Dynamic Properties for Laminate Composites in the Marine Environment

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Abstract. Dynamic properties of high strain rate and absorbing energy for laminate composites in the marine environment were studied in this paper. The high strain rate dynamic compressive tests were carried out on Split Hopkinson Pressure Bar (SHPB) experimental facility at strain rate 1800/s, 1530/s, 1230/s and 950/s. The front surface failure modes were analyzed by optical micrographs. A fractured fibres mode was discussed in high rate compression. The stress-strain rate curves showed that, the specimen dynamic properties were better for the samples immersed in marine environment for 12 days. The energy absorption properties were test by ballistic trajectory experiment. Experimental results and penetration faces showed that, the ballistic trajectory properties with 60 days of hygrothermal environment was better.

1. Introduction
Laminate composite has excellent impact resistance, low density and stable chemical performance, and is one of the ideal materials for ship protection structures. Under the marine environment, the protective laminate composite may be affected by environmental loads such as water, temperature and salt, resulting in the degradation of its performance. Therefore, it is of certain significance to study the effects of marine environment on the mechanical properties of the ultra high molecular weight polyethylene (UHMWPE) composites. The high-speed impact behavior of composites is influenced by the dynamic compressive properties of the material[1-2]. Extensive research has been conducted on the quasi-static and dynamic compressive behavior of composites and the split Hopkinson pressure bar (SHPB) was usually used to study the dynamic properties[3-7]. Song Bo[8] investigated the compressive behavior of the S-2 glass/SC15 composite. The peak stress along the through-thickness direction was found to be much higher than those along the in-plane direction. Khubab Shaker[9] investigated the high strain rate compressive properties of Dyneema H62, Dyneema H5T and UHMWPE/aramid hybrid composite and peak stress was found to increase with higher strain rate. The goal of this paper is to investigate the effects of marine environment on the dynamic compressive properties of laminate composites.

2. Experimental work

2.1. SHPB experiment
Dynamic properties were test for the UHMWPE laminate composite in out-of-plane direction. The high strain rate dynamic compressive tests were carried out on a split Hopkinson pressure bar (SHPB) experimental facility. Schematic of the SHPB equipment is shown in Figure 1.
The material of the SHPB facility bars are 60Si2Mn and had density of 7850 kg/m$^3$, elastic modulus of 206GPa. The 20 mm-diameter striking, incident and transmission bar had lengths of 300, 2000 and 1500mm, respectively. Bar wave velocity $c = \sqrt{\frac{E}{\rho}} = 5123$ m/s was verified by standardized experiments. Strain gauges, with sensitivity of 2.13 were attached to the incident and transmission bar. Distances of the strain gauges to the specimen/bar contact surfaces were approximately 1000 and 745 mm for gauges on the incident bar and transmission bar, respectively. The strain signals were measured using a DH5960 dynamic strain tester (sampling rate 20MHz) by half bridge connection to the strain gauges. During the test, the speed of the bullet was controlled by adjusting the driving pressure in the range of 0.2 - 0.45MPa. Annealed copper disks with thickness of 1mm and diameters ranging from 8 – 14mm were used to smooth and control the incident pulse. Molybdenum disulfide was used at the specimen/bar contact surface to reduce the friction. At least three replicates were conducted by SHPB for each driving pressure.

The SHPB experiment is based on the no-dispersion one-dimensional stress wave theory and dynamic stress equilibrium assumption in the specimen. A parameter $R$ was considered to evaluate the stress equilibrium.

$$ R(t) = \frac{\Delta \sigma(t)}{\sigma_{eq}(t)} = 2 \left[ \frac{F_1 - F_2}{F_1 + F_2} \right] $$

(1)

where, $F_1$, $F_2$ represent the specimen axial force history in the incident bar/specimen end and transmission bar/specimen end, respectively, and can be calculate according to Eq.(2)

$$ F_1 = A E (\epsilon_i + \epsilon_r) $$

$$ F_2 = A E \epsilon_r $$

(2)

Where, $A$ represent the equilibrium parameter; $E$ represent the modulus of elasticity; $\epsilon_i$, $\epsilon_r$ represent the strain.

Figure 2 shows a typical pulse received from the incident bar and transmission bar and the equilibrium parameter calculated according to Eq.(2), indicating that the specimen was in dynamic stress equilibrium from 5-130s. Thus, the strain rate, engineering strain and engineering stress of the specimen can be calculated according to Eq.(3)

$$ \dot{\epsilon}(t) = \frac{2c_0}{L} \epsilon_r(t) $$

$$ \epsilon(t) = \frac{2c_0}{L} \int \epsilon_r(t) d\tau $$

$$ \sigma(t) = \frac{S_B E}{S_e} \epsilon_r(t) $$

(3)

where, $c_0$ is the longitudinal wave velocity in the bar, $S_B$, $E$ are the cross sectional area and elastic modulus of the bar, $L$ and $S_e$ are the length and cross sectional area of the specimen.
2.2. Ballistic trajectory experiment

The ballistic trajectory experiment of UHMWPE composite was done on dry samples and samples subjected to hygrothermal aging for 30 and 60 days. The bullets were eradiated by ballistic trajectory gun with 14.5mm caliber, which was drive by powder. A laser equipment was used to measure the velocity of bullets in front and behind of the drone. The material of bullets was 45# steel with quenching, which was enwrapped by aluminum with 13.5g fragment simulated projectiles. The size of composite target shell was 300×300×10mm, which were fixed on shelves. The properties of resist bullets of composite were described by Eq.:

\[ E = \frac{1}{2} m (v_f^2 - v_i^2) / \rho \]  

Where \( m \) was the mass of bullets, \( v_i \) and \( v_f \) were the initial and final velocity, \( \rho \) was the plane density.

3. Results and discussions

3.1. SHPB properties

High strain rate compression tests were conducted on the virgin dry samples, 12days and 24 days hygrothermal exposed samples, respectively. Stress-strain curves of the 12 days hygrothermal treated samples at strain rate 950/s, 1230/s, 1530/s and 1800/s are shown in Figure 3. The stress increases with strain until reaching the maximum stress and strain softening occurs at large strain. Stress plateau was found around the maximum stress for the 1530/s and 1800/s curves. The strain softening and stress plateau may indicate the compression-induced damage such as matrix cracking and delamination[8]. For dynamic compression of UHMWPE composite, the high speed striking induced damages and the inner defects cannot be extended immediately, resulting in the lager loading capacity and striking energy absorption capacity. Thus, maximum stress increases with higher strain rate.

The failure modes of UHMWPE composite under high strain rate compression were quite different from the static compression failure modes. Figure 3 shows the failure patterns for the 12 and 24 days hygrothermal treated specimens at different strain rate. Damage appears on the specimen surface near the incident bar and we reference it as “front surface”.

![Figure 2](image)

**Figure 2.** (a) A typical pulse received from the incident bar and transmission bar (b) Force equilibrium parameter in the specimen

![Figure 3](image)

**Figure 3.** Stress-strain curves of the 12 days hygrothermal treated specimens
For the 12 days treated specimens, (1) fibres were knocked off on the front surface at 1230/s, as shown in Figure 4(a); (2) several layers delaminated and the outer region of the delaminated layers warped outwards the surface at strain rate 1530/s, as shown in Figure 4(b); (3) the periphery delaminated fibres were carbonized at strain rate 1800/s as shown in Figure 4(c). There were no obvious differences in failure modes for the 12 and 24 days treated specimens at strain rate 1800/s, as shown in Figure 4(c) and (d).

Figure 4. Optical micrographs of 12 days wet specimens at strain rate (a) 1230/s (b) 1530/s (c) 1800/s and the 24 days wet specimens at strain rate 1800/s(d)

During the high strain rate compression, a small amount of fractured fibres were ejected out from the front delaminated plies, as shown in Figure 5. High strain rate compression is a transient process during which a large amount of energy is transferred to the specimen, resulting in a temperature rise in the specimens. The outer delaminated fibres will be fractured and carbonized at higher strain rate, resulting in different damage patterns comparing with the quasi-static specimens.

Figure 5. The high speed images of specimens at strain rate 1530/s

The compressive stress-strain curves of both dry and wet specimens at dynamic strain rate around 1500/s and 1800/s are shown in Figure 6. Hygrothermal treatment improves the maximum stress (wet 12 days) and then decreases the maximum stress (wet 24 days) while the corresponding strain of the maximum stress were decreased firstly and then increased. The strain softening effects was degraded firstly and then upgraded as well.

Figure 6. (a) Stress-strain curves at strain rate 1500/s (b) Stress-strain curves at strain rate 1800/s

Figure 7 shows the maximum stress-strain rate curves of both the dry and wet specimens. Twelve days hygrothermal treatment increased the maximum stress and the improvement was declined in 24 days treatment especially at high strain rate above 1500/s. The fit curves of the maximum stress as a function of strain rate are as follows:
Matrix plays an important role in the out-of-plane compression and plasticization of the matrix improves the dynamic compressive properties while fibre/matrix interface degradation and voids expansion degrades the compressive properties. For the 12 days hygrothermal treated specimens, the effects of plasticization dominate the compressive properties and thus improve the maximum stresses. However, under the treatment of moisture and long-term high temperature, the degradation of fibre/matrix interface and expansion of the inner voids dominates the dynamic compressive properties for 24 days treated specimens. The dynamic compressive properties thus degraded while still stronger than the virgin dry specimens.

![Figure 7](image_url) Effects of hygrothermal treatment on the maximum stress of out-of-plane compression

3.2. Ballistic trajectory properties

The results of ballistic trajectory experiment were showed by table 1, which were dry and hygrothermal aging in 30 days and 60 days. The results show that average of absorbing energy were 186.3, 109.5 and 182.7 J=m²/kg. The uptrend of absorbing energy is initially increasing and then decreasing, and the dates of hygrothermal aging in 60 days were close to the dry composite.

| Status           | Designation | Thickness (mm) | Area density (kg/m²) | Mass of bullet (g) | Initial velocity (m/s) | Residual velocity (m/s) | E (J/m²/kg) |
|------------------|-------------|----------------|----------------------|--------------------|------------------------|-------------------------|-------------|
| Dry              | O-1         | 10.0           | 10.2                 | 13.4               | 546.1                  | No Perforation           | > 195.9     |
|                  | O-2         | 10.1           | 10.3                 | 13.4               | 554.0                  | 188.3                   | 176.6       |
|                  | HT30-1      | 10.0           | 9.8                  | 13.5               | 487.9                  | 288.0                   | 107.1       |
|                  | HT30-2      | 10.2           | 9.8                  | 13.5               | 503.6                  | 310.6                   | 108.7       |
|                  | HT30-3      | 10.1           | 9.8                  | 13.4               | 409.6                  | 60.7                    | 112.6       |
|                  | HT60-1      | 10.1           | 9.8                  | 13.4               | 497.2                  | No Perforation           | > 169.6     |
|                  | HT60-2      | 10.0           | 9.8                  | 13.4               | 512.1                  | No Perforation           | > 179.9     |
|                  | HT60-3      | 10.0           | 9.8                  | 13.4               | 616.2                  | 300.4                   | 198.6       |

The process of bullet ballistic trajectory include steps of compress upsetting, cut compress, and drawing distortion. Front faces and back faces of the HT30-2 and HT60-2 composite plates after penetration show in Figure 8. The Initial velocity of the two case were close, which front face of the composite were cut compress destroyed. The ballistic trajectory properties was depressed in 30 days of hygrothermal environment, which fiber was destroyed after margin drawing distortion. The ballistic trajectory properties with 60 days of hygrothermal environment was better, which can not penetrate by bullets.
4. Conclusions
The conclusion can be summarized as follows, which may be useful for engineering application.

(1) The Laminate UHMWPE composites have a relatively large strain rate sensitivity in the out-of-plane direction under dynamic compression. The peak dynamic compressive stress of the original dry samples increases by nearly 2 times as strain rates increasing from 950/s to 1800/s. Hygrothermal treatment has no effects on the elastic modules for dynamic compression.

(2) The ballistic trajectory properties was decreased in 30 days, and increased in 60 days, which is closed to the dry composite.

5. References
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