IMPACT ENERGY AND DAMAGE BEHAVIOR OF HYBRID COMPOSITE STRUCTURES UNDER HIGH VELOCITY IMPACT

Sung-Choong Woo[1], Jong-Tak Kim[2] , Jin-Young Kim[3], Tae-Won Kim[4]*
[1] Survivability Technology Defense Research Center, Hanyang University,
17 Haengdang-Dong, Sungdong-Gu, Seoul 133-791, Republic of Korea
[2] Department of Automotive Engineering, Hanyang University, 17 Haengdang-Dong,
Sungdong-Gu, Seoul 133-791, Republic of Korea
[3] Agency for Defense Development, 462 Jochiwon-Gil, Yuseong-Gu,
Daejeon 305-152, Republic of Korea
[4] School of mechanical Engineering, Hanyang University, 17 Haengdang-Dong,
Sungdong-Gu, Seoul 133-791, Republic of Korea

* Corresponding author(**twkim@hanyang.ac.kr**)

Keywords: *Hybrid composite structure; High velocity impact; Damage behavior; Finite element analysis*

Impact absorption energy together with the material damage of hybrid composite structure under high velocity impact was investigated. The hybrid composite structure studied in this work consists of six-layer, namely S2-glass-1, CMC, EPDM rubber, Al7039, Al-foam and S2-glass-2. A three-dimensional finite element simulation was conducted based on a progressive damage model using the commercial code program, LS-DYNA. In order to simulate the sufficient deformations and fractures, an extremely high velocity (5,000 m/s) was applied as impact loading to the hybrid composite structure. The damage parameter in continuum damage mechanics determined by the reduction of stiffness, and also the absorbed energy were calculated to analysis the local fracture of the hybrid composite structure. Results of finite element analyses revealed that S2-glass showed a wide range of damage and local delamination; CMC and aluminum foam revealed a narrow band of damage. It is therefore suggested that the progressive damage model was appropriate to simulate quantitatively the level of damage of hybrid composite structure under such high velocity impact.

1 Introduction

In a design of composite structures for impact energy absorption, brittle materials such as ceramics are stacked at the front and ductile materials are arranged at the rear. Ceramic/metal or ceramic/PMC (polymer matrix composite) composition is preferred in the stacking sequence considering material performances, deformation characteristics, and multi-layer manufacturing technologies etc.

Concerning an impact on composite laminates, determination of ballistic limits with the analysis of the penetration process has been widely studied during the last three decades. Numbers of literature may be found addressing these issues and problems [1-5]. Most of the works to determine the failure characteristics of hybrid composite structures, however, concerned about experimental investigation, and hence required a lot of time and effort. A popular trend enabling the increase of cost efficiency is to reduce destructive testing schemes by predicting the performance of materials through analytical modeling or numerical simulations. When multi-layered plates including diverse materials are subjected to ballistic impact, their response is determined by interactions of multiple stress waves generated at the layer interfaces [6]. Many works have been done to model the failure mechanisms of hybrid composite structures under relatively lower transverse impact loading [7–10]. However, limited studies have been done on the progressive failure of composites under high strain rate impact loading. It is generally accepted that composites fail in a progressive manner.

The objective of this work is therefore to understand the impact absorption behavior of hybrid composite structures consisting of many different materials by employing the progressive damage model. The material local damage together with the impact absorption energy was analyzed. In the numerical simulations, explicit commercial software LS-DYNA was used.

2 Numerical Analysis

2.1 Damage Model

LS-DYNA provides material model MAT161 and MAT162 (developed by Yen) which capture the progressive failure mode of composite laminates including both unidirectional and plain weave laminates during transverse impact. The material model MAT162, based on the Hashin's failure criteria [11] was assigned to model the plain weave composite laminate [12].

The continuum damage mechanics approach proposed by Matzenmiller et al. [13] has been incorporated into MAT 162. This model enables progressive damage of composite laminates to simulate by controlling strain softening after failure during high velocity impact. The continuum damage mechanics formulation takes into consideration the post failure mechanisms in a composite plate as characterized by a reduction in material stiffness. A set of damage variable (w_i) to relate the damage growth to stiffness reduction (E_{red}) in the material [12] is given by:

$$w_i = 1 - e^{\frac{1}{n_i}\left(1 - r_j^{n_i}\right)} \tag{1}$$

$$E_{red} = (1 - w_i)E_0 \tag{2}$$

where w_i is the damage variable, n_i the strain softening parameter, r_j the damage threshold, E_0 the elastic modulus and E_{red} the stiffness reduction. The damage variable w_i varies from 0 to 1 as r_j varies from 1 to infinite. For simplicity, the softening parameter n was assumed to be identical (n = 0.57) for the four strain softening damage modes.

The failure criterion for isotropic materials such as aluminum and ceramic is given by the following relation:

$$f = \left(\frac{\langle \sigma_2 \rangle}{S_2}\right)^2 + \left(\frac{\langle \tau_{23} \rangle}{S_{23}}\right)^2 + \left(\frac{\langle \tau_{12} \rangle}{S_{12}}\right)^2 - 1 = 0 \tag{3}$$

where f is the failure function for isotropic materials, σ_2 normal axial stress, S_2 failure strength, τ_{23} and τ_{12} shear stresses, S_{23} and S_{12} shear strengths, respectively. Mark < > denotes Macaulay bracket.

The fiber failure criteria of Hashin for a unidirectional layer are generalized to characterize the fiber damage in terms of strain components for a plain weave layer. The tensile/shear failure of fill and warp fibers are given by the quadratic interaction between the associated axial and shear stresses:

$$f_{fill} = \left(\frac{\langle \sigma_1 \rangle}{S_1}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{31}^2}{S_{1FS}}\right) - 1 = 0 \tag{4}$$

$$f_{warp} = \left(\frac{\langle \sigma_2 \rangle}{S_2}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{23}^2}{S_{2FS}}\right) - 1 = 0 \tag{5}$$

where S_1 and S_2 are the axial tensile strengths in the fill and warp directions, respectively, and S_{1FS} and S_{2FS} are the layer shear strengths due to fiber shear failure in the fill and warp directions [6].

MAT 162 provides an insight into the physics of the delamination of the composite plate as given by Eq. (6):

$$f_{del} = S_d^{\,2}\left\{\left(\frac{\langle \sigma_3 \rangle}{S_2}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 + \left(\frac{\tau_{31}}{S_{31}}\right)^2\right\} - 1 = 0 \tag{6}$$

where S_2 is the thickness tensile strength, and S_{23} and S_{31} are shear strengths assumed to depend on the compressive normal stress σ_3. Delamination factor, S_d was selected iteratively by the fitting the analytical prediction and found to be 0.3.

2.2 Finite Element Analysis

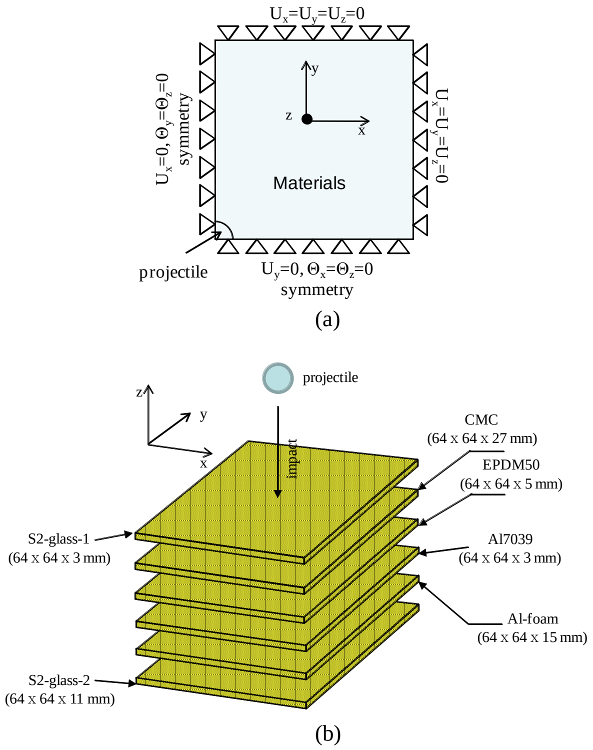


Fig. 1. Schematic of (a) boundary conditions and (b) a lay-up sequence of hybrid composite structure adopted in three dimensional finite element analyses.

Fig. 1 shows the schematic of boundary conditions and a lay-up sequence of hybrid composite structure adopted in three dimensional finite element analyses. Aforementioned damage model was applied to the hybrid composite structure. For the aluminum-foam and rubber, Fleck and Blatz-Ko models were applied respectively as in the literature [14-15]. Hypermesh^{TM} (Version 10) was used for pre-processing in the model development. LS-DYNA (Version 971) was used to analyze perforation mechanisms, failure modes, and damage evaluation during high velocity projectile impact on the six-layer hybrid composite target plates. The material properties and model No. used in the simulations are listed in Table 1. Only a quarter of the target plate was modeled considering the symmetry conditions with respect to the central axis as shown in Fig. 1(a). Both the projectile and the composite plates have been meshed with eight node brick elements with a single integration point. The spherical projectile was made using 896 brick elements and was assumed as a rigid body with no deformation. A total of 16,000 elements are used. Initial velocity of a spherical projectile with a mass of 40g and caliber of 9.5 mm was set to 5000 m/s for complete penetration. The rubber layer has been modeled with a hyperelastic continuum rubber element developed by Blatz and Ko [14]. In LS-DYNA, contact between the projectile and the target plate was defined using a contact eroding single surface [12]. The authors handled the penetration of the projectile using eroding elements with strain based failure criterion.

The impact absorbed energy of the plate was calculated according to the following equation:

$$E = E_I - E_R = \frac{1}{2} m \left(v_I^2 - v_R^2 \right) \qquad (7)$$

where E, E_I and E_R, are the absorbed energy, the kinetic energy of projectile at impact on the target plate and the residual energy of projectile through the target plate, respectively; v_I, v_R and m are the velocity of projectile at impact (impact velocity), the velocity of projectile through the target plate (residual velocity) and the mass of the projectile, respectively.

Table 1. Material properties and model No. of the hybrid composite structure [10, 16]. (S, N and Y denote shear, normal and yield stresses respectively and mark * indicates own experimental data)

Material (LS-DYNA model No.)	Density (g/cm^3)	Elastic or Shear modulus (GPa)	Strength (GPa) Failure Strain (%)
S2-glass (Mat 162)	1.40	E_x=E_y=61 E_z=0.24	S=0.1, N_x=N_y=1.26, N_z=0.05 (20%)
CMC (Mat 162)	3.60	G=113	Y=2.48 (0.9%)
EPDM50 (Mat 7)	1.14*	G=1.24*	-
Al7039 (Mat 162)	2.70	E=70	Y=0.055 (17%)
Al-foam (Mat 63)	0.25*	E=1.3*	Y=0.00133* (5.0%)*

3 Results and Discussion

The main objective of the finite element analysis is to investigate the deformation-failure response of the multi-layer composite plate in the event of a projectile striking at a velocity of 5000 m/s. Analyses of high velocity impact responses in terms of energy absorption and stress contour plot are presented below.

3.1 Penetration velocity variation of the projectile

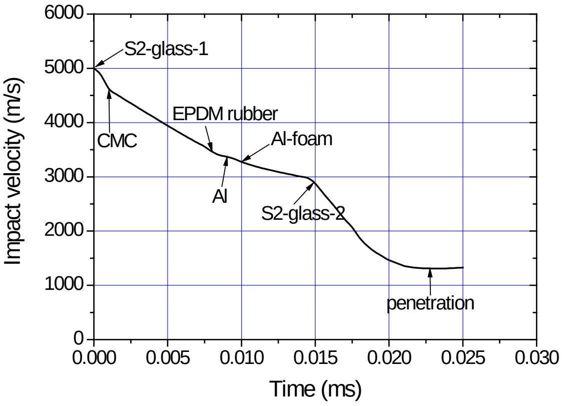
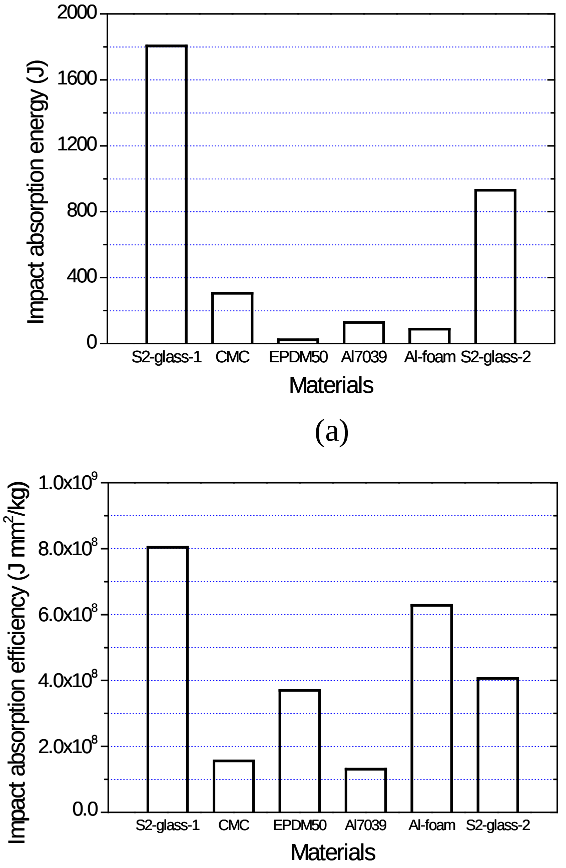


Fig. 2. Velocity variation of the projectile penetrating the target plate.

Fig. 2 shows the velocity variation of the projectile penetrating the target plate. The arrows in Fig. 2 indicate the impacting moment that the projectile reaches each layer. It is observed that penetrating velocity reduces at a fast pace. It seems that the kinetic energy also may be down as the projectile goes through the target plate. At first the projectile with an initial velocity of 5000 m/s penetrates the S2-glass layer and the residual velocity decreases to 4632 m/s passing through the S2-glass-1 layer. Immediately the projectile impacts on the CMC layer at a speed of 4632 m/s and goes through the CMC/EPDM interface layer at a speed of 3556 m/s. After this, the projectile penetrates aluminum, al-foam and S2-glass-2 layers in order and the final velocity of the projectile after complete penetration is 1310 m/s.

3.2 Impact Absorption Energy

Fig. 3(a) compares the energy absorption of each material under impact velocity of 5000 m/s. The impact absorbed energy can be calculated by using Eq. (7). It is found that the energy absorption of S2-glass is the largest whereas EPDM rubber is the smallest. As shown in Fig. 2, penetration velocity reduction rate in the S2-glass layer is larger than those in other layers. The reason for this is due to the stiffness discrepancies among the materials. The residual velocity of the projectile was influenced by the stress wave interactions, particularly by the amount of damage growth. Thus damage presence in each layer is predictable from the Fig. 2.



(a)

(b)

Fig. 3. Comparison of (a) impact absorption energy and (b) impact absorption efficiency of the hybrid composite structure.

Fig. 3(b) compares the impact absorption efficiency of each material. The impact absorption efficiency is defined as the absorption energy divided by area density of each material. Comparing Fig. 3(a) with

Fig. 3(b), the impact absorption efficiency of S2-glass is the largest and that of Al-foam has second largest value. Thus, it is confirmed that the roles of S2-glass and Al-foam are very significant in a view of impact absorption performance of multi-layer composite for protection structures.

3.3 Damage Modes

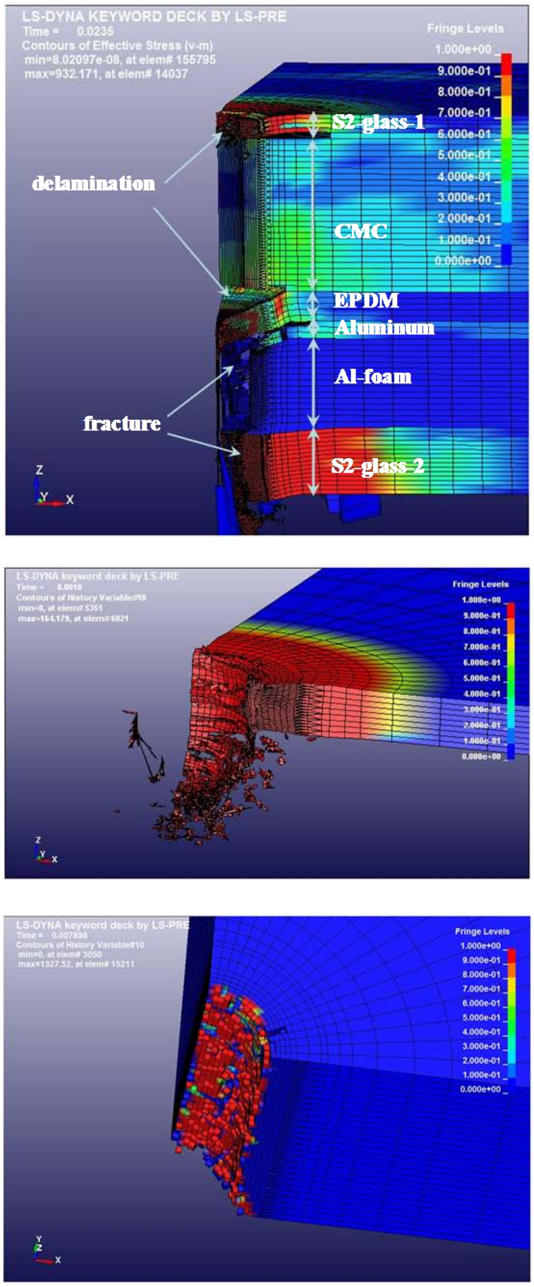


Fig. 4. Simulated damages showing (a) global fractures, (b) wide range of damages in the S2-glass layer and (c) brittle fractures in the CMC layer after the impact velocity of 5000 m/s.

Fig. 4(a) shows von-Mises stress contour plot and damage modes in each layer after complete penetration of the projectile. It is apparent that during complete penetration of the projectile localized fractures and damages occur in the vicinity of the impacting point along the target plate thickness. Particularly wide range of damages is found in the S2-glass layer as shown in Fig. 4(b). In addition, large delaminations between the S2-glass/CMC layers and between the CMC/EPDM rubber layers are found. It is widely accepted that in a typical composite system, the energy absorption mechanism during impact is the local deformation and fiber fracture. However, delamination has a major role in dissipating a large amount of energy in such multi-layer hybrid composite system. Fig. 4(c) shows the damage in the CMC layer. Unlike the damage mode in the S2-glass layer, damage zone is distributed only in the contact region that projectile penetrates. This may be due to the brittleness of CMC. From the results, a hybrid composite structure shows various types of damage modes according to the constituent materials.

4 Conclusions

In this study, the damage behavior and impact absorption energy in each layer of hybrid composite structures have been investigated based on the three dimensional finite element analyses. The results obtained are summarized as follows:

(1) By evaluating the impact absorption energy and impact absorption efficiency, S2-glass and Al-foam are superior to other materials.

(2) From the simulation, a wide range of damages and local delamination are occurred in S2-glass layer, whereas CMC and aluminum reveal a narrow band of damage only in the vicinity of the zone that the projectile penetrates.

(3) Delaminations between the CMC/EPDM rubber interlayer and between the S2-glass/CMC interlayer are found to be representative damage modes during high velocity impact.

(4) By applying progressive damage model to the LS-DYNA, it is possible to evaluate quantitatively the local fracture behavior of multi-layer composite structure under high velocity impact, particularly, by comparing

with the amount of impact absorption energy and efficiency.

Acknowledgment

This work was supported by the Research fund of Survivability Technology Defense Research Center of Agency for Defense Development of Korea (No. UD090090GD)

References

[1] Wu. E, Tsai. C, Chen. Y “Penetration into glass/epoxy composite laminates” *Journal of Composite Materials* , Vol. 28(18), pp.1783-1803, 1994.

[2] Goldsmith. W, Dharan. CKH, Chang. Hui “Quasi-static and ballistic perforation of carbon laminates” *International Journal of Solids and Structures*, Vol. 32(1), pp. 89-103, 1995.

[3] Lee. SWR, Sun. CT “Dynamic penetration of graphite/epoxy laminates impacted by a blunt ended projectile” *Composites Science and Technology*, Vol. 49, pp. 369-380, 1993.

[4] Zhu. G, Goldsmith. W, Dharan. CKH “Penetration of laminated kevlar by projectiles-I. Experimental investigation” *International Journal of Solids and Structures*, Vol. 29(4), pp. 399-420, 1992.

[5] Zh.u G, Goldsmith. W, Dharan. CKH “Penetration of laminated kevlar by projectiles- II. Analytical model” *International Journal of Solids and Structures*, Vol. 29(4), pp. 421-436, 1992.

[6] J. Leppänen “Experiments and numerical analyses of blast and fragment impacts on concrete” *International Journal of Impact Engineering*, Vol. 31, pp 843-860, 2005.

[7] GAO. Davies, X. Zhang “Impact damage prediction in carbon prediction composite structures” *International Journal of Impact Engineering*, Vol. 16, pp 149-170, 1995.

[8] MOW. Richardson, MJ. Wisheart “Review of low velocity impact properties of composite materials” *Composites Part A*, Vol. 27, pp 1123–1131, 1996.

[9] WJ. Cantwell, J. Morton “Impact perforation of carbon fiber reinforced plastic” *Composites Science and Technology*, Vol. 38, pp. 119-141, 1990.

[10] H. Mahfuz, Y. Zhu, et al. "Investigation of high-velocity impact on integral armor using finite element method" *International Journal of Impact Engineering*, Vol. 24, pp 203-217, 2000.

[11] Z. Hashin "Failure criteria for undirectional fiber composites" *Journal of Applied Mechanics*, Vol. 47, pp 329, 1980.

[12] LS-DYNA Theoretical Manual. Livermore Software Tech. Corp., 2003.

[13] A. Matzenmillar, J. Lubliner, RL. Taylor “A constitutive model for anisotropic damage in fiber composites” *Mechanics of Materials*, Vol. 20, pp. 125-152, 1995.

[14] Blatz. PJ, Ko. WL "Application of finite element theory to the deformation of rubbery materials" *Transection of Society of Rheology*, Vol. 6, pp 223-251, 1962.

[15] Deshpande. VS, Fleck. NA "Isotropic models for metallic foams" *Journal of the Mechanics and Physics of Solids*, Vol. 48, pp 1253-1283, 2000.

[16] Deka. LJ, Bartus. SD, Vaidya. UK "Damage evolution and energy absorption of E-glass/polypropylene laminates subjected to ballistic impact" *Journal of Materials Science*, Vol. 43, pp 4399-4410, 2008.