HYPER VELOCITY IMPACT STUDIES SIMULATING DEBRIS COLLISION ON COMPOSITES MATERIAL

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ABSTRACT

This paper describes the hyper velocity impact test to composite material. The composite material is already adopted as a structural material of many space craft. On the other hand, there is little debris collision data to composites material. Then, the hyper velocity collision experiment to the board of composite material was conducted by making board thickness, diameter and velocity of projectile into parameter. While the fracture situation by collision, internal damage, and residual compression strength are measured, since we acquired new knowledge, we report the relation between collision energy and damaged area.

1. INTRODUCTION

Composite material has various advantages (high specific elasticity and strength, possibility of weight reduction for structure etc.), so it has been considered as the most prospective structural material for aerospace use from early time of CFRP was invented. Owing to advancement of research and development on Carbon Fiber Reinforced Plastic (CFRP), these materials have been used as materials for secondary structure of spacecraft for these years. But there are some problems still left to use the composite material for the primary structure of spacecraft in the space field due to the harsh environment, such as deterioration and meltdown by debris collision during long duration of operation. At the moment, 9000 debris of 10 cm or larger are actually catalogued, and 40 million of sub-mm or larger are believed to exist around the earth orbit. In addition average impact velocity is said to be about 8 km/s in LEO and 200 m/s in GEO. They will become a serious threat to the structure of spacecraft.

The purpose of this study is to collect and evaluate the hypervelocity impact data on CFRP. This research has been aiming to make it clear the damage mechanisms and derive the relation between debris collision energy and damaged area of CFRP plate (especially related to internal delamination). Authors believe this approach will make it possible to derive specific damage equations from quantitatively co-relate the properties of both projectile and CFRP plates (e.g. projectile velocity and mass, target plate mechanical properties, stacking sequence of laminate, number of layers) by measuring a damage (hole size, penetration or not, internal delamination area, residual strength of plate). When adopting the CFRP as material for structural component, the design values should be decided considering the knock down factors for strength. The most dominated factor for strength reduction is compression strength after impact (CAI). Therefore, this property should be acquired carefully. And the delamination occurred by impact is the major reason of strength reduction, so the area of delamination is most important parameter for guessing characterise of CFRP laminated material.
This study will provide a basic data for relations between projectile energy and delamintion area of CFRP, and will discuss the ballistic performance and the protection capability of CFRP plate from CAI test appraisal method.

2. TEST PROCEDURE

The tests were conducted as following procedure.

Collision test to CFRP plates;
Executed by PadovaUniversity-CISAS, using the two stage light-gas gun.

Nondestructive test after impact;
Executed by JAXA, using the ultrasonic inspection device and X-ray scanning devices for detecting the internal damage and measuring size.

Compression test;
Executed by JAXA, using the compression test device for measuring the residual strength after impact.

Though there are many test specification of compression test, a SACMA standard (SRM2R-94) was selected for this research. This standard is widely adopted for evaluating and selecting the structural composite material of aircraft as general standard. The material of CFRP target plate is high strength fibers and modified toughed epoxy composite (IM600/133; TOHO TENAX, JAPAN)
According a SACMA standard, test specimens (CFRP plate) were prepared as sizing with 152.4*101.6 [mm] shown in Fig.1. Plate thickness was settled in three types and stacking sequence of each laminar is as sown in Table 1.

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2.1 COLLISION TEST TO CFRP PLATE

The experiments were conducted by shooting on each type of target with aluminium sphere projectiles of 0.8mm, 1.5 mm and 2.5mm diameter, at 0° impact angle, around speed 2-4-5 km/s (including 10% error), at room temperature, in the 70mbr vacuum chamber. The total number of tests was 27 shots. These collision experiments were conducted at the Hypervelocity Impact Facility in 'Centre of Studies and Activities for Space CISAS "G. Colombo" - University of Padova', by using the two-stage light-gas gun (shown in Fig.2).

The test specification is shown in Table.2. This two stage light-gas gun has an capability of shooting out the projectile 2~5.5km/s in speed, 0.4~3mm in projectile diameter and 100mg in mass using sabot. Fig.3 shows the fixation of CFRP target plate in the vacuum chamber of light-gas gun facility.

Fig.4 is the shadowgraph of the target plate shot by 2.71J/mm in kinetic energy and the CFRP plate was not penetrated. A debris cloud can not be observed by impact, but both surface layers of CFRP fiber was greatly flipped over in spite of the non-penetrated. There is a possibility that this phenomenon was not caused by the spall fracture. The mechanical property of carbon fibers is a high stiffness but is a low fracture strain than the metals. Therefore it can be supposed that the surface layer of CFRP plate has not enough strength up to hold the spall fracture occurrence limit. The fiber was cut down before up to spall limit and finally the surface layer were flipped over. Such phenomenon isn't seen with the metal material, and this destruction phenomenon is one of the characteristic of composite material.

Fig.5 is the shadowgraph of the target plate shot by 46.77J/mm in kinetic energy, and in this case, the plate was penetrated. It can be said when larger energy is given to CFRP target, the debris cloud occurred and it can be clearly observed.

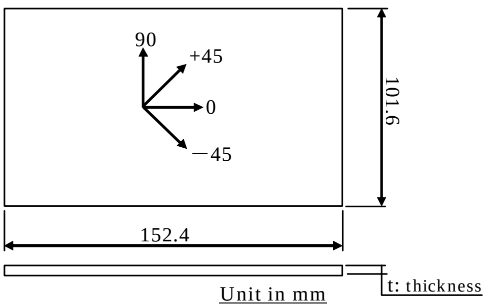

Fig.1 Target plate plan view

Table 1 Stacking sequence

Ply	Thickness	Laminated construction
16	2,2(mm)	[45/0/-45/90/90/-45/0/45]sim.
24	3.3(mm)	[45/0/-45/90/90/-45/0/45/45/0/-45/90]sim.
32	4.3(mm)	[45/0/-45/90/90/-45/0/45]2sim.

2.2 NONDESTRUCTIVE TEST

The delamination area which had occured inside the CFRP target plate by projectile collision was measured with the nondestructive test device. Ultrasonic flaw detector (SD5400R: Krautkramer Japan co., ltd.) was used with one probe fully immersion reflection method. The delamination shape is remarkably different from the case of low velocity impact experiment as shown in Fig.6. The right side of Fig.6 is the delamination shape in case of the hyper velocity impact energy done by this study, and the left side is in case of the low impact energy usually done for CAI test. The left image in Fig.6 is the ultrasonic image of the internal damage when damaged by falling weight impact. Both image have the inter-laminar delamination in fan pattern shape. Additionally, the right image of Fig.6 has greatly progressed damage in the 45 degrees direction. It is

Fig.2 Two stage light gas gun
(Pictured by CISAS)

Table 2. Test condition

Target	Ply	layer	16	24	32
Projectile	diameter	mm	0.8	1.5	2.3
	velocity	m/sec.	2000	4000	5000

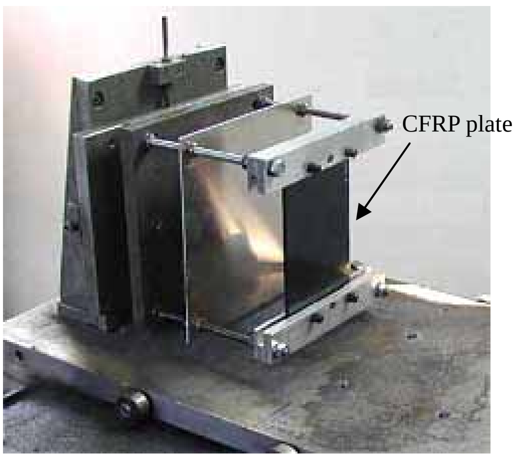

Fig. 3 Attachment of CFRP plate in vacuum chamber

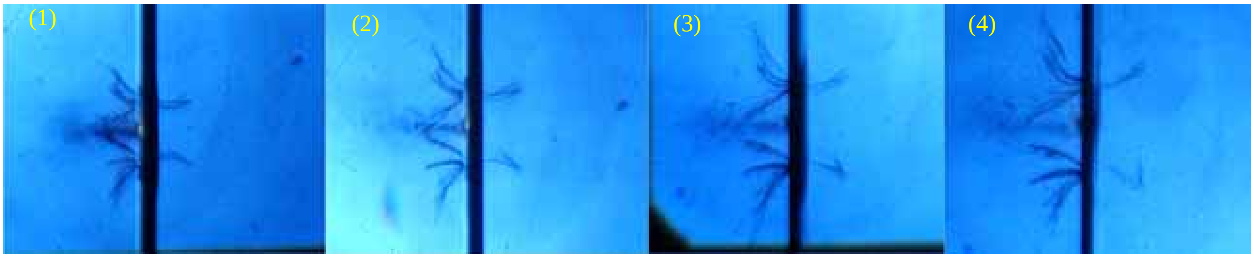

Fig.4 Hypervelocity impact on CFRP 24ply, dia.;1.5mm, Velocity; 1985m/sec.

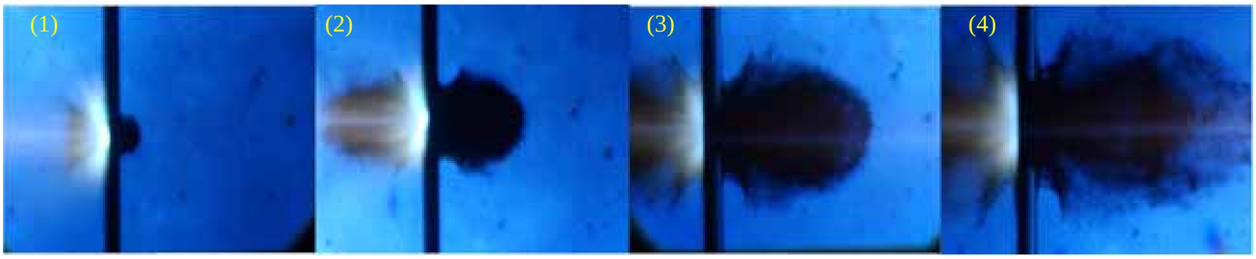

Fig.5 Hypervelocity impact on CFRP 32ply, dia.;2.3mm, Velocity; 5018m/sec.

believed that this cross damage was made in the surface layer by a shock wave of the hypervelocity impact. Because it could be observed that surface ply of both side were peeled out along the surface fiber direction (+45 degree) slightly larger size of projectile diameter. Such phenomenon does not appear in the examination of low velocity impact.

The image of Fig.7 is non-penetrated case and the same sample as Fig.4. Fig.8 is penetrated case and the same sample as Fig.5. Projectile was shot from "*front*" side, and went out from "*back*" side. After both sides had been scanned, then the damage area was measured by enclosing the damaged area shown in Fig.9.

It was observed that the *back* side damage area was

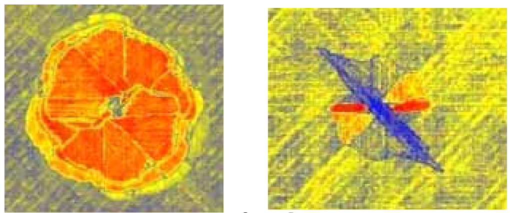

Fig.6 fan shape

slightly larger than the *front* side damaged area in some cases. However as for this phenomenon, the difference of damaged area between *front* side and *back* side did not appear so much when the plate was penetrated but it appeared remarkably when it was non-penetrated.

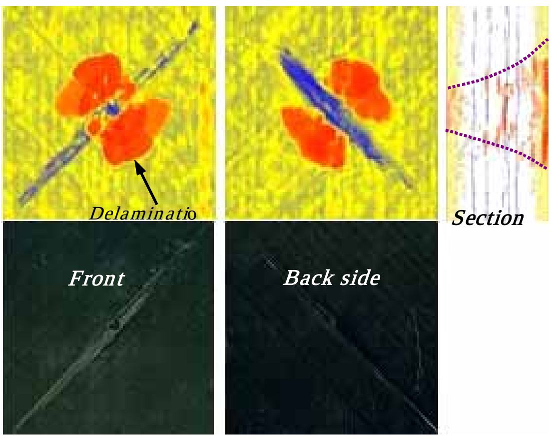

Fig.7 Ultrasound image

24ply (3.3mm), dia.:1.5mm, velocity:1985m/sec.

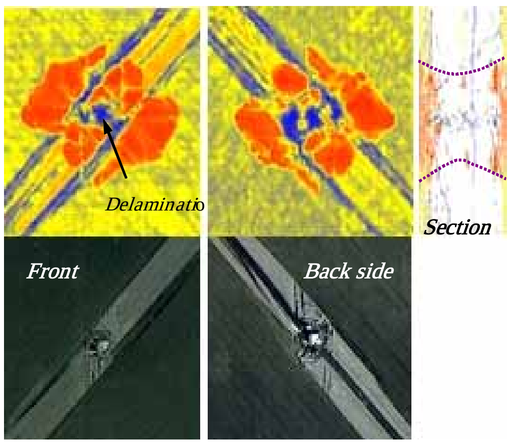

Fig8 Ultrasound image

32ply(4.3mm), dia.:2.3mm, velocity:5018m/sec.

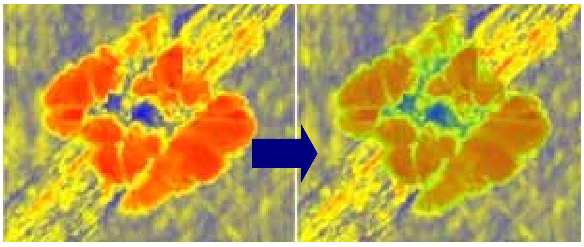

Fig.9 Image measurement of damaged area
(Surrounded by green line)

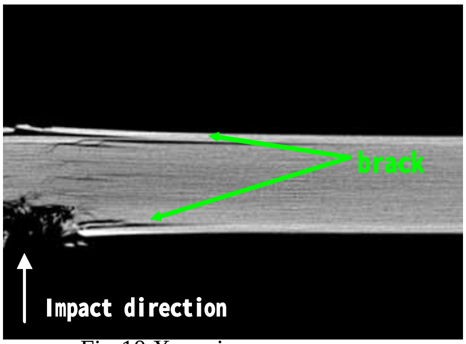

Fig.10 X-ray image
(24ply, ϕ1.5mm, 1985m/s)

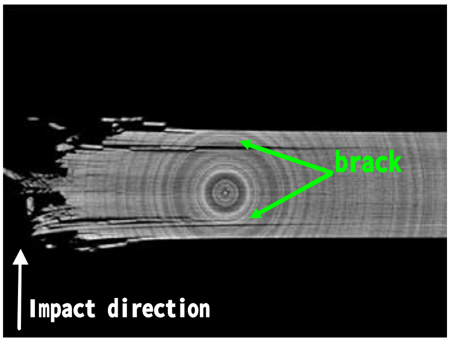

Fig.11 X-ray image
(32ply, ϕ2.3mm, 5018m/s)

Fig.10 and Fig.11 are pictures taken by the X-rays CT scan to investigate the damage minutely in the plate thickness direction. Then, we found out that near on the surface layer of the plate was peeled out greatly. It could understand that damage is greatly occurred near to the surface layer from ultrasonic images show in Fig.7 and Fig.8 as well. It is observed that the delamination did not extend internally, but the fiber of the surface ply has only peeled off in both *front* and *back* sides as show in Fig.10.

Fig.12 shows the relation between the damage area and impact energy by processing the images according to the definition of damaged area in Fig.9. A horizontal axis is the impact energy, and a vertical axis is the measured damage area.

It is understood that the characteristic is different between the case of non-penetration and the case of penetration. There are little relations to the plate thickness in non-penetration case, and most of values gather on one line. However, in penetration case, the damaged area became larger when the target plate thickness became thicker, even though impact energy was same for each plate thickness. It can be understood that thicker plate could absorb more energy than thin plate even though the same impact energy was given.

Fig.13 is the chart that normalized the both axis by the plate thickness. There is some possibility of including the observing and definition error by observer, so the result was arranged by both logarithms in Fig.13. As a consequence, the values are divided into almost on two lines of non-penetration and penetration.

2.3 COMPRESSION TEST

Instron1128 (capacity: 50ton) was used for measuring the residual strength on damaged CFRP plates. They were compressed at the speed of 1mm/sec according to the SACMA standard. Totally four strain gauges (two gages for both side of plate) were pasted on each test plate following the standard, and data were acquired in the right time. Moreover, the CCD Laser-Displacement Sensor was used to verify the beginning of buckling.

The destruction mode on 16ply targets were different from 24ply and 32ply plate when a compression test was performed, because the plate thickness of 16ply was very thin and a buckling was occurred before coming up to compression strength. Therefore, we discussed only with the residual stress of 24ply and 32ply plate in Fig.14.

Impact energy is normalized by plate thickness as same way as usual CAI test. In non-penetration case, different thickness plate has different residual strength. However, in penetration case, different thickness plate has same residual strength and they are on one line. It has been understood that there is a linear relation between the impact energy and residual strength in penetration case.

While conducting the compression test, the little sound of crack occurring could be heard continuously from half of the maximum load, and also surface layer of both sides were gradually yielding to out plane side. This is a phenomenon could not seen usually in the low velocity impact test as usual CAI examination. There is some possibility that many minute cracks have made inside the CFRP target by the stress wave when hypervelocity impact occurred.

3. NUMERICAL SIMULATION

In order to investigate the fibers are exfoliated greatly near the plate surface, the simulation was performed using AUTODYN. The model of projectile and plate were prepared for the SPH analysis. Fig.15 shows a result of numerical simulation to a time series from (1) to (4). Near the surface by the side of a collision, figure (2) shows that tensile strain of out plane direction has reached the fracture limit. This means that delamination has progressed near front side and Mode I fracture occurred near *back* side. By figure (3) and (4), it can be understood that delamination occurred and progressed near *back* side. These analysis results are effective in explanation of the phenomenon that actually occurred.

4. SUMMARY

A hypervelocity impact simulating debris collision on composite material was conducted, and the dynamic destructive situation was caught with the high-speed camera. The non-destructive test results showed the certain relation between damaged area and collision energy. When these data are normalized by plate thickness and plotted on log-log graph, the relations are more clearly shown. They are concentrated on two lines, which are non-penetration and penetration. The compression test results showed the relation between collision energy and residual strength. These relations are different from that of between damaged area and energy. When it is not penetrated, the residual strength depends on plate thickness. On the other hand, when it is penetrated, the relation is converged on one line. In addition, many minute cracks may exist inside the laminar by hypervelocity impact and it must affect the residual strength reduction. The numerical simulation about the fiber fracture mechanism of the back side, which was not explained correctly from the high-speed camera, or static examination has grasped it qualitatively.

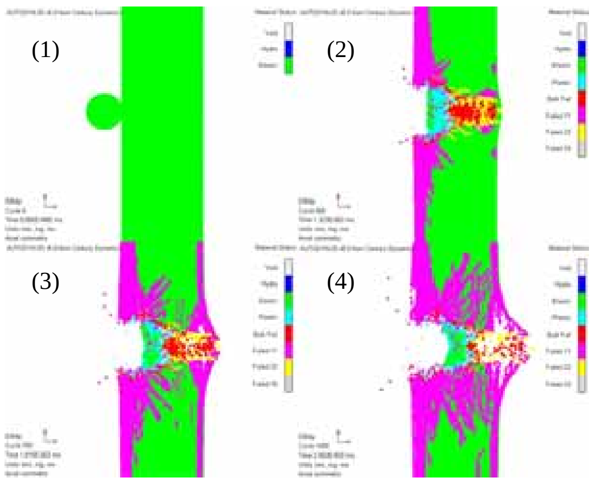

Fig.15 AUTODYN simulation results

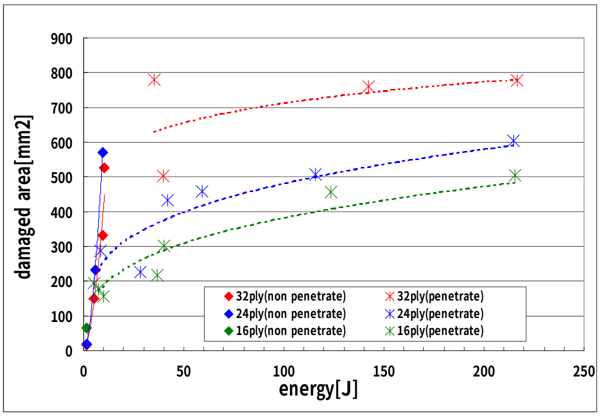

Fig.12 Relation between damaged area and Impact energy

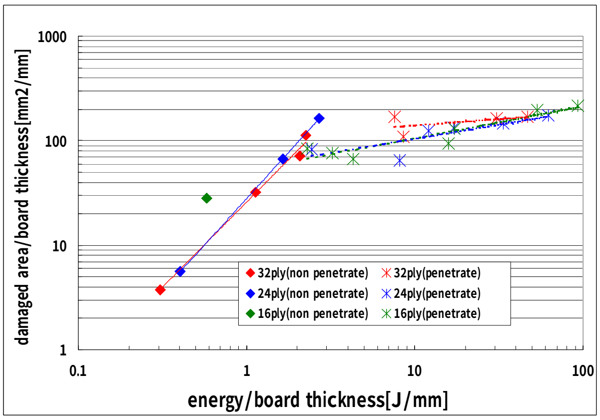

Fig.13 Relation between damaged area / plate thickness and impact energy / plate thickness (log-log)

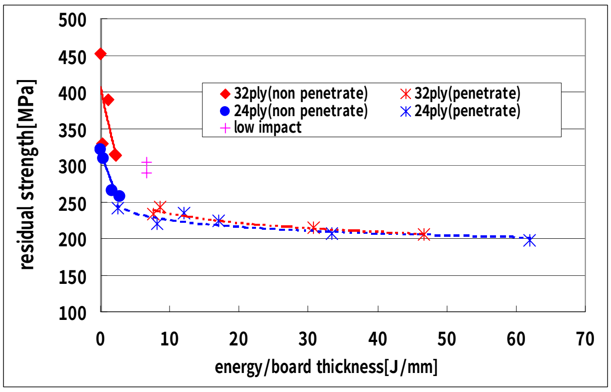

Fig.14 Relation between residual strength and impact energy / plate thickness

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