BALLISTIC IMPACT OF THERMOPLASTIC COMPOSITES REINFORCED WITH CARBON FIBERS

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1 Introduction
Fiber reinforced thermoplastic composites (FRTP), which consist of fiber reinforcements and thermoplastic matrices have some advantages over the conventional fiber reinforced thermosetting-plastic composites (FRSP). FRTP’s are expected to be of high-impact resistance due to the high toughness and high failure strain of the thermoplastic matrices [1], [2]. And also, since the thermoplastics soften by reheating, the impact-induced damage of FRTP can easily be retrofitted and recycled, which may lead to the environment-friendly composites. Therefore, lightweight and high impact resistant FRTP have increasingly attracted significant attention to automotive applications, where weight-saving and recyclability are required. In future applications of FRTP to automotive structural parts, the better understanding of dynamic/impact response is important for the structural design in relation to the crashworthiness of cars and the FOD problems. The purpose of this work is to experimentally and numerically study the dynamic response of carbon fabric and carbon short fiber reinforced polycarbonate composites. In particular, the ballistic impact response and properties are focused here, because they have thus far been poorly understood. In addition, the effect of carbon fibers on the ballistic performance of CFRTP with such ductile matrix as PC is also investigated.

2 Materials and Test system
2.1 Materials Preparation
Two kinds of CFRTP are selected for the present study. One is reinforced with continuous carbon fibers (fabrics), and the other with discontinuous carbon fibers (short fibers: content 20%). The matrix of both composites is polycarbonate (PC), which is lightweight transparent polymer. The mechanical behavior of PC is ductile and has superior impact and perforation resistance compared with other polymers. The continuous and discontinuous CFRTP’s are fabricated by hot press molding and by pultrusion molding, respectively. Monolithic PC specimens are also used for comparisons. The materials tested here are listed in Table 1.

2.2 Specimen Geometry
Continuous CFRTP specimen is a square plate of 90mm × 90mm with 0.8mm thickness, and discontinuous CFRTP a rectangular plate of 90mm × 75mm with 2.0mm thickness. The geometries of monolithic PC specimens are the same as those of the corresponding CFRTP specimens as shown in Table 1.

2.3 Test Procedure
Fig.1 shows the ballistic impact test system, which is developed incorporating high speed camera units with a gas gun type impact testing machine. The impact testing machine is capable of firing a steel ball projectile of 5mm in diameter and

Table 1 Materials and specimen geometries

<table>
<thead>
<tr>
<th>No</th>
<th>Material</th>
<th>General Specification</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Continuous</td>
<td>4-ply, Hot pressed with PC powder</td>
<td>90x90x0.8(t)</td>
</tr>
<tr>
<td>2</td>
<td>Discontinuous</td>
<td>Short Carbon Fiber reinforced PC (Vf:20%)</td>
<td>90x75x2.0(t)</td>
</tr>
<tr>
<td>3</td>
<td>PC_A</td>
<td>Pultrusion grade Polycarbonate</td>
<td>90x90x0.8(t)</td>
</tr>
<tr>
<td>4</td>
<td>PC_B</td>
<td>High flow grade Polycarbonate</td>
<td>90x90x1.0(t)</td>
</tr>
<tr>
<td>5</td>
<td>PC_C</td>
<td>High flow grade Polycarbonate</td>
<td>90x75x2.0(t)</td>
</tr>
</tbody>
</table>
0.51g by weight at a maximum velocity of 330 m/s by releasing high-pressurized nitrogen gas in a chamber. A specimen is mounted in a clamping rig with a circular window and struck normally to its surface by a steel ball projectile. The velocity of the projectile just before impinging on the specimen (impact velocity) is detected using two spatially separated laser-gate systems, and it is determined from the elapsed time of the projectile traveling between two specified points at a distance of 300 mm. The velocity of the projectile just after completely perforating (residual velocity) is also measured by the residual velocity detector Model XCORTECH X3200. The detected velocity of a projectile ranges from 10 m/s to 400 m/s.

The high speed camera units consists of camera unit VW-600M, flash lamp VW-L1, and controller VW-9000, which is developed by KEYENCE Co. Ltd.

The projectile’s motion and dynamic response of the specimen during testing are simultaneously visualized through the high speed camera, which are displayed on the monitor and stored in the controller for data analysis.

3 Finite Element Analysis

A computer simulation of ballistic impact response of discontinuous CFRTP and PC specimens was done using a finite element analysis. Three dimensional isotropic square target plate of these specimens were modeled using Abaqus/CAE & analyzed using Abaqus/Explicit package. Geometrical non-linearity is taken into account, and the maximum stress theory was used as a failure criterion, i.e., if we put

\[ I_F = \max \left( \frac{\sigma_{11}}{X}, \frac{\sigma_{22}}{Y}, \frac{\sigma_{12}}{S} \right) \]

, then failure occurs when \( I_F \geq 1 \). Here, \( \sigma_{ij} \)'s are stress components and \( X, Y, S \) are the corresponding strengths.

In the analysis, the target plate is modeled using shell elements and the projectile is assumed to be a rigid body. Predefined velocity fields were created to assign specific initial velocity (impact velocity) to the projectile. Fig. 2 shows the boundary condition of the target plate and central target location to define impact zone.

4 Semi-empirical analysis

The schema of the perforation process is illustrated in Fig.3, in which \( V_i \) and \( V_R \) are impact and residual velocities.
Ballistic Impact of ThermoPlastic Composites Reinforced with Carbon Fibers

Velocities of the projectile, \( v_R \) an average velocity of the scattering plate-fragments, \( M \) mass of the projectile, and \( m \) total mass of the fragments removed from the plate due to the perforation. In our previous paper [3-5], the semi-empirical expressions for ballistic limit velocity \( V_b \) and \( V_R \) are proposed using the balance of energy as follows:

\[
V_b = \sqrt{2E_p / M} \quad (1)
\]

\[
V_R = \alpha \sqrt{V_i^2 - V_b^2} \quad (2)
\]
in which, the mass coefficient \( \alpha \) is given by

\[
\alpha = \left( \frac{M}{M + m} \right)^{1/2} \quad (3)
\]

Perforation energy \( E_p \) and energy absorption ratio \( E_{ab} \) also characterize the ballistic impact properties of the plate, which are defined by

\[
E_p = E_i - E_R - E_{fs} \quad (4)
\]

\[
E_{ab} = \frac{E_p}{E_i} \times 100(\%) \quad (5)
\]

where,

\[
E_i = \frac{1}{2} MV_i^2, \quad E_R = \frac{1}{2} MV_R^2, \quad E_{fs} = \frac{1}{2} mV_{fs}^2 \quad (6)
\]

Once experimental data of some pairs of \( V_i \) and \( V_R \) together with \( \alpha \) are obtained from a series of impact tests, the perforation energy \( E_p \)'s are evaluated from Eq.(4). Then by substituting the average value of perforation energy \( E_p \) into Eq.(1), the ballistic limit velocity \( V_b \) is calculated, from which the residual velocity \( V_R \) is predicted as a function of impact velocity \( V_i \).

5 Results and Discussions

5.1 High Speed Photographs of Impact Response

Fig.4 shows high-speed photographs of ballistic perforation process, i.e., impact response of continuous CFRTP, which are taken for three different impact velocities with an inter-frame time of 20 \( \mu \)s. Small pieces of fragments are observed to scatter behind the steel ball projectile for the impact velocity of 212 m/s, while no scattering fragments are found for a lower impact velocity of 120 m/s. Fig.5 shows the same photographs of discontinuous CFRTP. In contrast to the case of continuous CFRTP, large pieces of fragments scatter behind the projectile. The perforated hole was also found to be greater when the impact velocity is decreased.

![Fig.4 Impact response of continuous CFRTP](image-url)
Fig. 6 shows impact response of monolithic PC plate, which corresponds to the matrix materials of CFRTP. In Fig. 6(c), the steel ball projectile does not pass through the target plate and found to be backed away.

No fragments and cracks are observed, which presents striking contrast to the cases of continuous and discontinuous CFRTP with PC matrix. The mechanical behavior of PC is ductile under impact.

![Fig. 5 Impact response of discontinuous CFRTP](image5)

![Fig. 6 Impact response of monolithic PC](image6)
loading as well as static one as is found from this figure. Comparison of impact response of these three target materials shows that the CFRTPs behave like brittle materials when the matrix PC is ductile material. This appears to be because the embedded fibers constrain matrix flow, which results in the embrittlement of the CFRTPs [6], [7], [8]. It is noted that the ductility of thermoplastics PC is lost when reinforced with carbon fibers. This is also discussed in the following section in terms of the ballistic impact performance measures like perforation energy, ballistic limit velocity, and residual velocity.

5.2 Ballistic Impact Properties

5.2.1 Perforation energy

Perforation energy is a critical factor associated with
the ballistic impact performance of protective equipment and structures against foreign objects travelling at very high speed, which is a most commonly used measure of the preventability of perforation in the design of protective structures. Figs.7-9 show perforation energy $E_p$ as a function of impact velocity $V_i$. The perforation energy $E_p$ is evaluated from Eq.(4), where the kinetic energies of the steel ball projectile before and after impact, and that of the scattering fragments are obtained from Eq.(6) using the experimental data of $V_i$, $V_R$, and $m$. The perforation energy can be regarded as almost constant for the impact velocities beyond the ballistic limit velocity although small scatters are found. The constant values of $E_p$ obtained from the averaged experimental data are 2.38J and 5.93J for the continuous and discontinuous CFRTP’s, while that of the monolithic PC is 5.19J. Fig.10 shows that the perforation energy of the continuous CFRTP is reduced by 54% as compared with that of the monolithic PC with the same thickness of 0.8mm. This is also true for the discontinuous CFRTP as shown in Fig.11. The decrease in perforation energy proves the brittle behavior of the CFRTP’s as shown in Figs.4 and 5.

5.2.2 Ballistic limit velocity
A ballistic limit velocity is another ballistic impact performance measure, which is the greatest projectile velocity a structure can resist without perforation. Knowing the perforation energy $E_p$, then we can calculate the ballistic limit velocity from the
equation \( V_b = \sqrt{\frac{2E_p}{M}} \). The values of \( V_b \) for these three target plates are 96.4m/s, 152.0m/s, and 142.0m/s. In comparison with that of the monolithic PC plate, the decrease in ballistic limit velocity of the continuous CFRTP plate is 32%.

5.2.3 Residual velocity
A residual velocity of a steel ball projectile just after perforating a target plate is a function of impact velocity with two constants of ballistic limit velocity and mass coefficient as shown in Eq.(2). Figs.(12)-(14) show residual velocity as a function of impact velocity. The velocity increases parabolically with an increasing impact velocity as predicted from Eq.(2). The mass coefficients \( \alpha \) are 0.975 and 0.857 for continuous and discontinuous CFRTPs. The smaller mass coefficient of discontinuous CFRTP is due to the larger pieces of scattering fragments when compared to the case of continuous CFRTP as shown in Figs.4 and 5. On the other hand, the mass coefficient of monolithic PC is unity, since no fragments are observed to scatter as shown in Fig.6. In Fig.15, comparison of the corresponding residual velocities for the same impact velocity beyond the ballistic limit velocity shows the preventability of perforation of these two target plates, i.e., the higher residual velocity presents the lower ballistic impact performance. By comparison, it follows that the ballistic impact performance of the continuous CFRTP is inferior to that of the monolithic PC. This is the same conclusion as mentioned in 5.2.1 and 5.2.2, where compared in terms of the perforation energy and ballistic limit velocity.

5.2.4 Energy absorption ratio
Energy absorption ratio \( E_{ab} \) is defined by the ratio of perforation energy to initial kinetic energy, which is evaluated from Eq.(5) using the perforation energy \( E_p \) obtained in 5.2.1 and the initial kinetic energy \( E_i \) of the steel ball projectile just before impact. Figs.(16)-(18) shows energy absorption ratio as a function of impact velocity. The ratios decrease monotonously with an increasing impact velocity. In Figs.(16) and (18), by comparing the corresponding energy absorption ratios for the same impact velocity, it is found that the preventability of perforation of the continuous CFRTP is lower than that of the monolithic PC.
5.3 Comparison of Experiment and FE Analysis

Fig. 19 shows the ballistic impact response of discontinuous CFRTP plate, where the experimental and FEA results are compared with each other for the impact velocity of about 250 m/s. It is found that FEA can simulate the global deformation of the target plate, but it cannot do the scattering fragments which are observed in the experiments. Fig. 20 also shows the impact response of monolithic PC plate for the impact velocity of 150 m/s, from which the response and deformation of the target plate is found to be well simulated.

Figs. 21 and 22 compare the FEA results with the experiments, where the perforation energy and residual velocity of the discontinuous CFRTP are plotted as a function of impact velocity. We can find a big difference in quantity between the FEA and experiment. In particular, the perforation energy calculated from FEA is not constant for the impact velocities beyond the ballistic limit velocity, while the experimental results are almost constant. In order to improve the difference between the two, a more refined FE analysis is needed in a future work.

Figs. 23 and 24 show the comparisons of the FEA and experimental results for the monolithic PC plate. Although the perforation energy obtained from FEA is almost constant as is the case of the experiment, the average value is greater than that of the experiment by about 57%. And also, for the ballistic limit velocity, FE analysis gives a greater value than

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Fig. 19 Impact response of discontinuous CFRTP

(a) Experiment \((V_i=250 \text{ m/s})\)

(b) FEA \((V_i=240 \text{ m/s})\)

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Fig. 20 Impact response of monolithic PC

(a) Experiment \((V_i=150 \text{ m/s})\)

(b) FEA \((V_i=150 \text{ m/s})\)
the experiment. The comparisons of the ballistic limit velocities, i.e., experiment vs. FEA and $V_{b1}$ vs. $V_{b2}$ are made in Tables 2 and 3. The values of $V_{b1}$ are obtained as an average of the impact velocities very close to the ballistic limit velocity, while those of $V_{b2}$ are calculated from Eq.(1). In the case of the discontinuous CFRTP, the ballistic limits $V_{b1}$, $V_{b2}$ obtained from FEA are 208 m/s and 231 m/s, which are greater than those of the experiments by 9.4% and 52%. On the other hand, for the monolithic PC, the corresponding values are 160 m/s and 179 m/s and these are greater by 6.7% and 26% compared to those of the experiments. And also, if we make a comparison between $V_{b1}$ and $V_{b2}$, then we find that $V_{b1}$ is greater than $V_{b2}$ in the experimental data, but the situation is reversed in the FEA, i.e., $V_{b1}$ is smaller than $V_{b2}$. The differences are more remarkable for the discontinuous CFRTP. The ballistic limits $V_{b1}$ obtained from the experiment and FEA are very close for these two target plates.

![Fig.21 Perforation energy of discontinuous CFRTP](image1)

![Fig.22 Residual velocity of discontinuous CFRTP](image2)

**Table 2 Ballistic limit velocity of discontinuous CFRTP**

<table>
<thead>
<tr>
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<th>Ballistic Limit $V_{b1}$</th>
<th>Ballistic Limit $V_{b2}$</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>190 m/s</td>
<td>152 m/s</td>
</tr>
<tr>
<td>FEA</td>
<td>208 m/s</td>
<td>231 m/s</td>
</tr>
</tbody>
</table>

![Fig.23 Perforation energy of monolithic PC](image3)

![Fig.24 Residual velocity of monolithic PC](image4)

**Table 3 Ballistic limit velocity of Monolithic PC**

<table>
<thead>
<tr>
<th></th>
<th>Ballistic Limit $V_{b1}$</th>
<th>Ballistic Limit $V_{b2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>150 m/s</td>
<td>142 m/s</td>
</tr>
<tr>
<td>FEA</td>
<td>160 m/s</td>
<td>179 m/s</td>
</tr>
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</table>
6 Conclusions
Ballistic impact response of continuous and discontinuous CFRTP plates along with monolithic PC ones has been studied both experimentally and numerically. In the experiments, a ballistic impact test system incorporated high-speed camera units with a gas gun type impact testing machine is used. The projectile's motion and impact response of these target plates during testing are simultaneously visualized through the high-speed camera. In the numerical analysis, finite element codes of Abaqus/CAE and Abaqus/Explicit package are employed. Semi-empirical analysis is also presented for evaluating ballistic impact performance measures such as perforation energy, ballistic limit velocity, residual velocity, and energy absorption ratio. The results obtained here are summarized as follows:
(1) Impact response of continuous and discontinuous CFRTP plates are accompanied by small or large pieces of scattering fragments, while that of monolithic PC no fragments.
(2) CFRTPs behave like brittle materials when the matrix PC is ductile. This appears to be because the embedded carbon fibers constrain matrix flow, which results in the embrittlement of the CFRTPs.
(3) The perforation energies of the CFRTPs are remarkably reduced compared with those of the monolithic PCs with the same geometrical dimensions. This is also true for the ballistic limit velocities and energy absorption ratios.
(4) The remarkable decrease in the ballistic impact performance measures evidences the brittle behavior of the CFRTPs.
(5) FE analysis can simulate the global deformation of the discontinuous CFRTP and PC plates, but it can not do the scattering fragments observed in the experiment of the CFRTP.
(6) A more refined FE analysis is needed for evaluating the ballistic impact performance measures of the CFRTP materials.

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References