Ballistic Impact Behavior and Properties of Double-Ply Woven Fabrics

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Abstract

This paper presents an investigation on the ballistic impact behavior and properties of double-ply woven fabrics. A normal impact of a steel ball projectile impinging on and passing through a multiple woven fabrics is described using an energy balance equation, from which semi-empirical expressions for predicting the residual velocity and the ballistic limit velocity are derived in the closed forms. The ballistic impact tests are also carried out on a single and double ply woven fabrics in order to verify the predictions. Finally, the ballistic performance measures such as the residual velocity, the perforation energy, the energy absorption ratio, and the ballistic limit velocity including the V_{50} limit velocity are evaluated.

1 Introduction

Ballistic impact performance of woven fabrics struck by free-flying projectiles at high speed is a critical issue in the design of protective equipment such as protective body armor, bulletproof jackets, helmets, and jet engine containment systems. The fabric-based equipment like these is commonly made up of multiple layers to stop the projectile not to perforate. Therefore, many investigations on the ballistic impact response of multiply woven fabrics have thus far been made using analytical modeling[(1)-(3)], computer simulations[(4),(5)], experiments[(6)], and so forth. More recently, ballistic impact of advanced composite material systems including multi-layered Kevlar woven fabrics is investigated using a hybrid particle-element simulation [(7)]. The purpose of this work is to present semi-empirical expressions for predicting the impact performance of multiple woven fabrics in closed forms, and also to verify the predictions by a series of ballistic impact tests. In the analysis, a normal impact of a steel ball projectile impinging on and passing through a multiple woven fabrics is described using an energy balance equation, from which semi-empirical expressions for predicting the residual velocity and the ballistic limit velocity are derived in the closed forms.

In addition, the ballistic impact tests are also carried out on a single and double ply woven fabrics in order to verify the predictions.

Finally, the ballistic performance measures such as the residual velocity, the perforation energy (absorption energy), the energy absorption ratio, the ballistic limit velocity including the V_{50} limit velocity are evaluated.

2 Semi-empirical predictions for residual velocity and ballistic limit velocity

Consider a normal impact of a steel ball projectile on double-ply woven fabrics as shown in Fig.1. Here, the projectile of mass *M* is supposed to impinge on the first layer at an impact velocity of V_{i1} and to exit from the second one at a residual velocity of V_{R2} accompanying no fragments as shown in Fig.1 (upper). In this system, if the first and the second layers are isolated as shown in Fig.1 (lower), then application of the conservation law of energy and introduction of some assumptions lead to the following expressions for the residual velocities V_{R1} and V_{R2} after completely passing through each of them [8]:

$$V_{R1} = \sqrt{V_{i1}^2 - V_{b1}^2} \qquad V_{R2} = \sqrt{V_{i2}^2 - V_{b2}^2} \tag{1}$$

, where V_{b1} and V_{b2} are the ballistic limit velocities of the woven fabrics placed in the first and the second layers. In the case of double-ply fabrics, it should be noted that the impact velocity V_{i2} of the projectile impinging on the second layer is not always equal to the residual velocity V_{R1} given by Eq. (1). However, the continuity condition of the projectile velocity must be fulfilled at the interface between two fabrics. Therefore we assume that V_{i2} is equal to the residual velocity of the projectile after partially perforating the first layer, i.e., $V_{i2} = \beta_1 V_{R1}$. Then in Eq. (1), by substituting the first equation along with this into the second one, we have the following expressions for the residual velocity and the ballistic limit velocity of the double-ply woven fabrics:

$$V_{R1} = \beta_1 \sqrt{V_{i1}^2 - V_B^2} \qquad V_B = \sqrt{V_{b1}^2 + \frac{V_{b2}^2}{\beta_1^2}} \tag{2}$$

In a like manner, for a multiple woven fabrics, the corresponding expressions are given,

$$V_{Rn} = B_{n-1} \sqrt{V_{i1}^2 - V_B^2} \qquad V_B = \sqrt{\sum_{m=1}^{n} \frac{V_{bm}^2}{\beta_{m-1}^2}} \qquad \beta_0 = 1,\ B_k = \beta_1 \beta_2 \beta_3 \cdots \beta_k,\ B_0 = 1 \tag{3}$$

These are modified expressions for those obtained in our previous papers [9],[10].
The expressions for the ballistic limit velocity thus obtained includes those of individual plies (single fabrics) consisting the multiple (n-plies) fabrics and interface coefficients β_m ’s depending on the layer construction and the interface conditions between two adjacent plies.

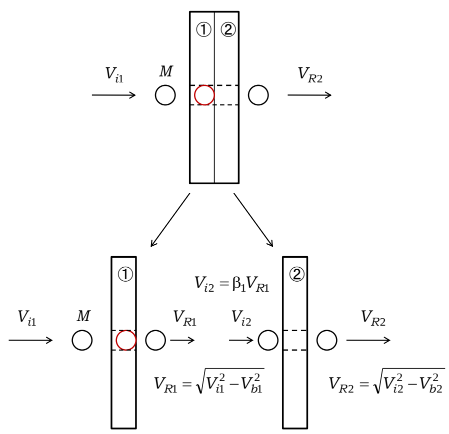


Figure 1. Illustration of Double-ply woven fabrics struck normally by a steel ball projectile.

Hence, the ballistic limit velocity of the multiple fabrics can be predicted if the corresponding properties (ballistic limit velocities) of the constituting single fabrics, which are evaluated experimentally, and the values of the coefficients are given, from which the corresponding residual velocity is predictable as well.

3 Specimen preparations and ballistic impact test

3.1 Woven fabric specimen

The present study has focused on the ballistic response of a single ply and double-ply woven fabrics. Two types of woven fabrics are used, which are commercially available and denoted here by fabric A and fabric B, respectively. Table 1 shows the specifications of these two single fabrics A and B. In addition, another type of fabric, which is coated with PVC on both sides of the fabric A, is also used. This is denoted by fabric C and the measured thickness is 0.68 mm. By laying up the two of these three single fabrics, four kinds of double-ply fabric specimens with dimensions of 120×120 mm^2 are constructed, which are denoted by A/A, B/B,A/C, and B/C.

3.2 Ballistic impact test system

The ballistic impact test system is developed incorporating high speed camera units with a gas gun type impact testing machine as shown in Fig.2. 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. A fabric specimen is mounted in a clamping rig with a circular window and struck normally by a steel ball projectile. The velocity of the projectile just before impinging on a fabric specimen (impact velocity) is detected using two spatially separated laser-gate systems, and it is measured 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 corresponding velocity detector.

The projectile's motion and dynamic response of these fabric specimens during testing are simultaneously visualized through the high speed camera, which are displayed on the high-resolution monitor and stored in the personal computer for data analysis.

Table 1. Specifications of two types of woven fabric

	Yarn		Number of yarns (/25mm)		Tensile strength (N/mm)		Areal density (g/m^2)	Thickness (mm)
	Warp	Weft	Warp	Weft	Warp	Weft		
Fabric A	3300T	3300T	17	16.5	347	339	463	0.60
Fabric B	1110T	1110T	31	31	225	238	291	0.38

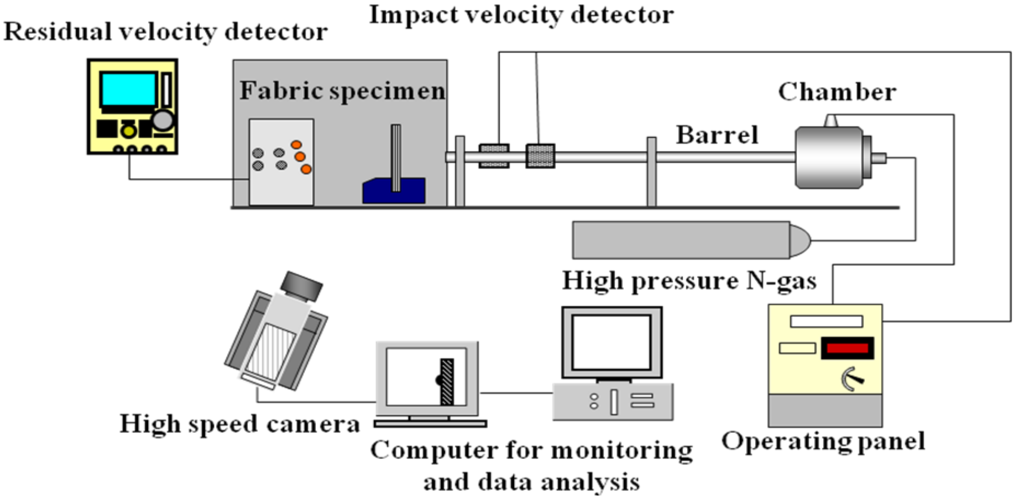


Figure 2. Schematic diagram of ballistic impact test system.

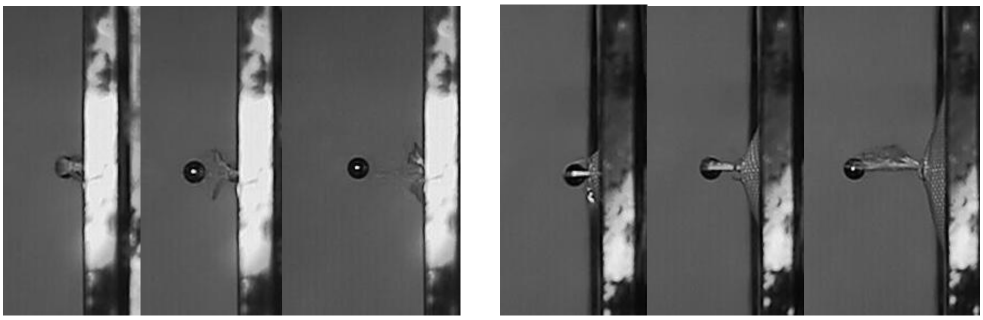
4 Results and discussions

4.1 High speed photographs of fabric deformation and failure

Fig.3 and 4 show the sequence of single and double-ply fabric deformation taken by high speed photography. In Fig.3, the projectile is passing through the single-ply fabric A with a small deformation, while for the single-ply fabric B, it is pulling the yarns when exiting. The situation is more remarkable for the double-ply fabrics as shown in Fig.4.

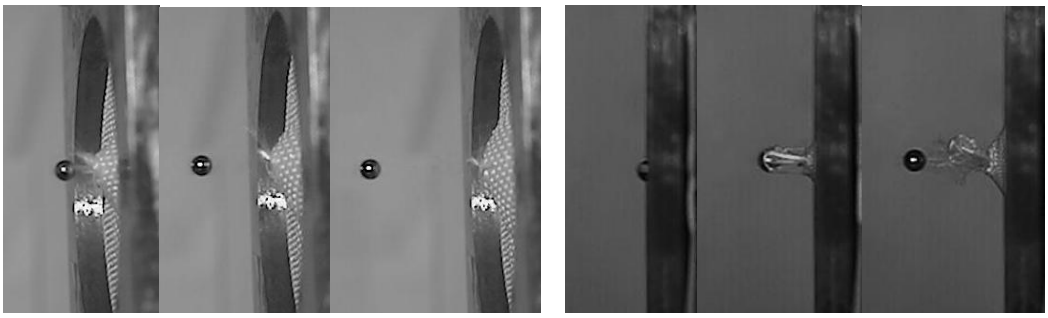
4.2 Perforation Energy and ballistic limit velocity

The perforation energy E_P is given by the difference of initial kinetic energy E_i of a projectile before impact from residual kinetic energy E_R after impact. Fig.5 shows the perforation energy as a function of impact velocity. For fabric A, the perforation energy is almost constant, from which the ballistic limit velocity $V_b = \sqrt{2E_p / M}$ is 124.1m/s. However, for fabric B, it remains almost constant for zone 1 ($V_i \leq 200\text{m/s}$), while it does for zone 2 ($V_i \geq 200\text{m/s}$), but the magnitude is different. Therefore, the ballistic limit velocity evaluated from the perforation energy for zone 1 is 148.3 m/s and that of zone 2 is 134.1 m/s.



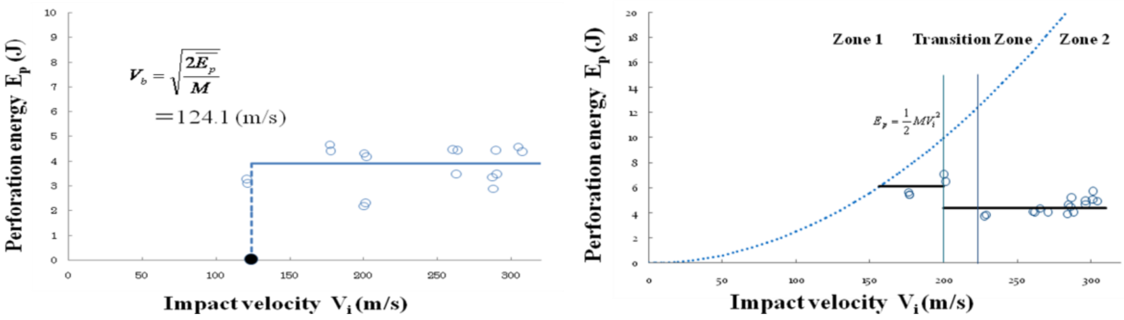
(a) Single fabric A (b) Single fabric B

Figure 3. Sequence of single ply fabric deformation and failure for impact velocity 177 m/s



(a) Double-ply fabric A/A (b) Double-ply fabric B/B

Figure 4. Sequence of double-ply fabric deformation and failure for impact velocity 280 m/s



(a) Single fabric A (b) Single fabric B

Figure 5. Perforation energy as a function of impact energy

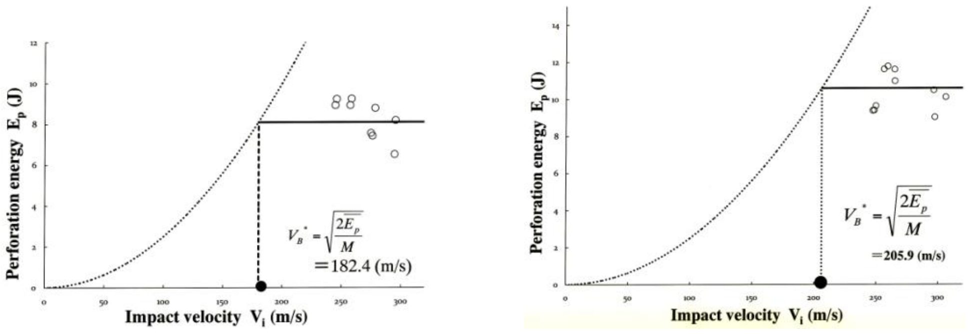
The reason why the magnitude of the perforation energy is different for zone 1 and 2 is that the fabric deformation is global for the lower impact velocity and local for the higher one. It follows that the energy required for global deformation is larger than that for the local deformation, which leads to the high perforation energy for zone 1 and low one for zone 2. In this connection, the probabilistic limit velocity V_{50} is 128 m/s, which is close to the ballistic limit velocity 134.1 m/s evaluated from the perforation energy for zone 2. Fig.6 shows the perforation energy as a function of impact velocity for double-ply fabrics A/A and B/B. The ballistic limit velocities evaluated using these average perforation energy are 182.4 m/s and 205.9 m/s for A/A and B/B, respectively.

4.3 Energy absorption ratio

Energy absorption ratio E_{ab} is defined by the ratio of perforation energy E_p to initial kinetic energy E_i, i.e., $E_{ab} = E_p / E_i = (E_i - E_R)/E_i$ (%). Fig.7 shows the energy absorption ratio as a function of impact velocity. The energy absorption ratio tends to decrease with an increasing impact velocity, and the value of E_{ab} for double-ply B/B is greater than that of A/A when compared at the same impact velocity.

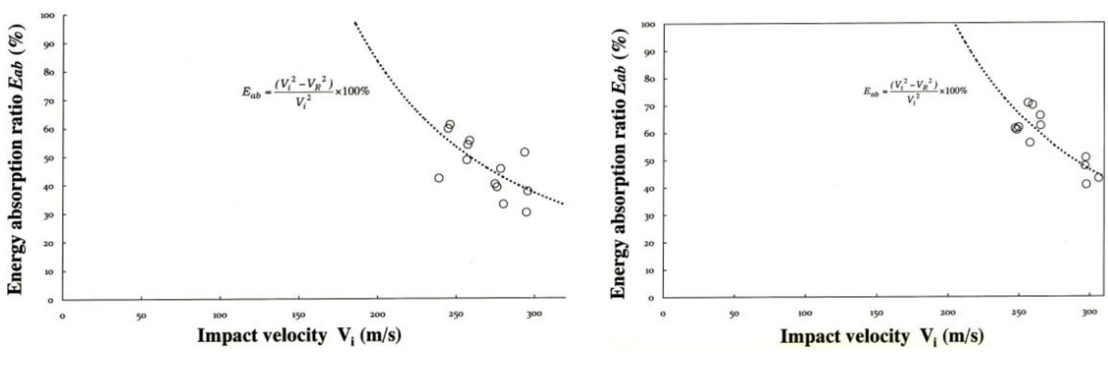
4.4 Residual velocity

Fig.8 shows the residual velocity of the projectile exiting from the fabric as a function of impact velocity. The residual velocity increases hyperbolically with an increasing value of impact velocity as predicted. Fig.9 shows the corresponding relationships for double-ply fabrics, where the predictions are compared with the experimental results. The solid lines are the predictions given by Eq.(2), in which we use the values of V_{b1} and V_{b2} evaluated from the perforation energy in Fig.5. In this case, given the values of the coefficients β_1 =1.0 and 0.95 for A/A and B/B, respectively, the V_R-V_i curves are found to give fairly good predictions.



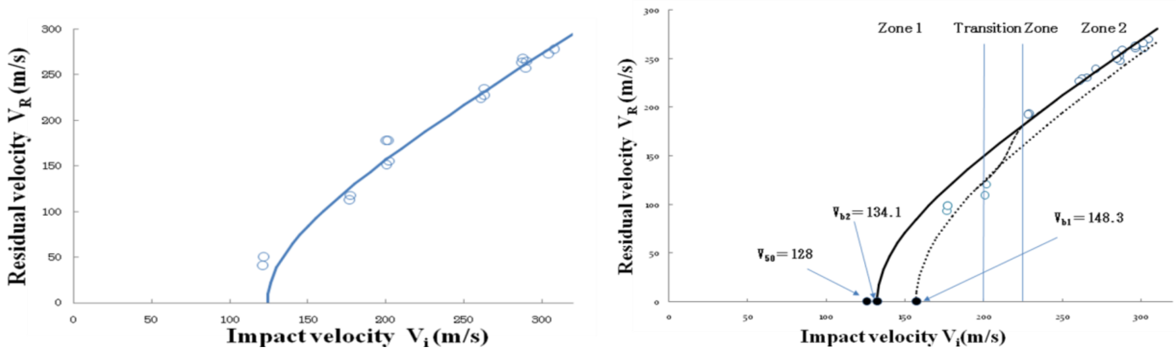
(a) Double-ply fabric A/A (b) Double-ply fabric B/B

Figure 6. Perforation energy as a function of impact velocity



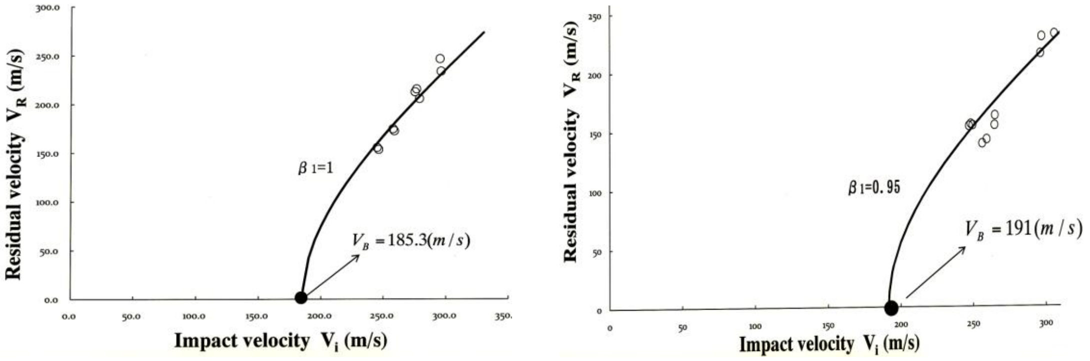
(a) Double-ply fabric A/A (b) Double-ply fabric B/B

Figure 7. Energy absorption ratio as a function of impact velocity



(a) Single fabric A (b) Single fabric B

Figure 8. Residual velocity as a function of impact velocity

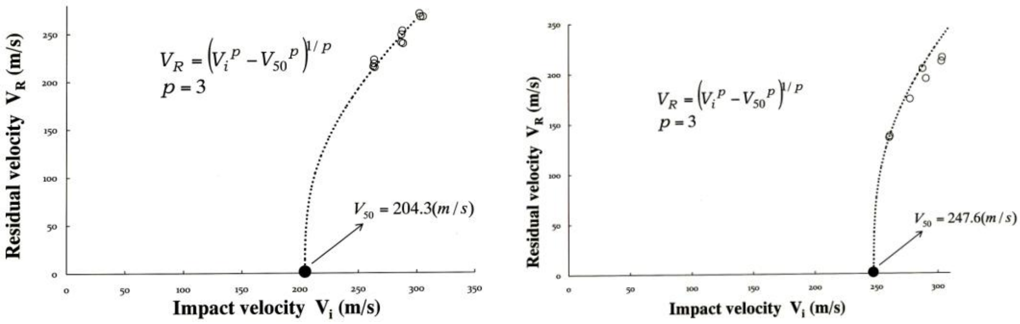


(a) Double-ply fabric A/A (b) Double-ply fabric B/B

Figure 9. Residual velocity as a function of impact velocity (predictions vs. experiments)

(a) Single fabric C

Figure 10. Sequence of single-ply fabric deformation and failure for impact velocity 263 m/s



(a) Single fabric C (b) Double-ply fabric A/C

Figure 11. Residual velocity as a function of impact velocity

4.5 Woven fabric C (fabric A coated with PVC)

Fig.10 shows a high speed photograph of the sequence of deformation and failure for single-ply fabric C. The fabric deformation is nearly visible, but we can find that a part of PVC coatings is scattering in fragments. This situation is different from those of the fabrics A and B as shown in Fig.3. Therefore, the semi-empirical prediction method mentioned above may not be applied to this case. We present here another predictive residual velocity expression (11). Fig.11 shows the residual velocity as a function of impact velocity for single-ply fabric C and double-ply fabric A/C, in which experimental data are limited within an impact velocity range of 250 m/s to 300 m/s. In this case, the residual velocity is supposed to be expressed with $V_R = \left(V_i^p - V_b^p\right)^{1/p}$, and the probabilistic ballistic limit velocity V_{50} to be used as V_b. The V_{50} values evaluated in our experiments are 204.3 m/s and 247.6 m/s for single fabric C and double-ply fabric A/C. Then, given the value of p=3 for both fabrics, the V_R-V_i curves give fairly good predictions.

5 Conclusions

The ballistic impact behavior and properties of double-ply woven fabrics are studied using a semi-empirical predictive approach and a series of ballistic impact tests. Two types of woven fabrics commercially available are prepared for evaluating the ballistic performance measures. The semi-empirical predictions are shown to be in good agreement with experimental results.

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References

[1] Cunniff, P.M. A semiempirical model for the ballistic impact performance of textile-based personnel armor. *Textile Research Journal*, **66-1**, pp. 45-59 (1996).
[2] Chocron-Benloulo, I.S., Rodrigues, J., Sanchez-Galvez, V. A simple analytical model to simulate textile fabric ballistic impact behavior. *Textile Research Journal*, **67-7**, pp. 520-528 (1997).
[3] Porwal, P.K., Phoenix, S.L. Modeling system effects in ballistic impact into multi-layered fibrous materials for soft body armor. *Int. J. Fracture*., 135, pp.217-249 (2005).
[4] Duan, Y., Keefe, M., Bogetti, T.A., Cheeseman, B.A. Modeling friction effects on the ballistic impact behavior of a single-ply high-strength fabric. *Int. J. Impact Eng.*, 31, pp.996-1012 (2005).
[5] Tan, V.B.C., Ching, T.W. Computational simulation of fabric armor subjected to ballistic impacts. *Int. J. Impact Eng.*, 32, pp.1737-1751 (2006).
[6] Atas, C., Liu, D. Impact response of woven composites with small weaving angles. *Int. J. Impact Eng.*, 35, pp.80-97 (2008).
[7] Son, K.J., Fahrenthold, E.P. Hybrid particle –element simulation of composite material impact physics in Proceedings of *18th Int. Conf. CM*., (2011).
[8] Kasano, H. Impact perforation of orthotropic and quasi-isotropic laminates by a steel ball projectile. *Advanced Composite Materials*, 10-4, pp.309-318.
[9] Kasano. H., Abe, K. Perforation characteristics prediction of multi-layered composite plates subjected to high velocity impact in Proceedings of *11th Int. Conf. CM*., pp.522-531 (1997).
[10] Kasano, H. Perforation characteristics of aluminum plates subjected to high velocity impact in Proceedings of *5th Int. SAMPE symposium*, pp.1013-1018 (1997).
[11] Zukas, J.A. *High Velocity Impact Dynamics*. John Wiley & Sons, Inc. (1990).