EFFECTS OF SALT WATER AGING ON THE POST-IMPACT BEHAVIOR OF POLYMERIC COMPOSITES

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SUMMARY: The study described in this report uses the split Hopkinson pressure bar (SHPB) apparatus to induce damage in a polymer matrix composite by low-velocity, transverse impact. The configuration used a three-point bend fixture in the SHPB for controlled loading and real-time diagnosis. The material analyzed was a glass-fiber reinforced bismaleimide matrix composite designated S2 glass/5250-4. Experiments were conducted to characterize the response of the composite by relating a range of impact energies to the post-impact tensile strength following salt-water aging. Results showed that following salt-water aging, a monotonic relation exists between the amount of impact energy absorbed by the specimens and both the post-impact tensile strength and the moisture absorbed by the specimens. In the S2 glass/5250-4 system examined, the effects of exposure to 5000 hours of salt-water following impact were minor, illustrating the insignificance of this type of environmental effect on the post-impact tensile strength.

KEYWORDS: fiber-reinforced composite laminates, time-resolved response, impact damage, salt water aging, residual strength, split Hopkinson pressure bar, damage characterization.

INTRODUCTION

Fiber-reinforced polymer matrix composites are being specified for an increasing number of marine structures. This class of material offers many advantages such as flexibility in design and high specific mechanical properties compared to standard marine materials. However, composite laminates also have inherent weaknesses, susceptibility to marine environments in the presence of impact damage being one example. Since many structures using laminated composites are likely to encounter impact by foreign objects in service, characterizing the impact response and quantifying the induced damage [1] in the presence of environmental factors such as sea water is an important issue which have attracted significant attention.

In the current investigation, a split Hopkinson pressure bar (SHPB) apparatus is used to characterize the impact response and damage of composite laminates. This technique provides direct measurement or inference of contact forces, contact-point velocities, displacement, mechanical work and energy dissipation within a fully dynamic framework. The mechanical quantities are measured in real-time with submicrosecond resolutions. Since the analysis is based on the theory of one-dimensional wave propagation associated with the elastic bars of the SHPB, no complicated data processing is necessary. The approach yields more accurate force and displacement measurements with better time resolutions than experiments using load cells or accelerometers. In addition, no assumption concerning the behavior of specimen material is needed. Therefore, this method is applicable for analyzing the complete range of impact response involving both elastic and inelastic deformations. A similar technique was used by Li and Harding [2] who obtained force and displacement histories for plates under transverse impact. In the current analysis, while the full histories of contact force and displacement are determined, the focus is on the histories of work transfers between the impactor and specimen and energy absorbed by the specimen during impact.

MATERIALS, EQUIPMENT AND EXPERIMENTAL PROCEDURES

The material system analyzed is the S2 glass/5250-4 composite. It is comprised of glass fibers embedded in a bismaleimide matrix. The material is a 16-ply laminate with a $[0/-45/90/0/90/45/0/90]_S$ quasi-isotropic layup. The S2 glass/5250-4 specimens, machined from a 60.96 cm x 91.44 cm panel, have dimensions of 152.4 mm x 19.05 mm x 3.78 mm.

The SHPB experimental system used in the current study allows multiple loading pulses to be applied to specimens without full intervening unloading, offering an excellent opportunity for analyzing repeated interactions between the impactor and specimen. Coupled with an improved data analysis technique which allows unambiguous determination of the full time histories of contact force, specimen deflection and work transfer over extended periods, this configuration enables damage and damage progression to be characterized through successive loading pulses. Rather than tracking individual damage mechanisms such as matrix cracking, fiber breakage, matrix-fiber debonding and delamination, the total energy dissipated is taken as a macroscopic measure of cumulative damage in the specimen. This treatment is similar to the approaches of Mast et al. [3] and Delfosse et al. [4]. The dissipated energy and the time-resolved mechanical diagnostics allow the full damage process in the laminates to be quantified during impact.

A three-point-bend loading configuration is used, enabling the specimen to be sandwiched between the cylindrical indentor and the die of the loading fixture. This fixture allows controlled loading and facilitates the development of localized damage in the specimen. In the experiments reported, the application of localized damage and the analysis of post-impact strength are the principal concern. Consequently, the particular configuration induces significant transverse shear as well as bending in the specimen. The loading fixture is placed between the input and output bars of a SHPB apparatus. A detailed schematic of the SHPB system, along with the three-point-bend loading apparatus and specimen configuration, is shown in Fig. 1.

The bars of the SHPB are made of C-350 maraging steel, and impact loading is applied through a compressive stress pulse generated when the striker bar impacts the input bar. This stress pulse has a duration of approximately 350 μs and a range of amplitude determined by the impact velocity of the striker bar. In the experiments reported here, the impact velocity ranged from 3.1 to 10.3 ms^{-1}, resulting in impact energy levels between 2.3 and 25.7 J/mm. The loading fixture is

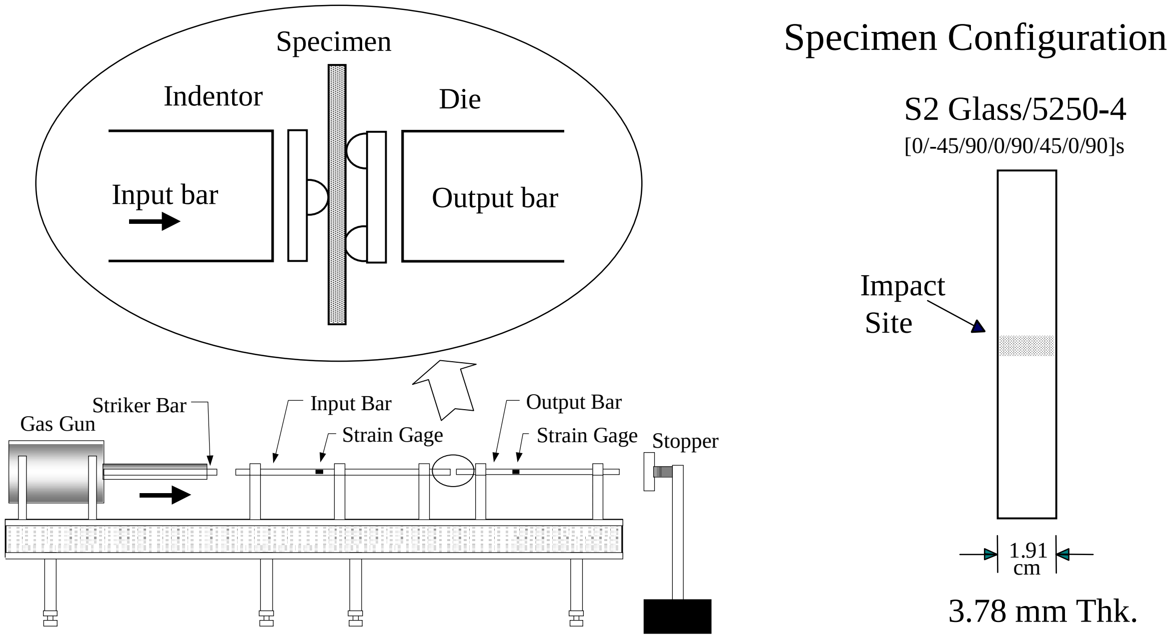

Fig. 1: A schematic illustration of the impact experiment and specimen on a split Hopkinson pressure bar apparatus

made of high strength tool steels and remains essentially rigid throughout the experiments. Since the transient time for stress wave reverberations in the indentor and the die is less than a microsecond and attention is focused on impact response over 350 μs, the contact forces on both sides of the specimen are essentially equal to the forces at the input bar/indentor and die/output bar interfaces, respectively. These contact forces and the velocities at both sides of the specimen can be inferred from the profiles of stress waves traveling in the input and output bars. Strain histories as shown in Fig. 2, measured at one location on the input bar and one location on the output bar at a sampling rate of 10^6 points per second, allow the tractions and displacements at the bar/specimen interfaces to be determined via the one-dimensional stress wave propagation theory [5]. Strain profiles were used in the analysis of the mechanical responses of the specimens.

In order to characterize the effects of impact-induced damage and salt-water aging on the post-impact properties of the S2 glass/5250-4 composite, impacted specimens were first subjected to salt-water aging and then to quasi-static, uniaxial tension. The salt-water aging was accomplished by immersing the impacted specimens for 5000 hours in a synthetic seawater consisting of Coralife® scientific grade marine salt dissolved in distilled water. A tensile test was chosen to avoid difficulties associated with premature buckling of the transversely impacted specimens under compressive loading. Tests were load-controlled and were conducted at a loading rate of approximately 150 N per second, corresponding to an average strain rate of approximately 33.4 m/m per second in accordance with ASTM-D3039. All tests were performed in laboratory air on a 100 kN servo-hydraulic test frame equipped with a digital controller and data acquisition capabilities. Hydraulic grips incorporating flat-faced wedges with a non-aggressive surface finish were used to allow for firm gripping of the composite without grip-induced failures. Uniaxial strain was measured on the surface of the specimen near the impact damage area using clip-on extensometers with a 25 mm gage section.

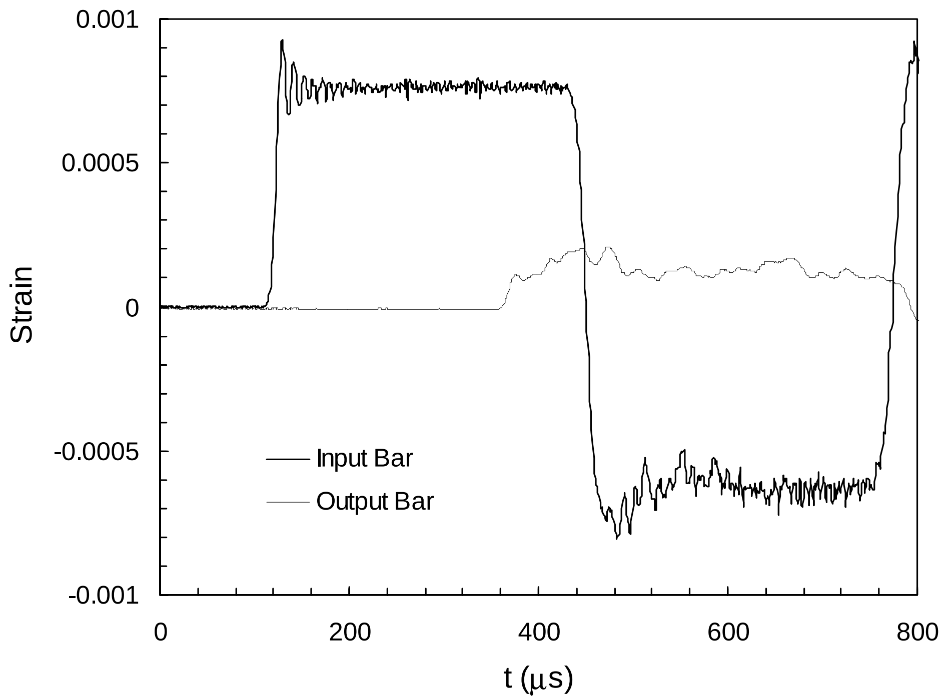

Fig. 2: Sample strain histories measured from the input and output bars (for E_{impact} = 14.0 J/mm)

ANALYSIS OF IMPACT RESPONSE

Analysis of the impact response focuses on the characterization of energy absorption by the composite laminate subjected to transverse impact. The unrecoverable part of the energy absorption is used as an indicator of the level of damage and later correlated with the post-impact strength and moisture absorption during salt-water aging. A brief summary of the relevant analysis procedure is presented in this section. Detailed analysis techniques involved may be found in [6, 7].

The longitudinal wave motion in a slender cylindrical bar can be described by the one-dimensional wave equation [8]. The general solution to this equation consists of two functions representing the waves traveling in the opposite directions of the bar. Consider a generic bar and assume strain functions ε_1 and ε_2 represent the two longitudinal waves traveling in the +x and –x directions, respectively. The longitudinal strain at any point, x, and at any time, t, may then be expressed as

$$\varepsilon(x,t) = \varepsilon_1(t - \frac{x}{c}) + \varepsilon_2(t + \frac{x}{c}), \tag{1}$$

where $c = (E/\rho)^{1/2}$ is the longitudinal wave speed of the bar, E is the Young's modulus, and ρ is the mass density of the bar material. The longitudinal stress in the bar is

$$\sigma(x,t) = E\varepsilon(x,t) = E\left[\varepsilon_1(t - \frac{x}{c}) + \varepsilon_2(t + \frac{x}{c})\right]. \tag{2}$$

The particle velocity can also be expressed in terms of ε_1 and ε_2, as

$$v(x,t) = c\left[-\varepsilon_1(t-\frac{x}{c}) + \varepsilon_2(t+\frac{x}{c})\right]. \quad (3)$$

Clearly, the conditions in the bar are uniquely determined if the functions ε_1 and ε_2 are known. Therefore, the objective of experimental measurements is to determine these two functions. The determination uses the strain histories at fixed locations on the bar. In order to characterize the material response over multiple loading pulses, it is necessary to determine these functions over an extended period of time. Park and Zhou [6] developed an analysis technique which allows these functions to be determined from the measured strain profile at one location and the traction-free condition at one end of the bar.

Other mechanical quantities now can be determined from the strain and velocity. For example, the work transfer from the input bar to the specimen is

$$W_{in}(t) = -AE\int_0^t \varepsilon_{in}(L,\tau)\mathrm{v}_{in}(L,\tau)d\tau\,, \quad (4)$$

and the mechanical work done by the specimen to the output bar is

$$W_{out}(t) = AE\int_0^t \varepsilon_{out}(0,\tau)\mathrm{v}_{out}(0,\tau)d\tau\,, \quad (5)$$

where $\varepsilon_{in}(L,\tau)$, $\varepsilon_{out}(0,\tau)$, $\mathrm{v}_{in}(L,\tau)$ and $\mathrm{v}_{out}(0,\tau)$ denote the strains and particle velocities at respective bar/specimen interfaces, and A and L are the cross sectional area and length of the pressure bar, respectively. The energy absorbed by the specimen is

$$E_{\mathrm{abs}}\,(t) = W_{in}\,(t) - W_{out}\,(t). \quad (6)$$

Finally, the total amount of energy available at the beginning of loading is the kinetic energy of the striker bar E_{impact} which is equal to $0.5\rho AL_0\mathrm{v}_0^{\,2}$, where L_0 and v_0 are the length and impact velocity of the striker. This energy is completely transferred into the input bar and may be calculated through

$$E_{impact} = \int_{t_a}^{t_a+\Delta t} AEc\varepsilon_A^2(t)dt\,, \quad (7)$$

where t_a is the time of arrival of the wave front at the strain gage location, $\Delta t=2L_0/c$ is the duration of the initial rectangular waveform, and $\varepsilon_A(t)$ is the measured strain history in the input bar at a. Here, use has been made of the fact that the kinetic and strain energies carried by the initial pulse in the input bar are equal to each other.

RESULTS AND DISCUSSION

Energy Absorption Characteristics

The histories of input and output mechanical work (W_{in} and W_{out}) are calculated from Eqn 4 and 5, respectively. The difference is the energy absorbed by the specimen. This energy consists of an elastic part and an unrecoverable inelastic part. The inelastic part is expended on inducing damage in the form of matrix cracking, fiber breakage, fiber/matrix debonding or delamination. The energy absorbed by the three-point bend loading fixture is very small and negligible. The energy absorption curves for S2 glass/5250-4 at four different impact velocities is shown in Fig.

3. Because of the possible need to compare the energy absorbed by specimens with different thicknesses, energy per unit thickness is used. The fluctuations in the profiles represent the storage and release of strain energy during the experiments as a result of multiple specimen/bar interactions. At low velocities, a significant portion of the input energy is stored during loading and released during unloading. The balance is permanently dissipated through damage. As impact velocity increases, the majority of the input energy is dissipated through damage and only a small fraction is stored and released as strain energy. Also, at high velocities the energy dissipation gradually accumulates over the impact cycles, suggesting that damage in the specimen accumulates over the successive load pulses.

Fig. 4 compares the impact and dissipated energies as functions of impact velocity for S2 glass/5250-4. The impact energy is the kinetic energy carried by the striker bar at the moment it comes into contact with the input bar. The dissipated energy does not seem to increase proportionally with the impact energy. It is expected that there is a level of impact velocity beyond which the dissipated energy will saturate. Such a level has not been reached in the experiments conducted. Czarnecki [9] reported that the size of the delamination area in graphite/epoxy laminates under transverse impact increases with impact velocity up to the point of penetration beyond which it remains essentially constant.

Post-impact Behavior

The stress-strain curves for specimens subjected to three levels of impact followed by 5000 hours of exposure to salt-water are shown in Figs. 5(a)-(c). Clearly with or without impact damage,

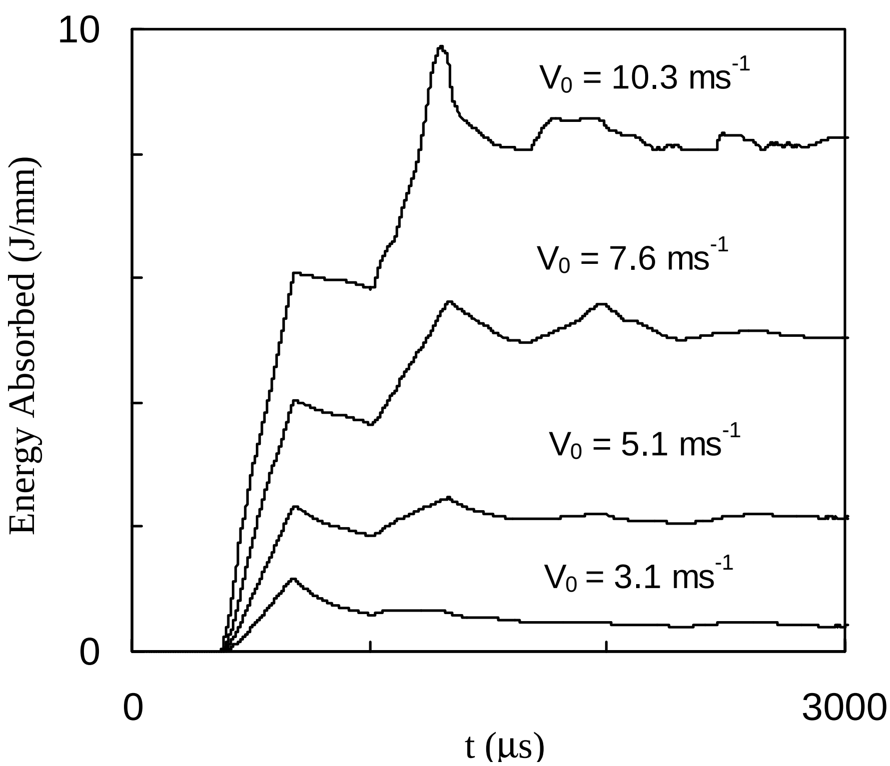

Fig. 3: Histories of energy absorption per unit thickness for the S2 glass/5250-4 composite

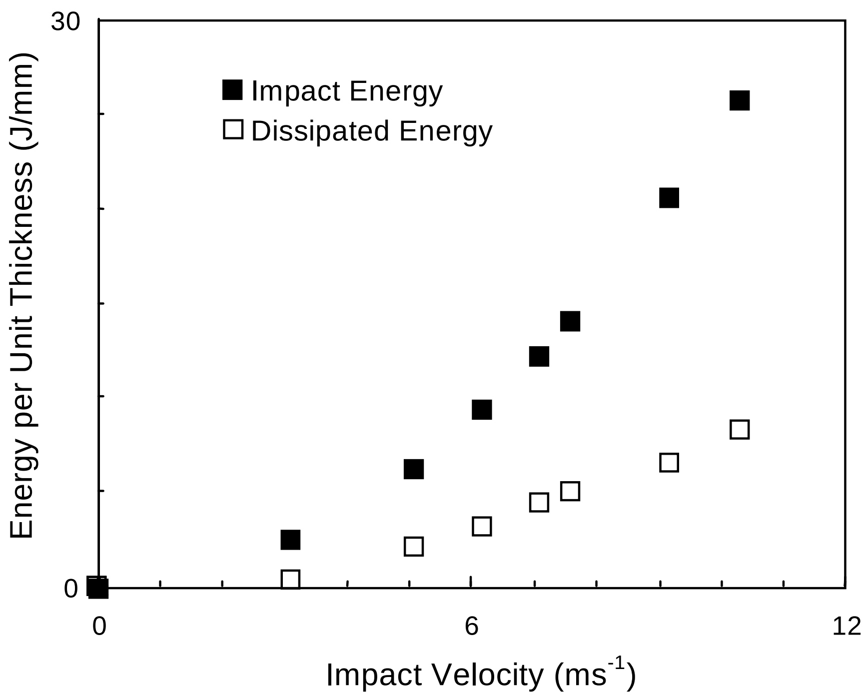

Fig. 4: Impact and dissipated energies per unit thickness at different impact velocities

aging in salt water decreases both the strength and stiffness of the composite. However, there is no corresponding evidence of a higher rate of reduction in stiffness with increasing impact level due to salt-water aging, suggesting a minor effect of this environmental exposure in the presence of impact-induced damage. The strain reported in this study was measured within, or in close proximity to, the impact damage zone of each specimen. Hence, the stress-strain curves in Figs. 5(a)-(c) represent the uniaxial, quasi-static behavior of the damaged portion of the specimens rather than that of the average behavior of the whole specimens.

To correlate impact-induced damage followed by 5000 hours of exposure to salt-water with post-impact strength, the tensile strength of impacted specimens with and without post-impact aging is plotted as a function of the impact energy in Fig. 6. Both the unaged as well as the salt-water aged strength of the S2 glass/5250-4 composite decreases linearly with impact energy at low impact levels but tends to level off at high impact levels. There was virtually no change in the post-impact strength due to 5000 hours of exposure to the salt-water environment at low impact levels, however a slight (less than 10%) loss in post-impact strength was observed at higher impact levels.

Moisture Absorption Characteristics

The moisture absorbed by the specimens during post-impact salt-water aging was measured by a digital balance and plotted as a function of the impact energy in Fig. 7. Although it is observed that a moderate amount (approximately 3 grams per 10 J/mm of impact energy) of moisture is absorbed by the impacted specimens immersed in salt-water, the post-impact tensile strength does not seem to decrease at the same rate. From the materials tested here, a clear relationship between the moisture absorbed and the post-impact strength does not exist.

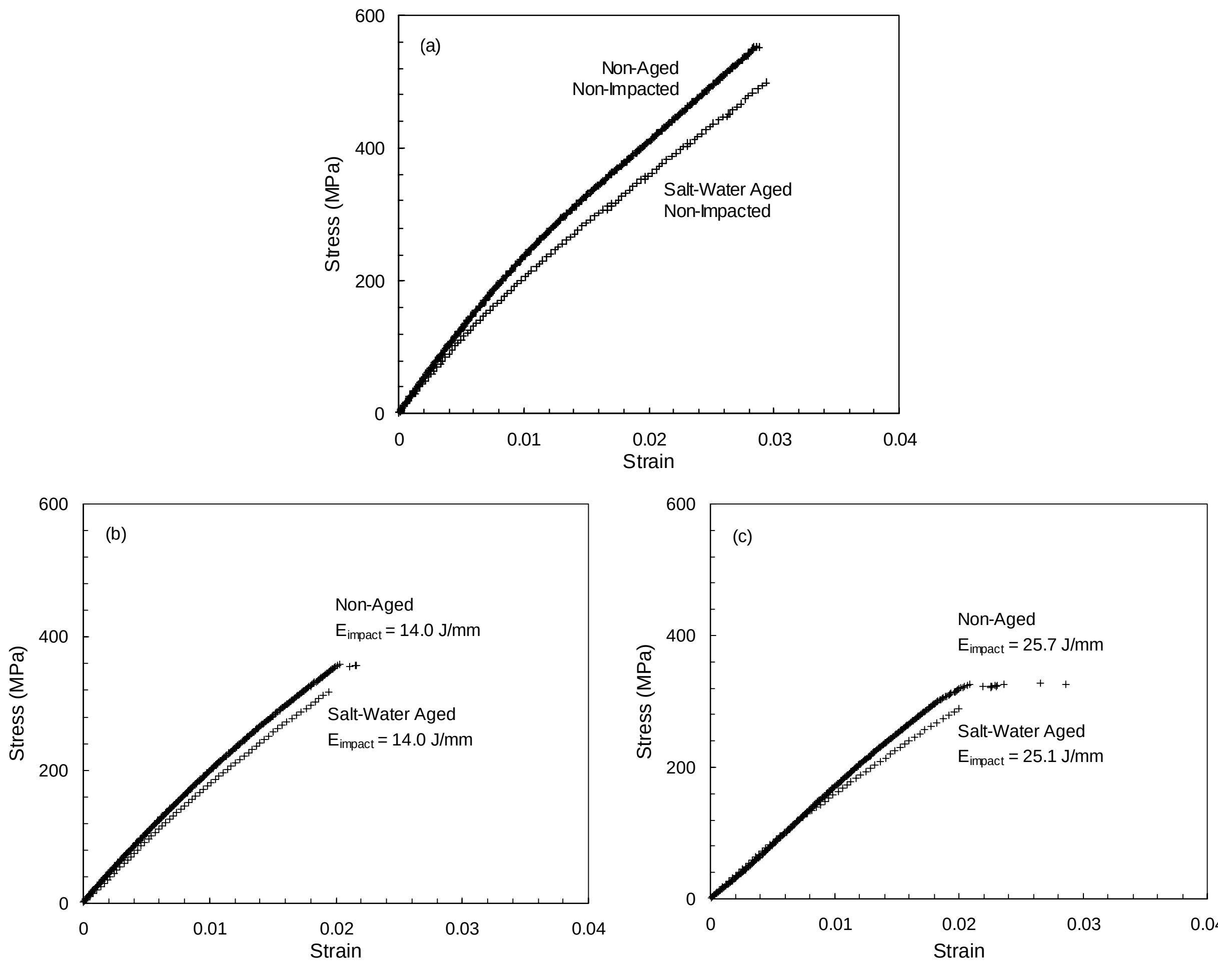

Fig. 5: Post-impact, tensile stress-strain behavior of S2 glass/5250-4 with and without 5000 hours of salt water aging after impact; (a) non-impacted specimen, (b) moderately impacted specimen, (c) severely impacted specimen

CONCLUSIONS

The impact response and damage of the S2 glass/5250-4 polymer-matrix composite is studied. The focus is on the time-resolved impact response and the residual strength following 5000 hours of exposure to salt-water. The analyses concern low-velocity, transverse impact with multiple interactions. A split Hopkinson pressure bar apparatus was used for controlled loading and real time measurement of mechanical quantities involved in the impact analysis. Quasi-static, uniaxial tension tests are used to determine the post-impact strength following the salt-water aging.

There was virtually no change in the post-impact strength due to 5000 hours of exposure to the salt-water environment at low impact levels, however a slight (less than 10%) loss in post-impact strength was observed at higher impact levels. Although a moderate amount of moisture was absorbed by the specimens immersed in salt-water, the post-impact tensile strength did not seem to decrease significantly. From the salt-water aged, post-impact test results of the S2 glass/5250-4 composite laminate, moisture absorption properties alone did not provide a clear correlation between the rate of salt-water absorbed and the reduction in residual strength.

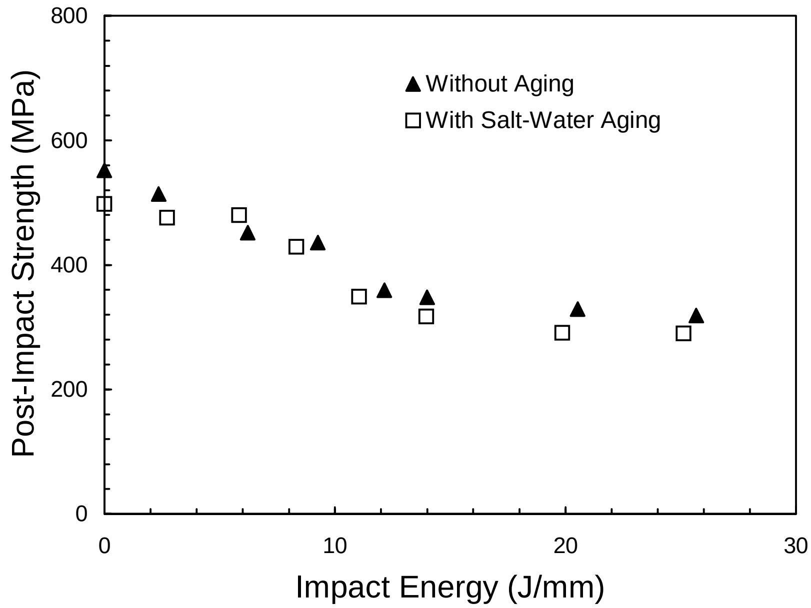

Fig. 6: Post-impact tensile strength of S2-glass/5250-4 with and without salt water aging as a function of impact energy

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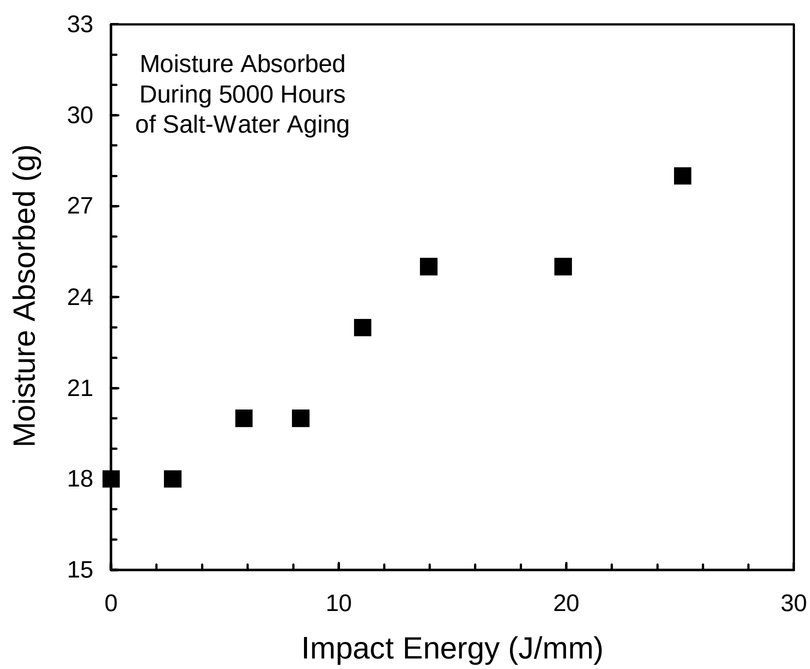

Fig. 7: Moisture absorbed by S2-glass/5250-4 specimens following 5000 hours of salt water aging as a function of impact energy

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