BALLISTIC IMPACT PERFORMANCE OF COMPOSITE PLATE WITH AND WITHOUT BONDING

H.Kasano[1]*
[1] Department of Mechanical Systems Engineering, Takushoku University, Tokyo, Japan
* Corresponding author (**hkasano@ms.takushoku-u.ac.jp**)

Keywords: *ballistic impact, composite plate, PC/PMMA, high-speed photography*

1 Introduction

Ballistic impact performance of plates struck by free-flying projectiles at high speed is a critical issue in the design of protective structures such as nuclear reactor containment vessels, jet engine turbine rotor casings, bulletproof shields, and so forth. In these structures, composite (multi-layered) plates are considered to be advantageous over monolithic (single layered) structures(1)-(3). The purpose of this work is to present a semi-empirical approach for predicting the impact performance of composite plate and to verify the predictions by comparing with the experimental results obtained from a ballistic impact test, where the impact characteristics like ballistic limit velocity, perforation energy, residual velocity, and energy absorption ratio are evaluated.

2 Semi-empirical Approach for Prediction

2.1 Monolithic Plate(4)

Consider a normal impact of a steel ball projectile on a monolithic plate. The projectile of mass M is supposed to pass through the plate accompanying plate-fragments of mass m. In this system, the conservation law of energy and introduction of some assumptions lead to the following expressions for ballistic limit velocity V_b and residual velocity V_R:

$$V_b = \sqrt{V_i^2 - V_R^2 / \alpha^2} \qquad V_R = \alpha \times \sqrt{V_i^2 - V_b^2}$$

where α is mass coefficient given by

$$\alpha = \sqrt{\frac{M}{M+m}}$$

2.2 Composite Plate

Two monolithic plates 1 and 2 are layered up with or without bonding at the interface as shown in Fig.1. In this case, the impact velocities of the projectile impinging on the first plate and exiting from the second plate are denoted by V_{i1} (=V_i) and V_{R2} (=V_R) Since the continuity condition of the projectile velocity must be fulfilled at the interface, we assume that the velocity V_{i2} of the projectile impacting the second plate is equal to the residual velocity of the projectile after partially perforating the first plate, i.e., $V_{i2} = \beta V_{R1}$,where V_{R1} is the residual velocity of the projectile after completely perforating the first monolithic plate. A coefficient β is a constant depending upon the bonding condition at the interface (bonded or non bonded), the stacking sequence of the two plates, and so on. Then the residual velocity V_R of the projectile after perforated the two layered plates is :

$$V_R = A\sqrt{V_i^2 - V_B^2}$$
$$A = \beta\alpha_1\alpha_2$$

and also the ballistic limit velocity V_B is,

$$V_B = \sqrt{V_{b1}^2 + \frac{V_{b2}^2}{\beta^2 \alpha_1^2}}$$

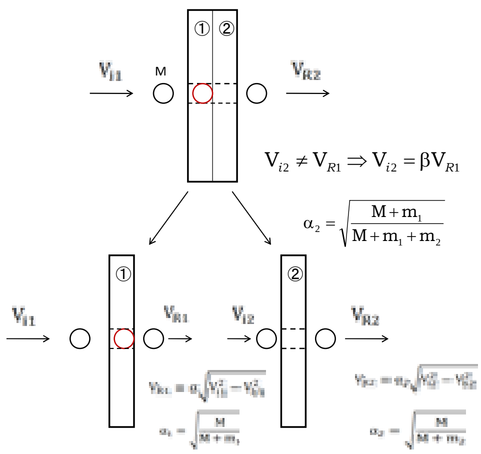


Fig.1 Two layered plate struck by a projectile

These are modified expressions for those obtained in our previous papers(5),(6), from which the impact performance of the composite plates are predicted if the impact characteristics (V_b, α) of the constituting monolithic plates are given and the coefficient β is selected properly.

3 Target Materials and Fabrication

Polycarbonate (PC) and Polymethylmethacrylate (PMMA) are adopted for the present study. These materials are lightweight transparent polymers which are used for protective equipment such as windshields and safety goggles. The mechanical behavior of PC and PMMA presents striking contrast to each other, e.g. PC is ductile, while PMMA brittle, although both of them fall within the thermoplastic resin systems.

The panels of PC and PMMA of thickness 0.5mm are cut into square plates of 100mm×100mm. The four kinds of composite plates are fabricated as shown in Table 1, where PC and PMMA monolithic plates are layered up on the front side and rear side, respectively, and vice versa. The surface of the front side is impacted by a steel ball projectile. The two kinds of adhesive sheets of different thickness are used for interface bonding.

Table 1 Composite plates tested

FRONT side / REAR side (adhesive sheet)	
PC/PMMA (GA25)	PC/PMMA (GA50)
PMMA/PC (GA25)	PMMA/PC (GA50)

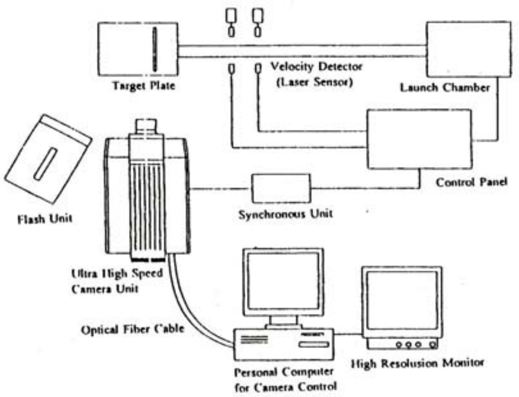


Fig.2 Ballistic impact test system

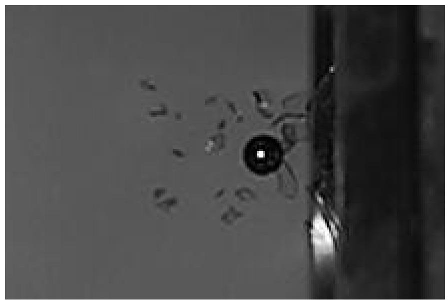
4 Ballistic Impact Test

In order to verify the validity of the proposed approach for predicting the impact performance of the composite plates, impact tests are carried out using the ballistic impact test system as shown in Fig.2. The system consists of gas gun type impact testing machine and high speed camera units. The test system 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 0.51g by weight at a maximum velocity of 330 m/s by releasing high-pressurized nitrogen gas in a chamber. The impact velocity of the projectile just before impinging on a composite plate is determined from the elapsed time of the projectile traveling between two specified points at a distance of 300 mm that is measured by a laser. The residual velocity of the projectile is also measured by the corresponding velocity detector. A composite plate is mounted and clamped in a fixture and struck normally by a steel ball projectile.

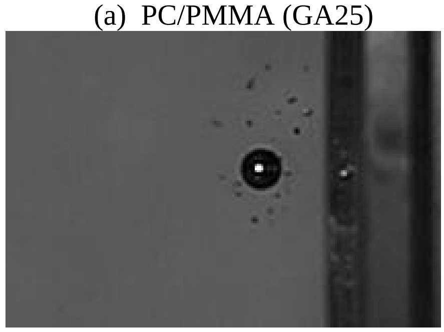
5 Results and Discussions

5.1 High Speed Photographic Observation

Fig.3 shows high speed photographs of the impact fracture of composite plates struck by a steel ball at



(a) PC/PMMA (GA25)



(b) PMMA/PC (GA25)

Fig.3 High speed photographs of impact fracture the impact velocity of 150m/s. The steel ball impinges on the front side (PC) and exits from the rear side (PMMA) in Fig.3(a) and vice versa in Fig.3(b). The scattering fragments are PMMA and very large in the former, while very small in the latter. The small PMMA fragments appears to pass through the PC plate along with the steel ball projectile.

5.2 Predictions

Given the impact characteristics (V_b, α) of the constituting monolithic plates, then the ballistic limit velocity and the residual velocity of the corresponding composite plate can be predicted using a properly selected value of the coefficient β as mentioned in Sec.2.2. The ballistic limit velocities V_b and the mass coefficients α of PC and PMMA used here are (133.7m/s, 0.995) and (29.2m/s, 0.979), which are obtained from our impact tests.

Fig.4 shows the predicted ballistic limit velocity V_B as a function of β. The predicted value of V_B of

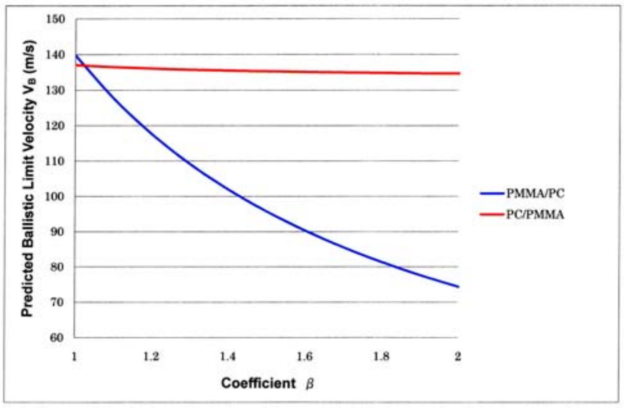


Fig.4 Predicted V_B vs. coefficient β

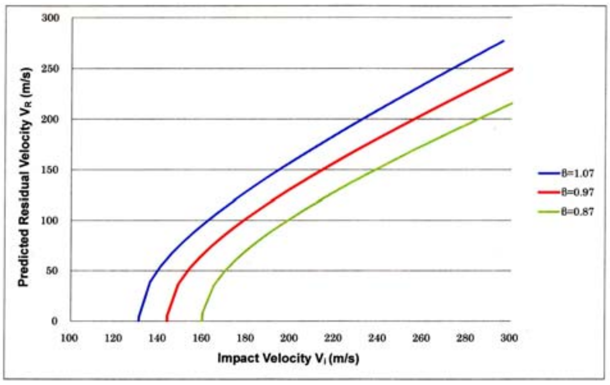


Fig.5 Predicted V_R vs. coefficient β

PMMA/PC composite plate decreases very quickly with an increasing value of β, while that of PC/PMMA composite plate does very slowly. This is due to a big difference of the ballistic limit velocities of PC and PMMA monolithic plates.

Fig.5 also shows the predicted residual velocity V_R for PMMA/PC as a function of impact velocity V_i for the different values of β. The predicted value of V_R increases hyperbolically with an increasing value of V_i. The V_R - V_i curves tend to shift rightward with an decreasing value of β, which means the ballistic performance is enhanced.

5.3 Comparison of Predictions and Experiments

Figs.6 and 7 show residual velocity as a function of impact velocity, where predictions and experiments are compared. The residual velocity can be predicted by using β=1.1 for higher impact velocity and 1.2 for lower one when PC and PMMA plates are not bonded, and when the two plates are bonded, β=1.1 gives a good prediction. It is noted here that the ballistic limit velocities given by the coordinate values of intersecting points of the V_R - V_i curves

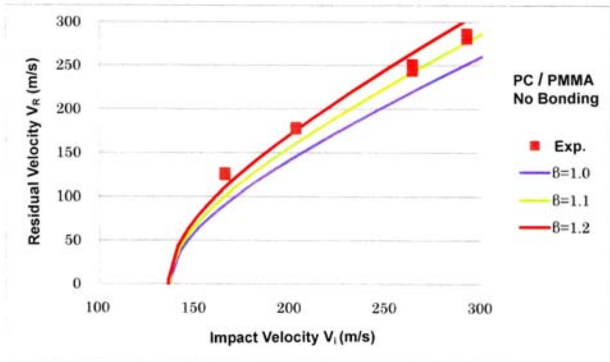


Fig.6 Predictions and experiments (PC/PMMA, N.B.)

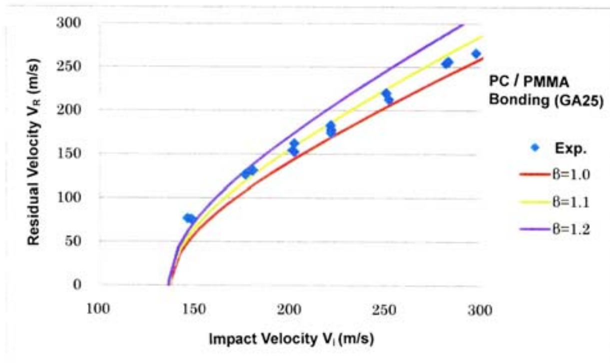


Fig.7 Predictions and experiments (PC/PMMA, B.)

and the abscissa make almost no difference for the different values of β. This is because the variation of the predicted ballistic limit velocity as a function of β is very small for PC/PMMA composite plate as shown in Fig.4.

Figs.8 and 9 show the V_R - V_i curves for PMMA/PC composite plate. The selection of β =0.96～1.16 gives a good prediction when the interface is not bonded, and also β =0.97～1.17 when bonded.

Figs.10 and 11 show the effect of interface bonding on the residual velocity, where three cases of no bonding, bonding with GA25 and GA50 adhesive sheets are compared. The residual velocity for PC/PMMA composite plate is slightly higher when the interface of two plates is not bonded than otherwise. When bonded, the coefficient of β =1.08 gives a good prediction for GA50 adhesive sheet, while β =1.1 for GA25 sheet as mentioned before. Meanwhile, for PMMA/PC composite plate, there is no difference between those of the plates with and without bonding, and the V_R - V_i curve with β =1.07 gives a fairly good prediction whether the interface of two plates is bonded or not.

5.4 Perforation Energy /Energy Absorption Ratio

Figs.12 and 13 show the perforation energy E_P (J) and energy absorption ratio E_{ab} (%) as a function of impact velocity V_i (m/s) for PC/PMMA composite plate bonded with adhesive sheet GA25. The perforation energy is given by the difference of the initial kinetic energy of a steel ball before impact from sum of the kinetic energy of the projectile and scattering fragments after impact. And also the energy absorption ratio is defined by a ratio of difference of the kinetic energy of the projectile before and after impact to the initial one before impact. The perforation energy is found to scatter. This is because the drop in projectile velocity after perforation is very small as shown in Fig.7 and also the mass measurement of the scattering PMMA fragments is very difficult. The average value of E_P is 1.6J. Meanwhile, energy absorption ratio tends to

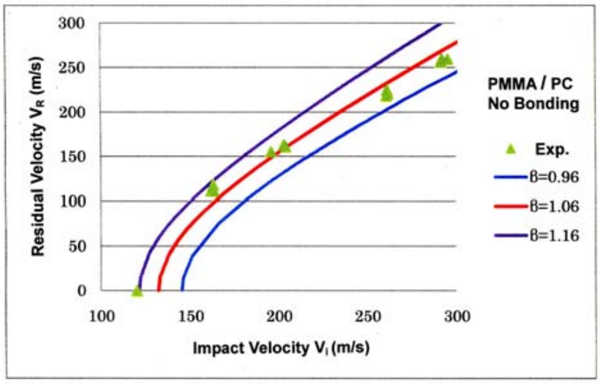


Fig.8 Predictions and experiments (PMMA/PC, N.B.)

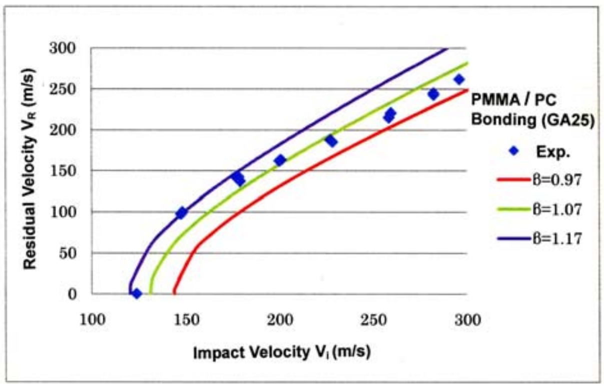


Fig.9 Predictions and experiments (PMMA/PC, B.)

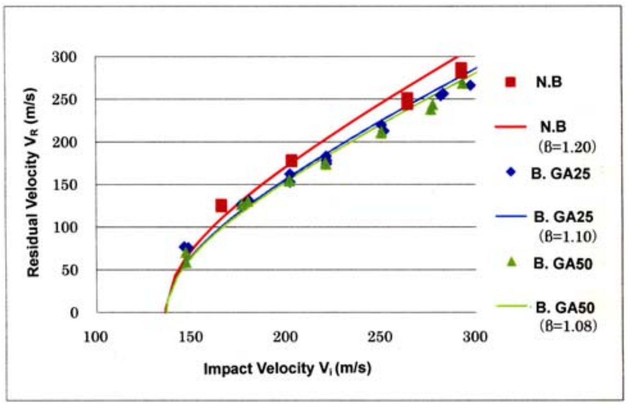


Fig.10 Effect of interface bonding (PC/PMMA)

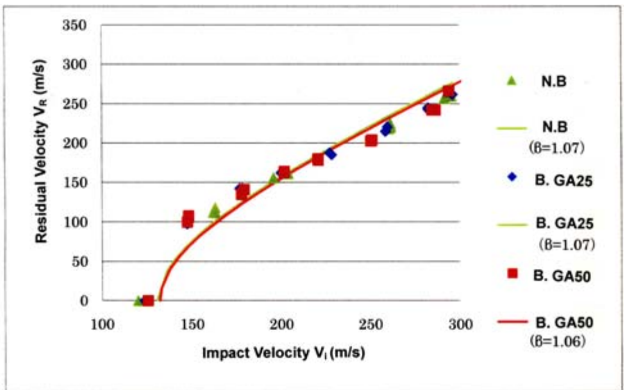


Fig.11 Effect of interface bonding (PMMA/PC)

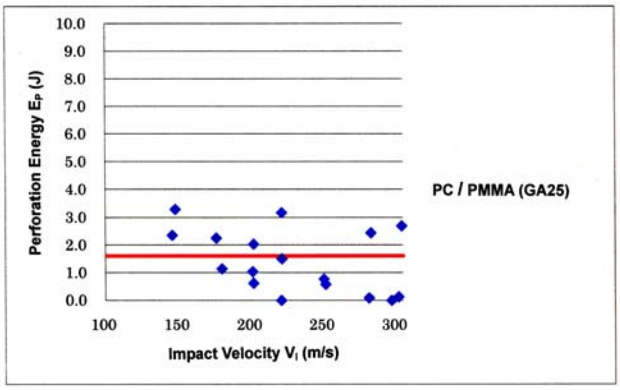


Fig.12 Perforation energy vs. impact velocity

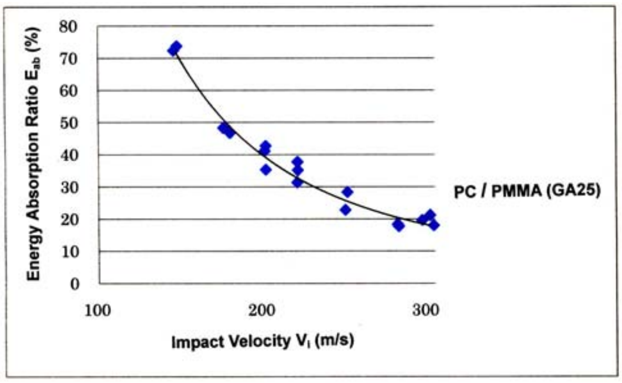


Fig.13 Energy absorption ratio vs. impact velocity

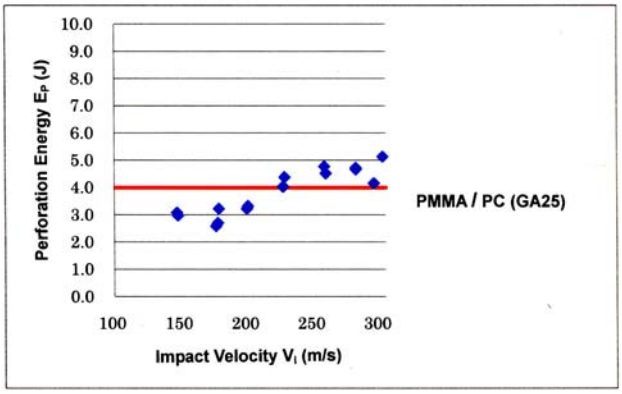


Fig.14 Perforation energy vs. impact velocity

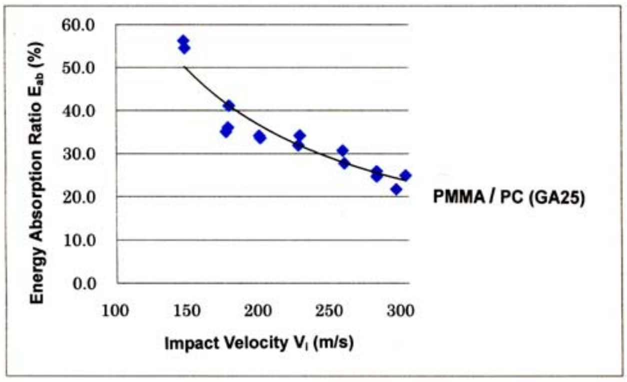


Fig.15 Energy absorption ratio vs. impact velocity

decrease with an increasing impact velocity from 70% to 20%. Figs.14 and 15 show the same relationships for PMMA/PC composite plate, where the scattering band of the perforation energy is smaller compared to that of PC/PMMA plate. The magnitude of the perforation energy is within the limit of 3.0J and 5.0J, and the average value is 4.0J.

The energy absorption ratio decreases with an increasing impact velocity as is the case of PC/PMMA.

6 Conclusions

Ballistic impact performance of two-layered composite plates consisting of PC and PMMA monolithic plates is studied. Semi-empirical approach for predicting the impact characteristics is presented and then ballistic impact tests are carried out to verify the predictions. The effects of interface bonding and placement of constituting monolithic plates on the impact performance are examined.

References

[1] I. Marom & S.R. Bodner "Projectile perforation of multi-layered beams ". *Int. J. Mech. Sci*., Vol.21, pp.489-504, 1979.

[2] J.G. Hetherington & P.F. Lemieux "The effect of obliquity of the ballistic performance of two component composite armours " *Int. J. Impact Engng*., Vol.15, No.2, pp.131-137, 1994.

[3] H.L. Gower, D.S. Cronin, A. Plumtree "Ballistic impact response of laminated composite panels" *Int.J. Impact Engng*., Vol.35, pp.1000-1008, 2008

[4] H. Kasano "Impact perforation of orthotropic and quasi-isotropic laminates by a steel ball projectile". *Advanced Composite Materials*, Vol. 10, No. 4, pp 309-318, 2001.

[5] H. Kasano and K. Abe "Perforation characteristics prediction of multi-layered composite plates subjected to high velocity impact". Proc. 11th ICCM, pp. II 522-531, 1997.

[6] H. Kasano "Perforation characteristics of aluminum plates subjected to high velocity impact". *Proc. 5th Int. SAMPE Symposium.*, pp 1013-1018, 1997.