affected the energy absorption process of the laminate during an impact [18].

The objective of this work is to identify the effects of hygrothermal conditioning on the behavior of CFRP (carbon fiber reinforced polymer) woven laminates under impact loading. Laminates were fabricated using a commercial CFRP prepreg material. Two hygrothermal conditions were selected for the aging of cured laminates. Low-velocity impact testing was conducted under a laboratory environment on hygrothermally conditioned specimens. The microstructures and damage modes were determined using a scanning electron microscope (SEM). The findings and the understanding of various phenomena are presented.

2 Materials and methods

2.1 Sample preparation

Laminates were fabricated using a 12 K, carbon/epoxy, woven prepreg that had a standard resin content of 40% by weight before curing. The prepregs were L-930HT (GT700) (manufactured by J.D. Lincoln Inc., Costa Mesa, CA, USA). The woven pregregs were cut into laminae of 100×100 mm^2 after being de-frozen under the lab condition for 4–5 h. The laminae were then stacked into laminates consisting of eight layers according to a stacking sequence of $[0/90]_8$. A roller was used to compact the plies during stacking in order to achieve void-free adhesion between adjacent layers. The laminated lay-ups were cured in a convection oven at 130°C for 4 h. A pressure measuring 5 kPa was applied to the laminates during the curing by placing dead weights on to the specimens. The average resin content of the cured laminates was found to be 38.87%.

2.2 Hygrothermal conditioning

As-fabricated specimens were either immersed in water at 80°C until saturation (isothermally conditioned group), or exposed to a number of hygrothermal cycles (cyclically conditioned group). The hygrothermal cycle had a duration of 12 h in water at 80°C and 12 h in a freezer at -30°C. A general water bath (Figure 1A) which provides a uniform temperature profile was used for water immersion conditioning. An analytical balance was used to measure the weight of the specimens periodically during conditioning. To ensure the removal of superficial surface water every time, the specimens were wiped dry using clean tissue paper and exposed to an ambient lab environment for around 10 min.

2.3 Impact testing

After conditioning, the impact resistance properties of CFRP woven laminates were studied by an instrumented low-velocity impact tester, Instron Dynatup 8250 drop tower impact tester (Figure 1B and C). The impactor height and weight applied during impact testing were 2.735 kg and 600 mm, respectively. The contact force,

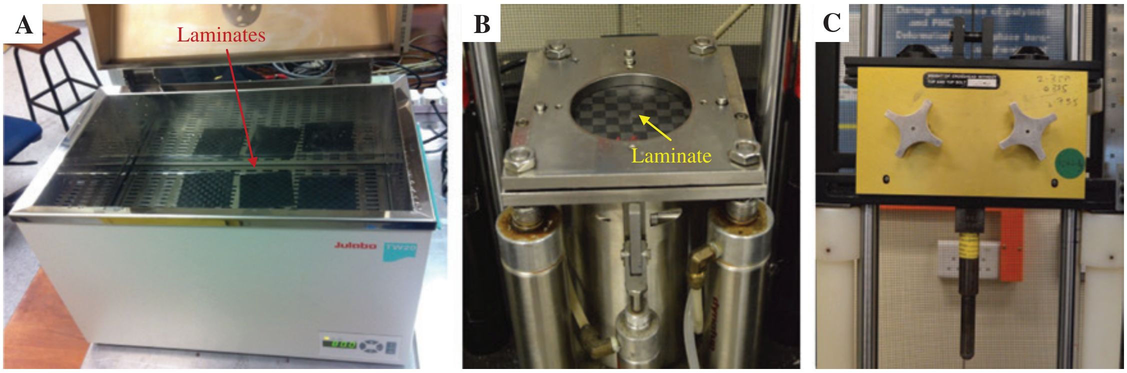

Figure 1: Key facilities used: (A) water bath; (B) clamping fixture of the impact tester; (C) impactor tup.

time, deflection, velocity and energy of each impact testing event were all output using the data acquisition system.

3 Results

3.1 Moisture absorption behavior

The hygrothermal conditioning scheme is summarized in Table 1. The reference group represents specimens not subjected to any prior hygrothermal conditioning. The weight changing history of two CFRP woven laminates immersed in water at 80°C is shown in Figure 2. Initially, the weight of the specimen increased linearly with $t^{1/2}$. After the percentage increase in weight reached a certain point, the rate of weight increase with $t^{1/2}$ reduced significantly. Eventually, the weight of the specimens increased exceptionally slow with immersion time. The diffusion of moisture inside CFRP woven laminates at 80°C manifested as typical Fickian behavior.

M_f in Table 1 was calculated as follows:

$$M_f = \frac{W_f - W_i}{W_i} \times 100\%. \tag{1}$$

D_z was calculated as follows according to ASTM D5229 [19]:

$$D_z = \pi \left(\frac{h}{4M_m}\right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2, \tag{2}$$

where

$\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}$ = slope of the moisture absorption plot in the initial linear portion of the curve.

Table 1: Hygrothermal conditioning results of CFRP woven laminates.

Group	Sample	W_i (g)	W_f (g)	M_f (%)	Time (h)	Thickness (mm)	Diffusivity D_z (mm²/s)
Reference (unconditioned) group	Ref 1	24.45333	–	–	–	1.768	–
	Ref 2	23.91144	–	–	–	1.714	–
	Ref 3	24.31863	–	–	–	1.730	–
	Ref 4	24.30728	–	–	–	1.768	–
	Average	24.24767	–	–	–	1.745	–
Cyclically conditioned group	Cyc 1	24.63879	25.15477	2.09	522	1.843	–
	Cyc 2	24.23862	24.80408	1.43	522	1.838	–
	Cyc 3	24.11994	24.60285	2.00	522	1.787	–
	Cyc 4	25.14306	25.63753	1.97	522	1.895	–
	Average	24.53510	25.04981	1.87	522	1.841	–
Isothermally conditioned group	Iso 1	24.77896	25.44373	2.68	522	1.850	1.777×10^{-6}
	Iso 2	24.34138	24.99595	2.69	522	1.845	1.527×10^{-6}
	Iso 3	24.66145	25.30232	2.60	522	1.786	1.032×10^{-6}
	Iso 4	24.37871	25.01305	2.60	522	1.785	1.075×10^{-6}
	Average	24.54013	25.18876	2.64	522	1.817	1.353×10^{-6}

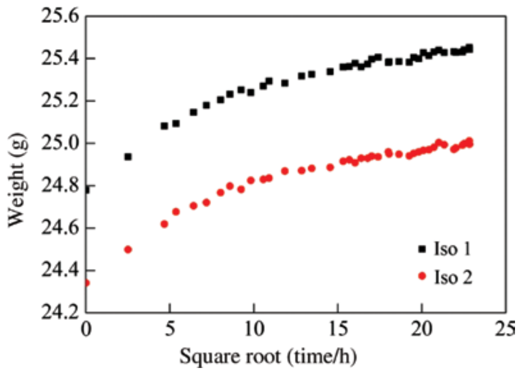

Figure 2: Weight change history of laminates immersed in water at 80°C.

Research work on isothermal conditioning of composite materials can be easily found in the literature. However, cyclic hygrothermal conditions, which are inevitable environments for aerospace composite structures, received relatively less attention. In this study, a hygrothermal cycle, which had a duration of 12 h in water at 80°C and 12 h in a dry freezer at -30°C, was designed to simulate certain in-service hygrothermal conditions. CFRP woven laminates were exposed to a number of such hygrothermal cycles and their weight was measured regularly each time after being taken out from the water bath or the freezer. Little variation in weight was observed when the specimens were aged in the freezer, indicating that moisture resided inside CFRP laminates lost their transport capability at -30°C. The actual state of moisture inside composite materials is still not fully understood and substantial disagreement needs to be resolved. Zhou and Lucas [20] proposed that water molecules bind with epoxy resins through hydrogen bonding, while Woo and Piggott [21] found that the moisture did not appear to be bound to polar groups in the resin although water inside did not behave as free water. Clustering of water molecules was found based on experimental results. However, whether absorbed moisture could form clusters that were large enough to allow the formation of ice crystals is not completely answered [22]. In our study, it was found that the absorbed moisture did not migrate out from the composite materials at -30°C.

3.2 Microstructure after hygrothermal conditioning

After hygrothermal conditioning, the microstructure of the laminates was characterized by observing their cross-sections using a JOEL 5600LV SEM. Prior to SEM observations, the laminates were sectioned by a diamond saw and later polished by 800, 1200, 2400 grit SiC paper and 0.3 μm micro-polish alumina powder. The typical microstructure of the laminates from different hygrothermal groups is shown in Figure 3.

The two constituents of a composite laminate, fiber and matrix, have the coefficient of thermal expansion (CTE) of different magnitudes. The epoxy resin has a CTE greater than that of carbon fiber; as a consequence, the laminate cannot expand or contract freely at changing temperatures, inducing thermal stresses at the fiber-matrix interface and interlaminar region. The diffusivity of moisture in the carbon fiber is negligible compared with the epoxy resin. Stresses are also introduced at the fiber-matrix interface and interlaminar region when the expansion of the moisture-saturated epoxy resin is constrained by the fibers. These moisture- and temperature-induced stresses may cause the degradation of the microstructure of the laminate, such as micro-cracks [23] and fiber debonding.

The specimens of the isothermally conditioned group were put in 80°C water for 522 h and their average moisture content reached 2.64%. However, no surface micro-cracks were found and their microstructure was analogous to that of the unconditioned samples (Figure 3C) without delamination and fiber-matrix interface failure. The specimens of the cyclically conditioned group experienced both temperature cycling and possible volumetric expansion associated with the water-to-ice transition. However, microstructure degradation was not found in the SEM image of this group of specimen. Both Figure 3B and C show that no cracks at the fiber-matrix interface and the interlaminar region were found, indicating good environmental durability of the composite materials investigated. In summary, the current hygrothermal conditioning and time span of environmental aging did not have detrimental effects on the microstructure of the CFRP laminates.

3.3 Damages of woven laminates under impact

As concluded in the previous section, the hygrothermal conditioning carried out in the current investigation did not bring about any visible structural defects. The major difference between specimens of different groups was that they had different moisture contents. The isothermally conditioned group had the highest moisture content, while the reference group had the lowest. After the hygrothermal conditioning, specimens with different moisture saturation levels were tested under the same impact energy level.

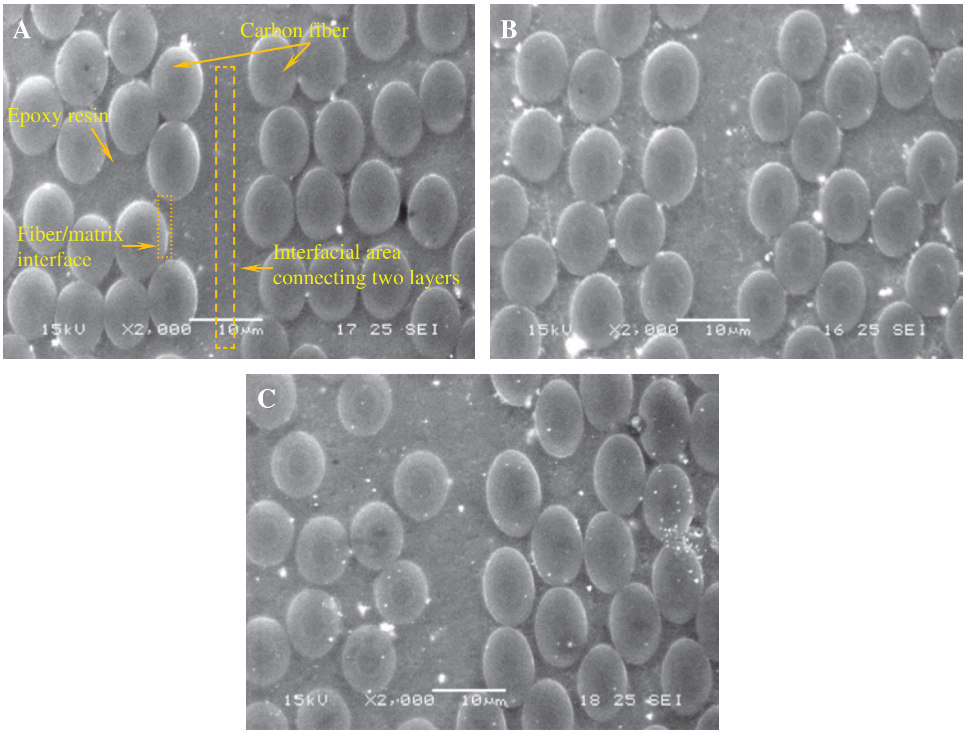

Figure 3: Microstructure of laminates of different groups: (A) unconditioned group, (B) cyclically conditioned group and (C) isothermally conditioned group.

An impact load normal to a clamped laminate is a bending load in nature. The largest stress and strain usually appear near the top and bottom surface of the composite, and the general damage modes include matrix cracking, delamination and fiber breakage. As shown in Figure 4, when tested under the same impact energy level, Ref. 1 had evident indentation, while no visible indentation was found at the top surface (surface that had direct contact with the impactor) of Iso 2. This apparently means that the specimen with higher moisture contents had lighter impact-induced damage. Severe fiber and tow splitting was observed at the bottom surface of Ref 1, while no splitting was found at the bottom surface of Iso 2. Only minor delamination and matrix cracking were found at the bottom surface of Iso 2. The photographs of the three specimens with different moisture contents proved that the extent of impact damage decreased with moisture content.

A careful observation of the damage site of the bottom surface of these three laminates revealed that delamination and fiber breakage are the major modes of damage for CFRP woven laminates under impact. As the degree of impact damage increased, the scale of delamination and volume of fiber breakage also increased.

In order to examine the damage modes inside the laminate, the cross-section of the laminate near the damage site was observed under an SEM; the micrographs of the laminates from each group are presented in Figures 5 and 6.

It was found that the specimen with highest moisture content, Iso 2, had minimum impact damage (Figure 5A–D). There was no evident damage near the top surface of the specimen (Figure 5A). Minor matrix cracking and delamination were observed near the bottom surface (Figure 5B). Thus, the major damage mode for Iso 2 was delamination. More severe delamination and fiber breakage were observed in Cyc 1, as shown in Figure 5C. The epoxy resin in this composite material is a type of brittle polymer. Therefore, large-scale matrix cracking was expected when severe delamination occurred (Figure 5C). Compared with Iso 2, Cyc 1 experienced more severe delamination (Figure 5C), large-scale matrix cracking (Figure 6C) and evident fiber breakage (Figure 6D). However, catastrophic failure was found in Ref 1 (Figure 5D), which was not hygrothermally conditioned and had the lowest moisture content. The damage modes of Ref 1 included large-scale delamination (Figures 5D and 6A) and severe splitting (Figure 6B). Among all the three laminates, Ref 1 experienced the most severe delamination (Figure 5D) and fiber breakage (Figure 6B). In summary, moisture significantly affected the damage characteristics of the laminates during impact testing. The degree of

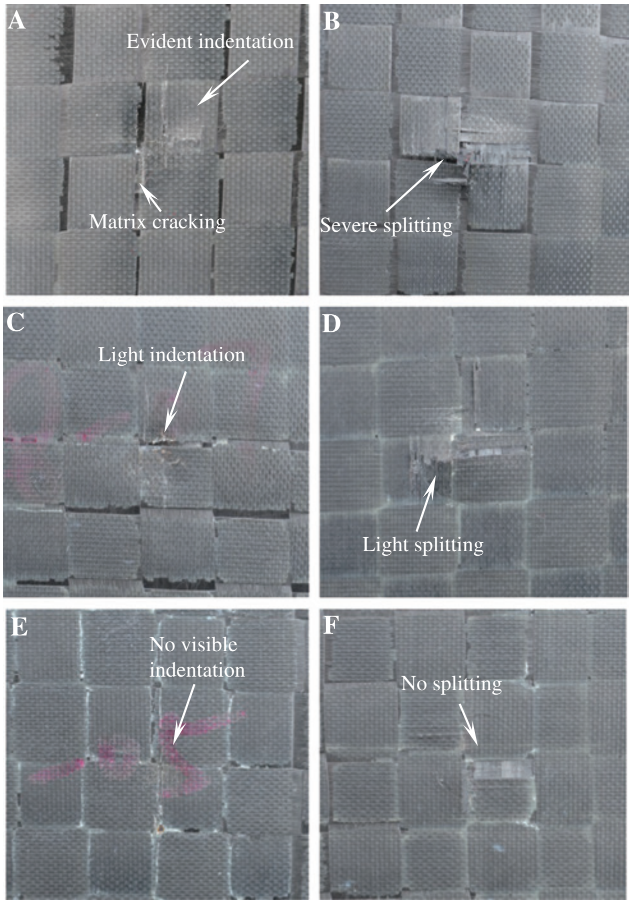

Figure 4: Photographs of impact tested specimens from different groups, M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 2): (A) top surface of Ref 1; (B) bottom surface of Ref 1; (C) top surface of Cyc 1; (D) bottom surface of Cyc 1; (E) top surface of Iso 2; (F) bottom surface of Iso 2.

impact damage decreased rapidly with moisture content, which equally indicates that absorbed moisture alleviated the damage characteristics of CFRP woven laminates.

3.4 Impact testing results

During an impact test, process parameters including contact force, time, energy and deflection were output by the data acquisition system to be used for the comparison and observation of the impact properties of testing structures. The characteristic parameters include F_i, F_p, D_i, D_p, D_{max}, E_d, E_{el}, the definitions of which are also found in the literature [16, 17]. E_{d2} was also adopted in the discussion of impact properties in this study. E_d consists of two parts, namely, E_d up to the peak load point (E_{d1}) and E_d beyond the peak load point (E_{d2}). Under the assumption that after the peak load point the most impact energy is devoted to the formation of damage, E_{d2} is calculated as

$$E_{d2}=E_{total}-E_p. \tag{3}$$

Lower values of E_{d2} indicate that less impact damage has been imparted to the test specimen by the impactor after the peak load point.

The load vs. time, load vs. deflection and energy vs. time curves of the three specimens selected from each group are plotted in Figures 7–9, respectively. The relationship between the moisture contents of these three specimens was M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 1).

In Figure 7, the load vs. time curve of Iso 1 is more symmetrical than that of the other two specimens. The contact force dropped suddenly for Ref 1 and Cyc 1, while the instant sharp load drop of Ref 1 occurred earlier in time than that of Cyc 1. The oscillations and sharp load drops on the load vs. time and load vs. deflection curves are indications of the initiation and propagation of damages, such as matrix cracking, fiber breakage and delamination. Once certain damage occurred, the stiffness of the structure would decrease and become more compliant. Iso 1, which had the highest moisture content, experienced the lowest level of impact damage. Therefore, no sharp load drop was observed on the load vs. time curve of Ref 1.

The area under the load vs. deflection curve represented the portion of impact energy that was stored in the laminate, and therefore was a measure of the degree of impact damage. It is evident that the area under the load vs. deflection curve decreased as the moisture content inside the material increased, which was consistent with the conclusion that the extent of impact damage decreased with the moisture content. No sharp load drop occurred for Iso 1, while the sharp load drop of Cyc 1 occurred at larger projectile deflection when compared with Ref 1. A sharp load drop on the load vs. time and/or load vs. deflection curve should be attributed to a significant damage created in the laminate. Damage modes that could contribute such an evident drop in contact force to the laminate are generally either severe delamination or fiber breakage. However, if it were fiber breakage that caused the sharp drop in contact force, the three samples in Figure 8 should experience a sharp load drop at approximately the same projectile deflection. Therefore, it was the severe delamination that brought about the sharp drop in contact force in Cyc 1 and Ref 1. Iso 1 did not exhibit such severe delamination, while Cyc 1 suffered from severe delamination at a larger projectile deflection than Ref 1. This led to the important finding that moisture could prevent or postpone the occurrence of delamination in a CFRP woven laminate.

The slope of the initial linear part on the load vs. deflection curve generally reflects the magnitude of the

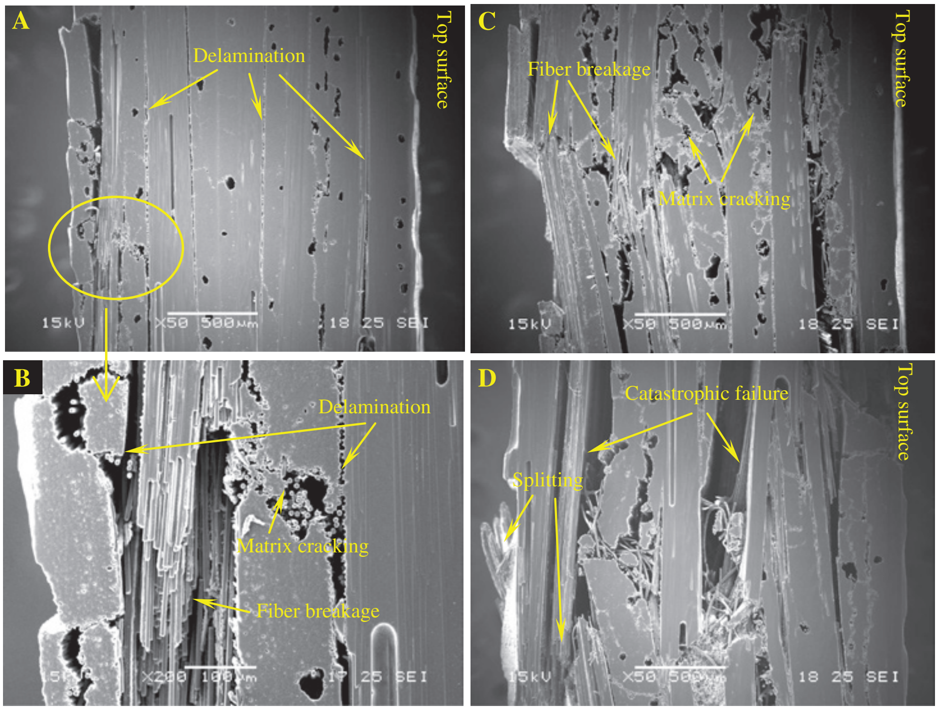

Figure 5: SEM graphs of the cross-sections of impact tested specimens with different moisture levels, M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 2): (A), (B) Iso 2 with the minimum level of impact damage; (C) Cyc 1 with more severe delamination and fiber breakage; (D) Ref 1 with catastrophic failure.

out-of-plane contact stiffness of the laminate. In Figure 8, the curves of all the three samples coincide with each other at the initial linear part. Therefore, before impact laminates with different moisture contents had approximately the same out-of-plane stiffness. Moisture did not affect the out-of-plane stiffness of CFRP woven laminates.

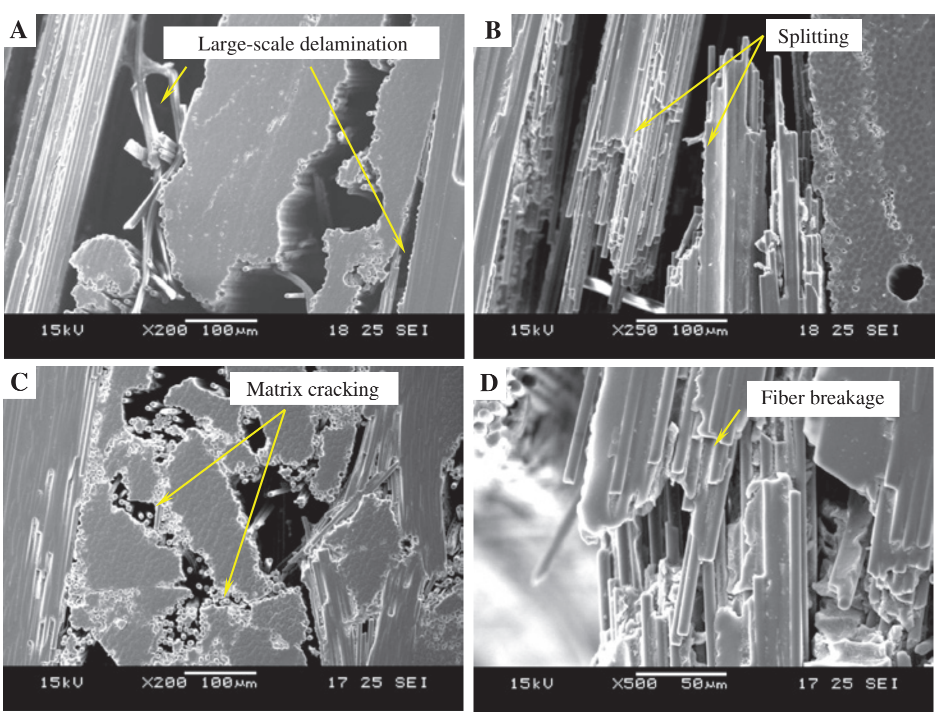

Figure 6: Comparison of the damage features of Ref 1 and Cyc 1, M_f (Ref 1)<M_f (Cyc 1): (A) Ref 1 with large-scale catastrophic delamination; (B) complete fiber splitting in Ref 1 after impact; (C) matrix cracking in Cyc 1; (D) fiber breakage in Cyc 1 after impact.

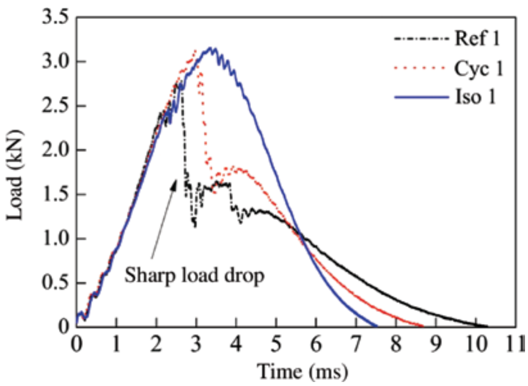

Figure 7: Typical load vs. time curves of woven laminates under low-velocity impact, M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 1).

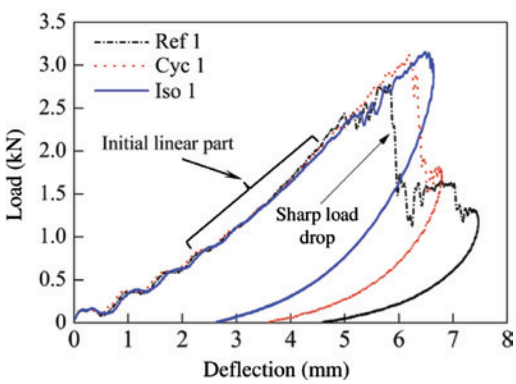

Figure 8: Typical load vs. deflection curves of CFRP woven laminates under low-velocity impact, M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 1).

This could be explained by the fact that the fibers in the laminate carried the majority of the applied load and moisture did not affect the mechanical properties of the carbon fiber.

In Figure 9, there is no evident difference between the initial parts of the energy vs. time curve of each specimen.

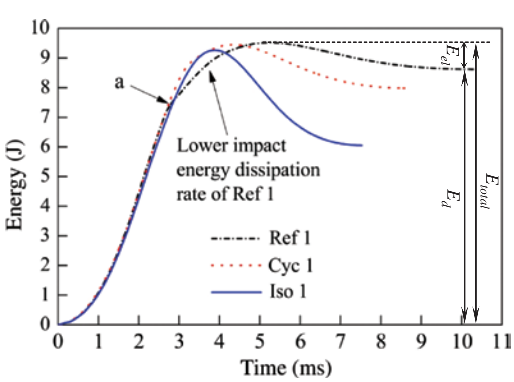

Figure 9: Typical energy vs. time curves of CFRP woven laminates under low-velocity impact, M_f (Ref 1)<M_f (Cyc 1)<M_f (Iso 1).

However, after point a (Figure 9), the impact energy dissipation rate of Ref 1 becomes lower than the other two laminates. As shown in Figure 7, there was no sharp load drop on the curve of Iso 1, while the instant sharp load drop of Ref 1 occurred earlier in time than that of Cyc 1. Compared to the other two laminates, Ref 1 suffered from severe impact damage at an earlier time. Therefore, the contact stiffness of Ref 1 suffered from a significant decrease earlier than that of the other two specimens, which consequently reduced the energy absorption ability of the laminate. Moreover, the specimen with higher moisture content had lower E_d and higher E_{el}, which proves that specimens with more moisture consumed more of the impact energy through elastic deformation and the energy accounting for damage generation reduced.

The impact testing results of the three groups of specimens are plotted in Figures 10–13. As shown in Figure 10A, D_i of both cyclically conditioned and isothermally conditioned groups was higher than that of the unconditioned reference group. This indicates that for conditioned laminates, the incipient damage or first significant damage occurred at larger deflections (higher strain levels accordingly) on an average scale. Thus, moisture absorbed during conditioning played a positive role in the CFRP woven laminates by improving their ability to sustain higher deflections without damage. Projectile deflection at the peak load point increased monotonically with average moisture content, proving that CFRP laminates with higher moisture content could retain their resistance to the impactor up to larger deflections. The increase in D_i and D_p proves that the elastic response of the laminate improved after absorbing moisture.

As shown in Figure 10A, D_{max} decreased with average M_f. This should be attributed to the difference in the overall contact stiffness of the laminates with different moistures. As proved in Figure 8, before impact testing the laminates had approximately the same contact stiffness. However, specimens with higher moisture content suffered from lower impact damage and hence had a less decrease in contact stiffness, which consequently resulted in the higher overall contact stiffness of conditioned laminates. Therefore, the intruding impactor was stopped faster and traveled shorter distance (smaller projectile deflection accordingly).

As shown in Figure 10B, the average peak load of the conditioned specimens increased with average moisture content. As shown in Figure 8, when a sharp drop in load occurred, the contact force no longer continued to increase. This explained why Iso 1 had relatively larger F_p than the other two specimens. Cyc 1 experienced the sharp load drop at a larger deflection, resulting in a larger

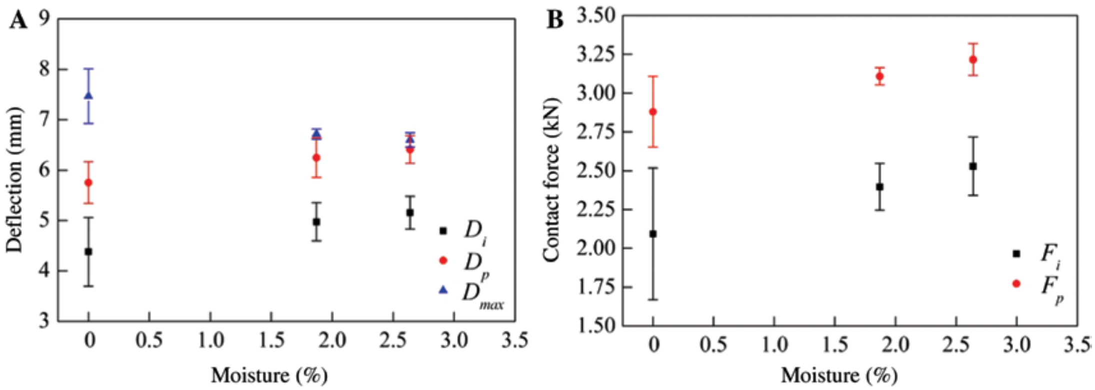

Figure 10: Relationship between average moisture content and projectile deflection, contact force of CFRP woven laminates during the impact test: (A) D_i, D_p and D_{max}; (B) F_i and F_p.

F_p than that of Ref 1. Therefore, after absorbing moisture, the sharp load drop was either prevented or postponed to larger deflections, resulting in the increasing trend of average F_p with moisture content. The average F_i also exhibited a monotonic increasing trend with moisture content. Despite some scatter in the test data, overall, the values of F_p and F_i showed a rising trend. The increase in F_i was due to the higher D_i of the conditioned CFRP laminates. Before the incipient damage point, the contact force generally increased with projectile deflection (Figure 8). Therefore, higher D_i would bring about higher F_i. The F_i values of the CFRP woven laminates tested are plotted against their respective D_i in Figure 11. The test results within the shown band prove that in general F_i is directly proportional to D_i.

As shown in Figure 12, the average elastic energy E_{el} of each group of specimens increased evidently with the average moisture content, while E_d showed an opposite trend. For specimens of the isothermal group, E_{el} increased by nearly 2 times, while E_d decreased by 27.7%. After absorbing moisture, the portion of the kinetic energy of the impactor dissipated by CFRP woven laminates through elastic deformation increased, and the rest of the impact energy which accounted for the damage induced to the laminate decreased. This is consistent with the conclusion that moisture alleviated the extent of impact damage in CFRP woven laminates. The

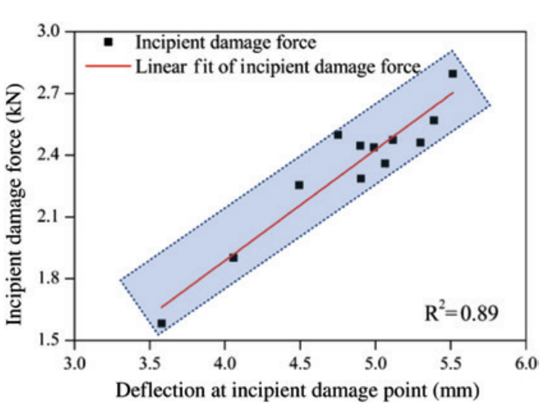

Figure 11: Relationship between F_i and D_i of CFRP woven laminates.

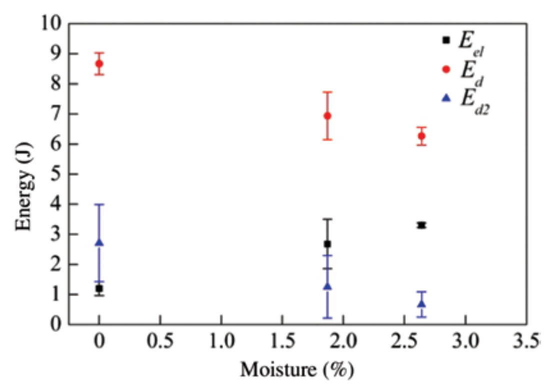

Figure 12: Relationship between average moisture content and E_{el}, E_d and E_{d2}.

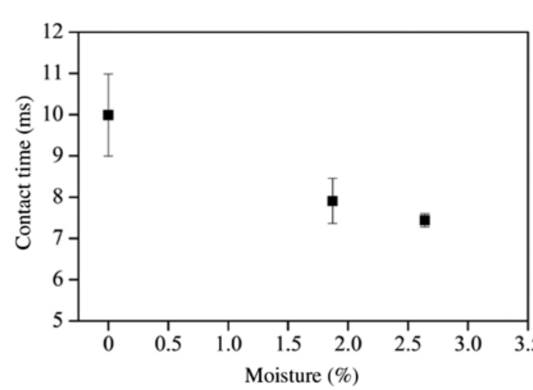

Figure 13: Relationship between average moisture content and contact time.

increase in E_{el} further supported the conclusion that the elastic response of CFRP woven laminates improved after absorbing moisture. It was also noted that E_{d2} decreased with M_f. For unconditioned laminates, after the peak load point the impactor still had certain speed which was relatively higher when compared with the case of conditioned laminates. Therefore, E_{d2} of the unconditioned group was larger than the other two groups. This also explained the fact that D_{max} of the reference group was larger of the two conditioned groups.

For the drop weight impact testing of composite materials, contact time between the impactor and the laminate is also a parameter that generally reflects the behavior of the laminate under an impact load. Figure 13 shows the variation of contact time with respect to the average moisture content of each group, which clearly shows that specimens with higher moisture content had shorter contact time. The impactor stroke the laminate with approximately the same speed (same impact energy). If the laminate had relatively higher overall stiffness (lower compliance), the speed of the impactor would be reduced to zero faster and shorter contact time would be expected. In this study, it is assumed that initially laminates of different moisture contents had approximately the same stiffness (Figure 8). However, laminates with less moisture content experienced more severe impact damage, which reduced their contact stiffness consequently. Therefore, specimens with less moisture content had longer average contact time.

Thus, the experimental results showed that the moisture absorbed by CFRP woven laminates during hygrothermal conditioning alleviated the degree of impact-induced damage. Another important finding from the data collected during the impact test was that moisture delayed the occurrence of delamination. Laminates with higher moisture contents could deform to larger projectile deflections without damage. The moisture also altered the energy dissipation mechanism of a CFRP woven laminate. The kinetic energy of the impactor consumed by elastic deformation increased with moisture content, while less impact energy was left for damage generation resulting in the alleviated damage state in the laminate. Although the fibers in the laminate carried the majority of the load, it was moisture that improved the impact resistance of the CFRP woven laminate.

4 Mechanism behind improvement

In Figure 5, the damage characteristics of the three laminates with different moisture levels are depicted. Moreover, Figure 5 also provides three degrees of impact damage of the CFRP woven laminate investigated in this study. When the laminate experienced only moderate impact damage such as that of Iso 2 (Figure 5A), the major damage modes included light delamination and moderate matrix cracking. This type of damage is schematically depicted in Figure 14B. If the impactor strikes the laminate with higher velocity, more severe impact damage is expected. More severe delamination and large-scale matrix cracking and fiber breakage will occur (Figure 5C). As the impact energy increased, catastrophic delamination and severe fiber splitting also occurred. This process is depicted in Figure 14C. The impact damage evolution process of the CFRP woven laminates shown in Figure 14 proves that the first significant damage was delamination and the catastrophic failure of the laminate usually occurred after severe delamination was initiated. For laminated structures, once large-scale delamination was initiated, the laminate lost its structural integrity and hence the mechanical properties along the through-the-thickness direction.

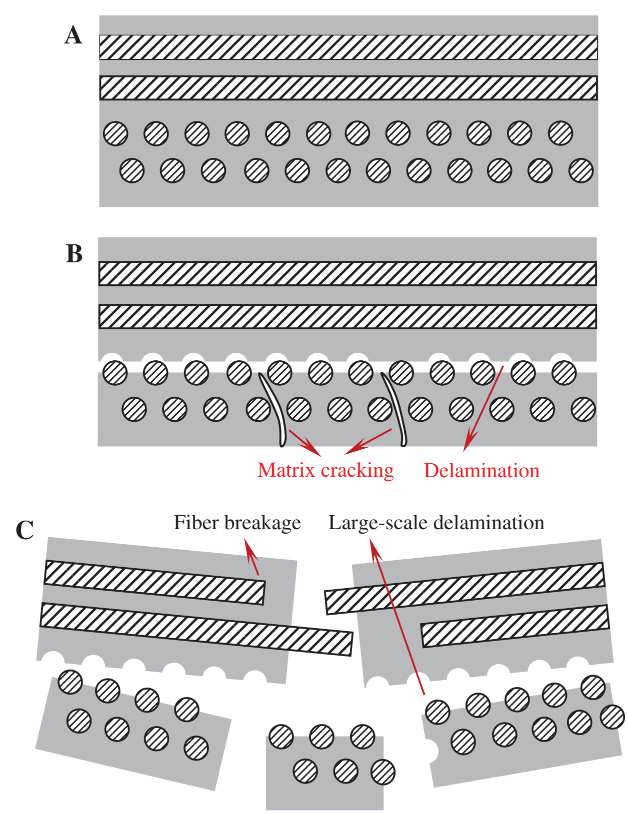

Figure 14: Schematic representation of the evolution of impact damage in a CFRP woven laminate. (A) Laminate before impact; (B) moderate impact damage consisted of delamination and matrix cracking; (C) severe impact damage with fiber breakage, splitting and large-scale delamination.

Moisture improved the elastic deformation ability of the epoxy resin within this prepreg material by weakening Van der Waals forces and by reducing the number of hydrogen bonds. The mobility of the various mers (or the chain segments) of the epoxy molecules was therefore promoted. Consequently, the ductility of the epoxy resin improved [24]. A matrix with higher ductility would benefit the laminate by effectively preventing or postponing the occurrence of interlaminar failure and matrix cracking. Therefore, after absorbing moisture the first significant failure occurred at larger projectile deflections (higher D_i). The rapid decrease in load which was attributed to severe delamination was also delayed (Figures 7 and 8). This explains the important finding that Iso 1 which had the highest moisture content did not experience such a sharp load drop while Cyc 1 experienced a sharp load drop at a larger projectile deflection compared with Ref 1. Moisture extended the elastic limit of the epoxy resin, which in turn delayed the initiation of matrix cracking and delamination in the laminate and maintained the structural integrity of CFRP woven laminates. The elastic response of the laminate was therefore improved, which explains the higher E_{el} exhibited by conditioned laminates.

5 Conclusions

The hygrothermal conditioning experiment was conducted by exposing a commercial carbon fiber/epoxy composite material to two different hygrothermal environments. The low-velocity impact test was conducted on hygrothermally conditioned CFRP woven laminates. Important findings include the following:

1. Weight-change curves of the laminates revealed that the transport of moisture in this material followed Fickian behavior. At -30°C, the absorbed moisture lost its capability of migrating out from the laminate.
2. Both cyclic hygrothermal conditioning and isothermal water immersion conditioning did not exhibit detrimental effects on the microstructure of the CFRP laminates. No cracks were found at the fiber-matrix interface and the interlaminar region. The major difference between laminates from the different groups lay in their moisture contents.
3. The moisture trapped within significantly alleviated the extent of damage to CFRP woven laminates attacked by low-velocity impact. When tested under the same impact energy level, the unconditioned laminate suffered from catastrophic delamination and severe fiber splitting, while the isothermally conditioned laminate with 2.69% of moisture experienced only minor delamination and light matrix cracking near the bottom surface.
4. For laminated structures, its resistance to low-velocity impact depends largely on its capability of resisting interlaminar failure. Once large-scale delamination was initiated, the laminate lost its structural integrity and hence the mechanical properties along the through-the-thickness direction, resulting in an instantaneous drop in contact force.
5. It was proposed that absorbed moisture promoted the mobility of the chain segment of the epoxy molecules and increased the ductility of the epoxy resin. The epoxy matrix with higher ductility benefited the laminate by effectively preventing or postponing the occurrence of delamination and matrix cracking. The elastic response of the laminate was therefore improved. The portion of the kinetic energy of the impactor dissipated by the laminate through elastic deformation was increased by nearly 2 times after absorbing 2.64% wt. of moisture. This explains the alleviated impact damage in conditioned CFRP woven laminates.

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