High Velocity Impact Experiment on Ti/CFRP/Ti Sandwich Structure

Huan Dajun（还大军）*, *Ding Bing*（丁冰），*Li Yong*（李勇），*Xiao Jun*（肖军）

College of Material Science and Technology，Nanjing University of Aeronautics and

Astronautics，Nanjing 210016，P. R. China

Abstract：Aircraft laminated composite components often suffer a variety of high velocity impacts with large quantity of energy，which usually affects aircraft behavior and would incur component damages，even disastrous consequences. Therefore，one investigates the impact resistance of a new type of composite material，Ti/CFRP/Ti sandwich structure，and launches impact tests by using an air gun test system. Then one acquires the critical breakthrough rate of the structure and analyzes the damages. The results show that the main failure mode of the front titanium sheet is shear plugging and brittle fracture of adhesive layer with fiber breakage，while the back titanium sheet is severely ripped. The rear damage is worse than the front one. Compared with traditional CFRP laminates，the critical breakthrough rate of Ti/CFRP/Ti sandwich structure is improved by 69.9% when suffered the impact of a bearing ball with 2 mm radius.

Key words：Ti/CFRP/Ti sandwich structure; high velocity impact; critical velocity; damage mode

CLC number：O324   **Document code**：A   **Article ID**：1005-1120(2015)01-0121-07

0 Introduction

Aircraft laminate composite structures often encounter various impacts，including low velocity impacts，e. g. missing a part during fabrication or dropping a tool on the structure during maintenance；and high velocity ones，like splashing sand while taking off and landing or bird-striking in flight[1-2]. Since composite structures are vulnerable to impacts，it is necessary to minimize impact damages on them.

The impact resistance of metals is much better than that of laminated composites. However，specific strength，specific modulus and fatigue resistance of most metals cannot compete with those of composites. Therefore，aramid fiber reinforced aluminum alloy laminates (ARALL)[3-4] and glass fiber reinforced aluminum alloy laminates (GLARE)[5-6] were developed to take full advantages of the two materials. The properties of fiber metal laminates (FMLs) are strongly related to the types of reinforced fiber and the met-al：(1) Carbon fiber′s unidirectional mechanical property is excellent，and its crack growth rate is very low；(2) Titanium alloy has no potential corrosion problem with carbon fiber，and can effectively improve shock resistance of the composite. Therefore，the research on high velocity impact damage for carbon fiber reinforced titanium alloy laminates is academically significant.

Most carbon fiber reinforced titanium alloy laminates are manufactured with polyether ether ketone (PEEK) currently. But the processing of PEEK prepreg is complicated；the price is extraordinarily high；and it lacks stickiness. Compared with thermoplastic materials，thermosetting materials will undoubtedly dominate the market for a long time. Therefore，for practical reason，the impact property of Ti/carbon-fiber-reinforced polymer (CFRP)/Ti sandwich structure with the adhesive of epoxy resin (Fig. 1) was investigated. Furthermore，to improve the impact resistance of structures，titanium is sticked on the margin of the composite fan blades as used

in GE90 engines, which have run safely for nearly 20 years with only three blades been substituted.
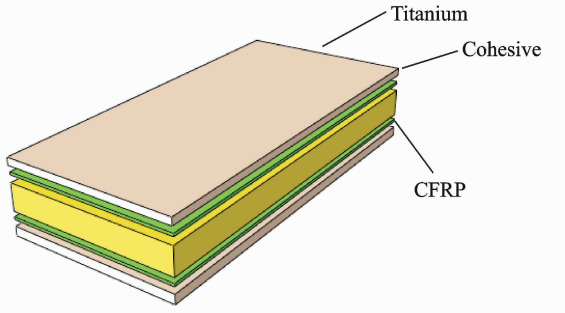

Fig. 1   Schematic figure of Ti/CFRP/Ti sandwich structure

Many researches to date have been conducted to study high velocity impact damage of single fiber composite materials or homogeneous metals[7-9], though few of them focus on the damage of FMLs. Nakatani et al.[10] studied the damage behavior of titanium/GFRP hybrid laminates subjected to low-velocity impacts. The observation and experimental results of the four-point bending tests indicated that internal damages and residual out-of-plane deformation of the GFRP layer were suppressed by the energy absorption via plastic deformation and crack initiation in the titanium layer on the side opposite the impact. Cortés et al.[11] revealed the energy-absorbing mechanisms of fiber metal laminates during impact. Low velocity impact testing had shown that the specific perforation energy of the CF/PEEK-based FMLs was similar to that offered by the CF/PEEK composite. The experimental evidence proved that the inclusion of strong titanium alloy plies could not improve the perforation resistance of FMLs. Extensive and detailed optical microscope study had shown that interfacial and inter laminar delaminations were the principal energy-absorbing mechanisms during low and high velocity impacts. Chen et al.[12-13] explored the high velocity impact damage modes of fiber metal composite target boards. The board presented a local failure mode. The damage modes of the front fiber were a shear fracture, while the back steel presented a petal-crack damage. When the positions of fiber and steel are switched, the damage modes of the back fiber become tension fracture while the front

steel experiences shear destruction damage. Experimental tests show that the energy absorption of the latter combination is superior.

We used air gun test system to carry out the impact tests for Ti/CFRP/Ti sandwich structure. The ply stacking sequence was $[0/90]_{3s}$. The critical velocity of passing through the structure was identified. The damage modes of both the pure CFRP and the Ti/CFRP/Ti sandwich structure were analyzed. And the damage area was analyzed to determine the impact resistance.

1   Experiments

An air gun test system developed by Nanjing University of Aeronautics and Astronautics was utilized to carry out the impact test. The system consisted of a foreign object damage launcher, a speedometer and a retaining protection device. The projectile with a 2 mm-radius bearing ball was used, and the initial speed was between 150 m/s and 400 m/s.

Here, Ti/CFRP/Ti sandwich structures were manufactured by bonding titanium alloy sheet (Ti-6Al-4V, 0.2 mm thick) to the cross-plied CFRP laminates, which were cured in advance by a hot press machine using CF/Epoxy prepreg (Hengshen Co., Ltd.) with epoxy adhesive (J-272, Institute of Petrochemistry Heilongjiang Academy of Sciences). The mechanical properties of the constituents obtained by static tensile tests were listed in Table 1.

The specimens included two types of target boards, i.e. Ti/CFRP/Ti sandwich structure and pure CFRP. The Ti/CFRP/Ti sandwich structure board consised of two outer layers of titanium sheets sandwiching a CFRP layer as the core which was 1.5 mm thick and comprised of twelve plies with a stacking sequence of $[0/90]_{3s}$. The 2 mm thick CFRP panel was made of 16 plies with alay-up sequence of $[0/90]_{4s}$. The square specimens (120 mm×120 mm) were clamped by a special fixture with an 80 mm-diameter central opening. The average thickness, the average weight, and the location of the neutral line in each laminate are shown in Table 2.

Table 1   Mechanical properties of constituents

Constituent	Thickness/mm	Density/(kg · m^{-3})	E/GPa	E_{11}/GPa	E_{22}/GPa	v	v_{12}	G_{12}/GPa	σ_b/MPa
Titanium	0.2	4 440	115			0.34			895
Adhesive	0.2	1 200	1.62			0.38			30
CFRP UD single ply	0.125	1 450		146.8	9.06		0.314	4.58	

Table 2   Properties of impact specimens

Specimen	Average thickness/mm	Average mass/g	Impact position
CFRP board	2.00	42.50	Center
Ti/CFRP/Ti sandwich structure board	2.00	63.20	Center

2   Experimental Results

2.1   Critical penetration velocity

Successive approximation is used to obtain the critical penetration velocities of the CFRP target and the Ti/CFRP/Ti sandwich structure. It is easy to identify whether the plates are punched or not by examining the damage of the plates. And the critical penetration velocity is defined by the incident velocity when the projectile drops on the baseboard of the fixture. The experimental data and damage status of the boards are shown in Table 3.

Table 3   Experimental data and damage status of penetration

No.	Board	Distance of laser tube/mm	Count time/ μs	Velocity/ (m · s^{-1})	Energy/ J	Damage status of board
1		60	341	176	4.0	No penetration
2		60	322	186	4.5	No penetration
3		60	308	195	4.9	No penetration
4	CFRP	60	276	217	6.1	Penetration
5	boards	60	291	206	5.5	Penetration
6		60	314	191	4.7	No penetration
7		60	300	200	5.2	No penetration
8		60	295	203	5.3	Penetration
9		60	231	260	8.8	No penetration
10		60	214	280	10.2	No penetration
11	Ti/CFRP/Ti	60	192	313	12.7	No penetration
12	sandwich	60	186	323	13.6	No penetration
13	structure	60	165	364	17.2	Penetration
14	boards	60	176	341	15.1	Penetration
15		60	178	337	14.8	No penetration
16		60	174	345	15.5	Penetration

As shown in Table 3，CFRP plates are penetrated three times，and fail five times. Apparently，when a projectile with a 4 mm-diameter bearing ball impacts a CFRP plate，the critical penetration velocity is 203 m/s. However，when a projectile with a 4 mm-diameter bearing ball impacts the Ti/CFRP/Ti plate，the critical penetration velocity is 341 m/s，increaing by 69.9% thanks to titanium alloy skin.

2.2   Analysis of damage modes

Many researchers have investigated the high velocity impact damage of pure CFRP laminates[14-17]. One compares the damage patterns between CFRP and Ti/CFRP/Ti sandwich structures. Back bulge，fibrous fracture，matrix cracking and delamination are the main damage modes of composite materials. Figs. 2—4 show the damage morphology of CFRP laminates im-
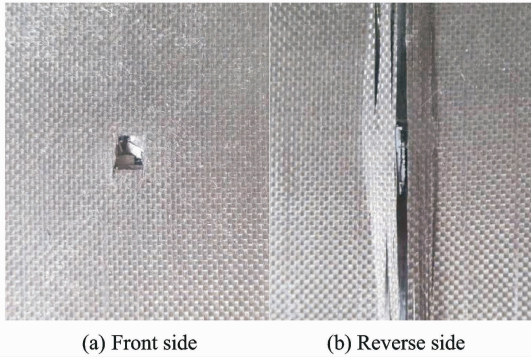
pacted by projectiles with different impact ener-
gy.

(a) Front side   (b) Reverse side

Fig. 2 Damage morphology of plate impacted by 4. 5 J
       energy

(a) Front side   (b) Reverse side
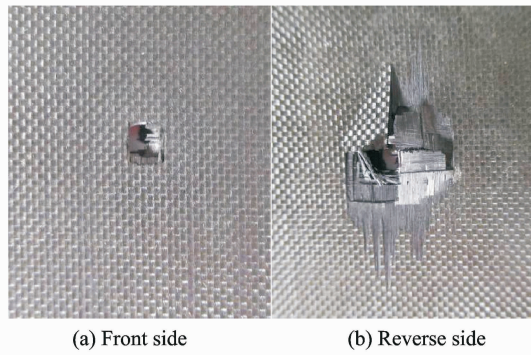
Fig. 3 Damage morphology of plate impacted by 5. 3 J
       energy

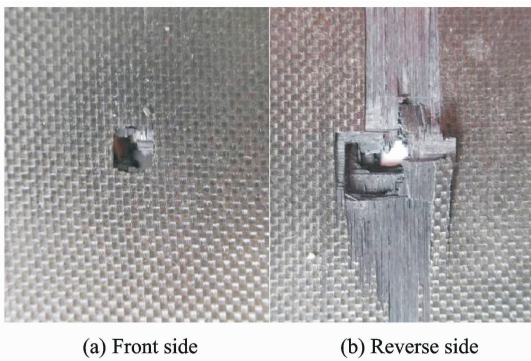(a) Front side   (b) Reverse side

Fig. 4 Damage morphology of plate impacted by 6. 1 J
       energy

It is seen that pure CFRP plate impacted
with 4. 5 J energy is not punched through. When
the impact energy increases to 5. 3 J, the CFRP
plate has a critical damage. And a projectile with
impact energy of 6. 1 J is powerful enough to
punch through the CFRP plate completely. Ap-

parently, although damage areas of the front side
of the three kinds of target boards are small, the
back ones are seriously damaged. The morpholo-
gy results show that the target boards on the
front present shear plugging failure and compres-
sion failure in different levels. The fiber of the
back mainly presents a tensile failure, and the
crack propagates along fiber direction. Further-
more, the back of the target boards is de-bonding
and the damage evolution tends to be perpendicu-
lar to fiber direction.

Ti/CFRP/Ti sandwich plates impacted by
high velocity projectiles display different failure
modes, and the damage morphologies of the Ti/
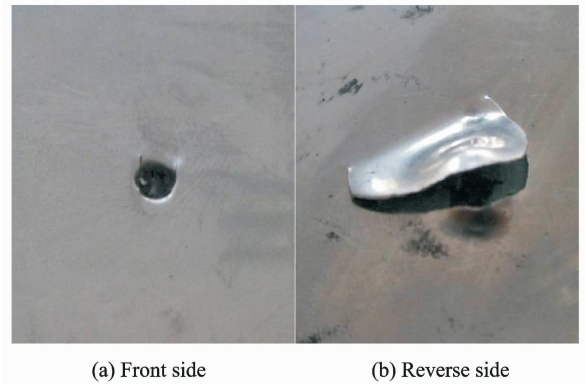CFRP/Ti sandwich structure plates are shown in
Figs. 5—7.

(a) Front side   (b) Reverse side

Fig. 5 Damage morphology of plate impacted by 12. 7
       J energy
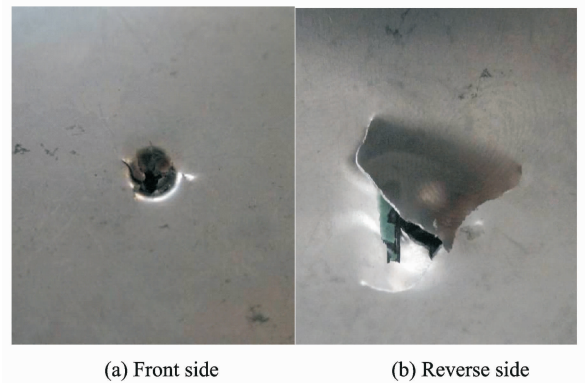

(a) Front side   (b) Reverse side

Fig. 6 Damage morphology of plate impacted by 15. 1
       J energy

Ti/CFRP/Ti sandwich structure plate im-
pacted by the energy of 12. 7 J is not punched
through. When the impact energy rises to 15. 1 J,
the target has critical failure. And a projectile
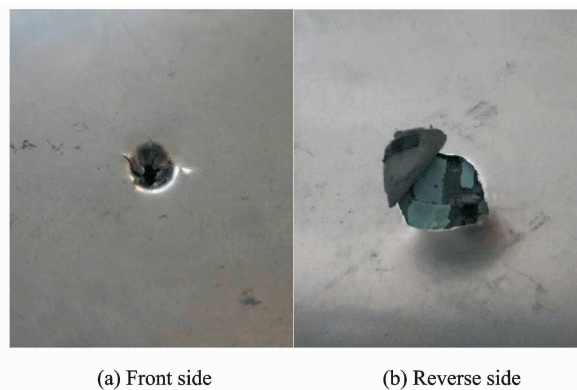
(a) Front side   (b) Reverse side

Fig. 7　Damage morphology of plate impacted by ener-
　　　gy of 17.2 J

with 17.2 J impact energy is powerful enough to punch the Ti/CFRP/Ti sandwich structure.

As shown in Figs. 6—7, the area near the impact contact point presents shear plugging and plastic deformation. This is because the front plate is directly impacted by the projectile, and the deformation of the front plate is restricted by the core composites. Therefore, the front sheets are inclined to exhibit shear plugging, and the damage region is limited within the impact zone. Thus, the response of the front titanium sheets is a local failure response.

Different from the small damage area of the front sheets, the rear titanium plates are damaged seriously. The main failure mode of the rear titanium plates is ripping failure. This is because the existence of the front plate and the core composites lowers the projectile speed, and the fiber attached to the surface of the projectile enlarges the contact area. When the impact energy is high, the shear plugging will appear. Therefore, the response of the rear titanium sheets is a local failure response.

Moreover, the rear plate impacts with energy of 12.7 J presents a tear failure of C shape, and the sheet is not destroyed. When the impact energy increases to 17.2 J, the rear sheet on the contact point is totally damaged. The bullet hole and the rattled adhesive can be examined breezily. The projectile residual speeds of the three cases after crossing the front plate and core composites are obviously different.

2.3　Analysis of damage area

The damage area of the target plates impacted by projectiles was detected by terminology, a nondestructive testing-infrared testing. Fig. 8 shows the damage infrared area of Ti/CFRP/Ti sandwiched target boards suffers by different impact energy. The highlight parts in the pictures represent the damaged areas.

(a) 0 J   (b) 8.8 J   (c) 10.2 J

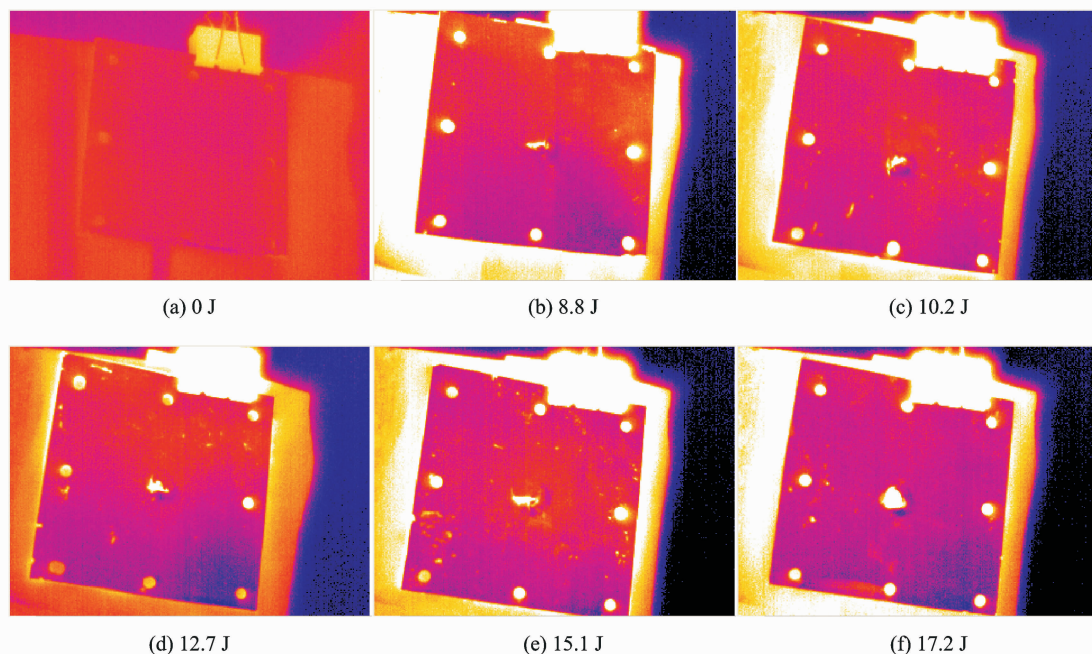(d) 12.7 J   (e) 15.1 J   (f) 17.2 J

Fig. 8　Infrared detection results of plates impacted with different energy

The Matlab platform was utilized to process the images: The image size was determined by pixels with the external contours as boundaries. The images were captured by a sequence of operations of image grabbing—image smoothing—image enforcing—edge detecting—image segmenting—binary denoising. Fig. 9 presents the damage area of Ti/CFRP/Ti sandwiched target boards suffer by different impact energies. We can find that the damage areas increase with the increase of impact energy. And the rising slope is abrupt at an initial stage, and then slows down gradually.
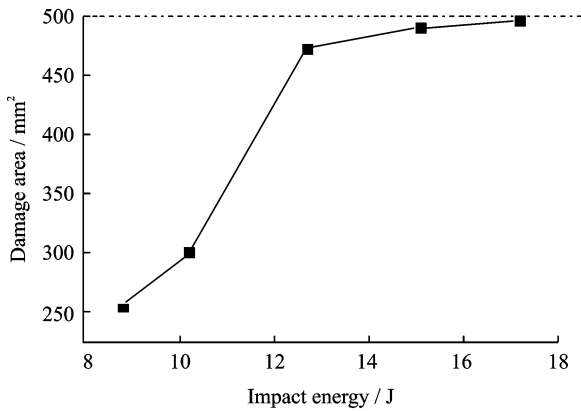

Fig. 9 Damage area of Ti/CFRP/Ti sandwich structure impacted with different energy

3 Conclusions

One launches a high velocity impact test on the Ti/CFRP/Ti sandwich target boards and pure CFRP plates, and draws the following conclusions:

(1) The critical penetration velocity of the 2 mm thick Ti/CFRP/Ti sandwich structure target boards impacted by ball bearings with 2 mm radius is 341 m/s, while that of the 2 mm thick pure CFRP target boards is 203 m/s. The critical breakthrough speed of Ti/CFRP/Ti sandwich structure is increased by nearly 70% thanks to the thin titanium alloy sheets.

(2) The damage mode of the front titanium sheets of the Ti/CFRP/Ti sandwich structure is shear plugging and plastic deformation, and that

of the reverse sheets is a ripping failure, while the back damage of the pure CFRP target boards is serious: the fiber on the back face sheet is uplifted, and the stratification along the fiber direction is slighter.

(3) The results show that the damage area of target boards increases with the growth of impact energy. The damage area stops enlarging when the target board is punched through. And the damage area is close to a fixed value.

Acknowledgement

References:

[1] Jorge L, Ramón Z, Carlos N U. Experimental and numerical analysis of normal and oblique ballistic impacts on thin carbon/epoxy woven laminates [J]. Composites Part A: Applied Science and Manufacturing, 2008, 39(2):374-387.

[2] Zhang Aying, Zhang Dongxing, Li Dihong, et al. Impact damage of carbon fiber reinforced epoxy laminates[J]. Aerospace Materials and Technology, 2010 (5):1-3.

[3] Zhang Guangcheng, He Qingkong, Yang Yufang. Study on the mechanical properties of ARALL/aluminium alloy laminates [J]. Fiber Composites, 2001,19(4):19-21.

[4] Marissen R. Fatigue crack growth in ARALL:A hybrid aluminium-aramid composite material, crack growth mechanisms and quantitative predictions of the crack growthrate[D]. Delft: Delft University of Technology, 1988.

[5] Wang Shiming, Wu Zhongqing, Zhang Zhengjun, et al. Research of glare laminates performance comprehensive evaluation applied to large aircraft [J]. Stanford Materials, 2010, 17(9):88-95.

[6] Vogelesang L B. Fiber metal laminates—The development of a new family of hybrid materials[C]// Proceedings ICAF Sr-yarposium. Lucern: [s. n.], 2003.

[7] Nunes L M,Paciornik S, d′Almeida J R M. Evaluation of the damaged area of glass-fiber-reinforced epoxy-matrix composite materials submitted to ballistic impacts[J]. Composites Science and Technology,

2004,64(7/8):945-954.

［8］　da Silva J E L，Paciornik S，d′Almeida J R M. Eval-
　　　uation of the effect of the ballistic damaged area on
　　　the redusial impact strength and tensile stiffness of
　　　glass-fabric composite materials ［ J ］. Composites
　　　Structures，2004,4(1):123-127.

［9］　Fan Jinjuan，Zhao Xu，Chen Xiaoquan. Compression
　　　damage characteristics of composite laminates after
　　　low velocity impact[J]. Failure Analysis and Preven-
　　　tion，2006,1(2):33-35.

［10］　Nakatani H，Tatsuro K，Osaka K，et al. Damage
　　　characterization of titanium/GFRP hybrid laminates
　　　subjected to low-velocity impact[J]. Composites Part
　　　A: Applied Science and Manufacturing，2011,42(7):
　　　772-781.

［11］　Cortés P，Cantwell W J. The impact properties of
　　　high temperature fiber metal laminates[J]. Journal of
　　　Composite Materials，2007,41(5):613-632.

［12］　Chen Changhai，Zhu Xi，Hou Hailiang，et al. An
　　　experimental research on low-velocity projectiles per-
　　　forating fiber and metal combined thin targets ［J］.
　　　Acta Armamentarii，2012,33(12):1473-1479.

［13］　Chen Changhai，Zhu Xi，Hou Hailiang，et al. Influ-
　　　ence of structure configuration on perforation-resist-
　　　ance of a warship topside composite armor system
　　　［J］. Journal of Vibartion and Shock，2013,32(14):
　　　58-63.

［14］　Lee S W R，Sun C T. Dynamic penetration of graph-
　　　ite/epoxy laminates impacted by a blunt-ended pro-
　　　jectile ［J］. Composites Science and Technology，
　　　1993,49(4):369-380.

［15］　Ellert E P，Cimpoeru S J，Woodward R L. A study
　　　of the effect of target thickness on the ballisticperfo-
　　　ration of glass-fibre-reinforced plastic composites[J].
　　　International Journal of Impact Engineering，2000,24
　　　(5):445-456.

［16］　Jin Ziming，Sui Jinling，Zhang Hanying，et al. Study
　　　of ballistic performance and research process of fiber
　　　reinforced composite bulletproof plate ［J］. Glass Fi-
　　　ber Reinforced Plastic，2001,(1):1-6.

［17］　Chen Xiaoquan，Kou Changhe，Li Zhengneng. Study
　　　on damage of composite honeycomb core sandwich
　　　panels under low velocity impact[J]. Acta Materiae
　　　Compositae Sinica，1998,15(3):124-128.

（Executive editor: Zhang Tong）