# BEHAVIOR OF CARBON-EPOXY COMPOSITE FOR HYPERVELOCITY IMPACTS AT OBLIQUE ANGLE ON SPACECRAFT IN LOW EARTH ORBIT ENVIRONMENT

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## Abstract

In this study, the hypervelocity impact on the spacecraft composite wall, made with stacking sequence of $[(0/\pm45/90)_2]_s$ at oblique angle is being studied, analyzed and compared with the existing data for normal impacts both for Aluminium alloys and Composites. Initially the composite spacecraft wall using CU125NS prepreg was manufactured by using autoclave and then exposed to LEO space environment with UV light, Atomic Oxygen, high vacuum and thermal cycling. In the end the composite spacecraft wall was impacted by Aluminium Al2017 projectile having 5.56mm in diameter using light gas gun for the space debris attack simulation. Because of LEO space environment and its synergistic effects, along with degradation in other properties, mass loss in the composite was found around 0.40%. The energy absorption because of space debris attack on wall was 35% more in the velocity range of 1 km/sec with that of normal impacts on Composite and Aluminuim plates. Concluding all, if spacecraft composite shielding system is made in such a way that impacts are oblique, than it can be protected from debris attack more effectively and efficiently.

**Keywords**: HVI, Spacecraft, Carbon-epoxy Composite, Space Debris, LS-DYNA

## 1 Introduction

Hypervelocity impacts (HVI) of space debris lead to the destruction of spacecraft subsystem functionality and sometimes spacecraft itself. This is more devastating especially in low Earth orbit (LEO) environment. By low Earth orbit means ranging from 200km to 1400km above from the surface of Earth. Till date only 6% population of low Earth orbit are operational spacecraft, while rest are more or less lie in the category of space junk. Approximately 19,000 objects are greater the 10cm, while in between 1 to 10cm diameter objects population is around 500,000 in numbers with major concentrations around 800-850km[1, 2]. For this the spacecraft has to be protected from the debris attack and it is usually done by providing the perfect shielding system. The philosophy adopted by NASA till date is to avoid the big size debris and protect against the small junk. Evidence from the experimental study of space debris by NASA shows the impacts of debris on the spacecraft are only 10~20% normal to the surface while rest are at oblique angles. For this shielding of spacecraft is of important concern in low Earth orbit missions. In this paper the impact on the first wall of spacecraft made of carbon-epoxy is being studied. Afterwards the results of this analysis being compared with the cases of normal impact of space debris on Composite and Aluminium walls. Aluminuim alloy is tested as it's still used widely in space industry.

### 1.1 Difference between the propagation of Normal and oblique impact on spacecraft

The impact on spacecraft from space debris is of two kinds as shown in Figure 1. In case of normal impact there is only one cloud generated which having the remains of space debris and spacecraft wall with very few amount of Ejecta cloud which move in opposite direction to incoming debris. While if the comparison is made with oblique impact, there are three clouds usually formed namely: Normal debris cloud, In-line debris cloud and Ricochet debris cloud [3]. Ricochet cloud mainly consists of space debris remains while In-line and Normal clouds comprise of both debris and wall fragments. The composition and constituents of different debris clouds totally depends on the angle of attack of space debris.

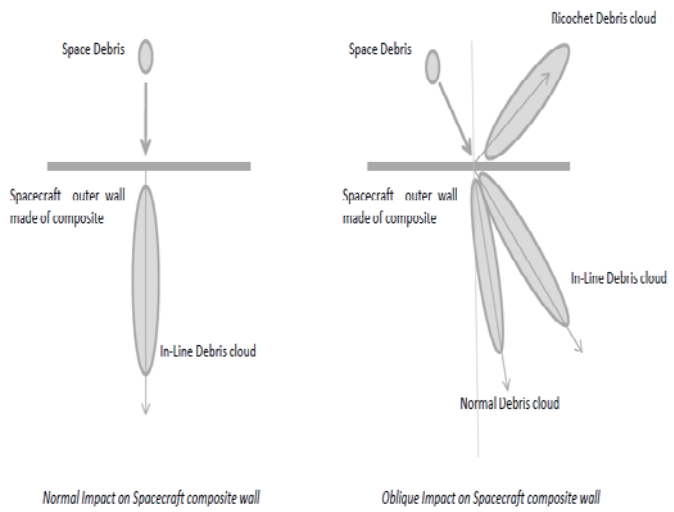


*Figure 1 : Difference between Normal and oblique impact.*

### 1.2 LS-DYNA

LS DYNA is general purpose transient dynamic finite element analysis software used for real world problems [4] like hypervelocity impacts and used here for the validation of experimental results.

In this research LS-DYNA is used to validate the initial results for Aluminium plates to get the differences between experimental and numerical profiles for the Aluminium projectile impacts.

## 2 Procedure & Experimental setup

Till date, different shielding concepts has been adopted and tested ranging from simple whipple shield to mesh double bumper shield but all those includes metal composition along with Kevlar fabric and Nextel ceramic [5]. But the potential of Carbon-epoxy composites being less in weight and better in strength then Aluminium still has to be exploited. In this research, Carbon-epoxy composite, the first part of Hybrid composite shielding (HCS), and its behavior is tested and validated for oblique angle of attack.

Firstly, the composite laminate was made with 16 layers of stacking sequences $[(0/\pm45/90)_2]_s$. The prepreg were provided by Hankuk Fiber Glass Corporation (South Korea) where it manufactured by a hot-melting process. The thickness of laminate was found to be 1.748mm. The profile adopted in autoclave for the curing is shown in the Figure 2.

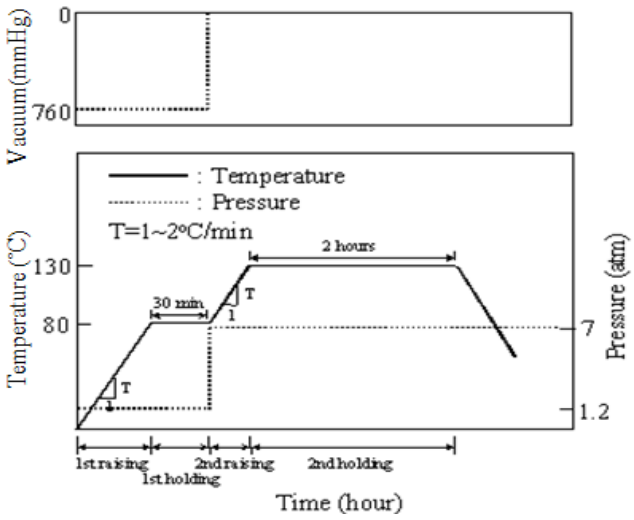


*Figure 2 : Autoclave working temperature and pressure profile.*

After manufacturing of the specimen, the specimen was exposed to Low Earth Orbit environment by using LEO Space Environment Simulation Facility (LEO-SESF). The schematic of the LEO-SESF is shown in Figure 3. In the simulation chamber the specimen is exposed to Ultraviolet (UV) radiation having wavelength less then 200nm, high vacuum on the order of $10^{-6}$ Torr, Atomic oxygen (AO) and

14 thermal cycles ranging from 100°C to -70°C. The specimen is exposed in LEO-SESF to encounter the real time effects of LEO space environment which were fatigue cracking because of thermal cycling, AO lead to surface erosion, mass loss with structural modification because of out-gassing due to high vacuum, material properties modification such as C-C breakage due to UV radiation exposure and thermal cycling to encounter sun facing and shadow scenarios while spacecraft is in LEO regions [6]. The specimen was placed on the copper plate as shown in Figure 3 by means of Aluminuim tape to make a proper thermal contact for simulating the shadowing effect temperature. Only 14 thermal cycling were done because most of the failures if occurred due to thermal cycling usually happened in first few cycles [7].

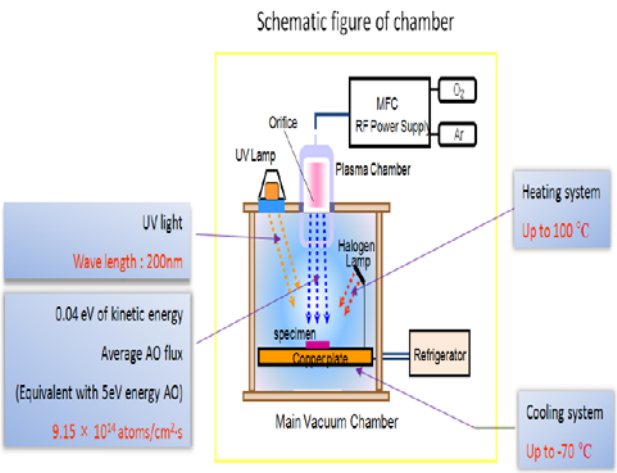


*Figure 3:LEO Environment Simulating Chamber[8].*

In the end, two stage light gas gun (LGG), using Helium and Argon gas, facility is used to get the experimental profile, energy absorption and behavior of composite. In this, the angles of attack were kept oblique by keeping the plate (Spacecraft) at inclined angle (45° degrees) with respect to Aluminum (Al 2017) projectile (debris) 5.56mm in diameter as shown in Figure 1. For HVI testing of the spacecraft structure, the philosophy adopted, is the same as done for ballistic limit. The specimen were tested under velocity range of 1km/sec and then validated by commercially available software. However, the debris velocity range in low Earth orbit region is higher than this. The reference used here is the ballistic limit curve for Whipple shield [3].

## 3 Results

In this research the carbon-epoxy composite spacecraft wall having 16 layers is made and then exposed to LEO environment with 100nm UV light, high vacuum, AO attack and 14 thermal cycling to properly simulate the space environmental conditions to test. Because of high vacuum, out-gassing phenomenon was observed resulting in the mass loss. UV attack on the composite plate might affect its properties, but found to be negligible. AO attack degrades the surface and lastly the debris attack was simulated by using LGG. During experimentation frictional and acoustic energy were assumed to be negligible.

### *3.1 Total Mass Loss (TML)*

The exposure to space environment caused the loss in mass properties along its weight. It was found by using the below expression

$$\%TML = \frac{M_I - M_f}{M_I} * 100$$

Where $M_I$ is the initial and $M_f$ is the final mass

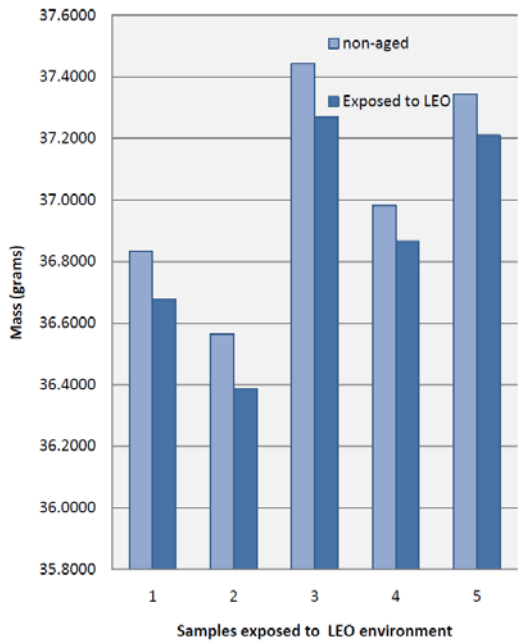


*Figure 4 : Total Mass Loss after exposed to Low Earth Orbit environment.*

which we get after exposing the specimen to LEO environment. The Figure 4 showed the mass loss in composite while exposed *to* high vacuum available in LEO environment. On average there was a 0.40% loss in weight was recorded while exposed to space.

### 3.2 Energy absorption at Oblique angle

When the space debris hit the spacecraft, it always transfers energy to the later one. The energy absorbed by the spacecraft protection system also depends upon at which angle, debris hit the spacecraft. To simulate the exact scenario, Al (Al-2017) projectile, with known properties, was used in this research to work as space debris because most of the debris in space, are the remains of spacecraft which were made of Al-2017.

The results for impacts at oblique angle of projectile with laminate of $[(0/\pm45/90)_2]_s$ are given below in the form of Figure 6 and 7. The oblique angle impacts lead to multi-axial loading on composite wall and showing complex behavior than that of normal angle case. An example of that mechanism can be observed in debris cloud propagation as shown in Figure 1. The energy absorption for the laminate is calculated by using simple equation

$$\boldsymbol{E_{absr} = \frac{1}{2}\, m\,(v_1^2 - v_2^2) - E_{air}}$$

Where $\mathbf{E_{absr}}$ is the energy absorbed by the laminate while $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$ are the velocities of projectile before and after the impact and $\boldsymbol{E_{air}}$ is the energy absorbed by air. The impact of debris was done in the air presence and air drag was found. The values for this has already been calculated elsewhere [9] and it's just used here.

$$\boldsymbol{E_{air} = 0.0183\, v - 2.8908}$$

Where V is the velocity and it was compensated for both before and after the impact. In Figure 5, the non-aged composite specimen is used to observe the impacted pattern. It's been obvious that energy absorbed by the non aged composite laminate is of average 20 Joules more and its keep on with the increase of the velocity of impacting projectile. They showed the dominancy of oblique angle impact energy absorption in comparison to normal impact. The data for Normal impacts is being used from published work [9].

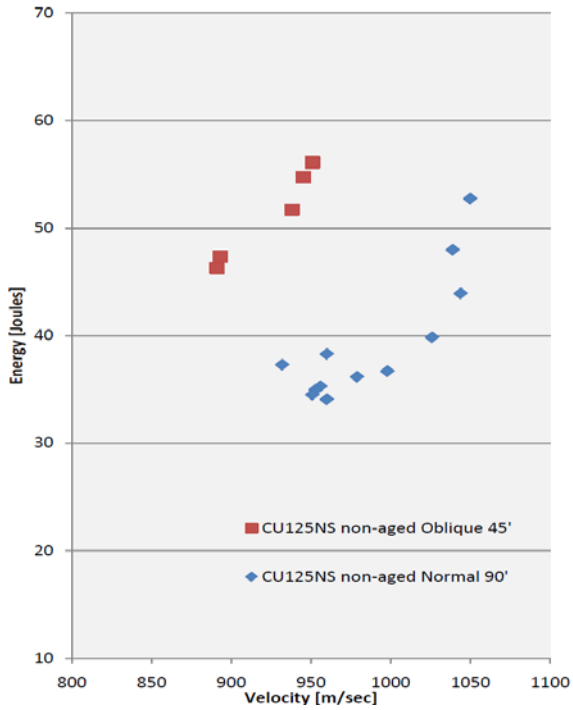


*Figure 5 : Impact of Al projectile on Composite Non-aged plate at Normal and Oblique angles.*

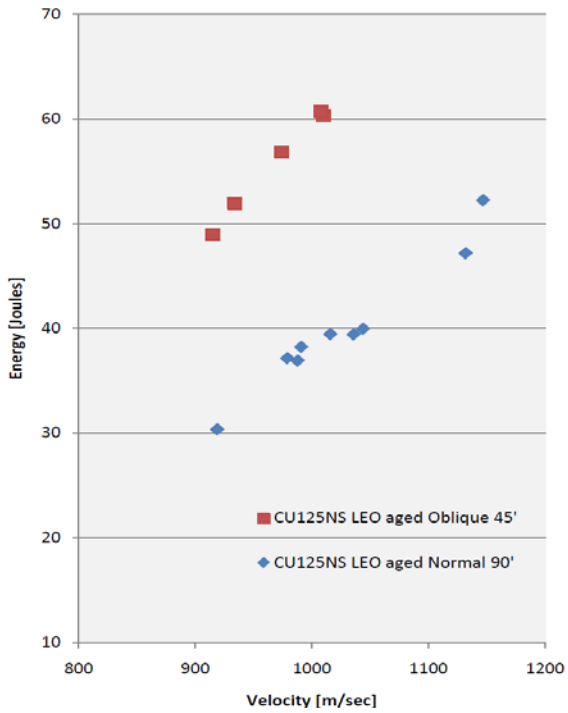


*Figure 6 : Impact of Al projectile on Composite LEO-aged plate at Normal and Oblique angles.*

The Figure 6 showed the comparison of the CU125NS composite laminate exposed to complete LEO space environment and then attacked by the space debris in ballistic range. It is observed that the energy absorption is around 20 joules more than the normal impacts.

## 4 Validation of results by LS-DYNA

Because of the high strain rate involved in the hypervelocity impacts, simple finite element modeling in LS DYNA is not sufficient to produce the results. Therefore SPH modeling technique is adopted here to get the energy profile for the projectile. The debris cloud propagation was observed in the same pattern as described in Figure 1. The ricochet cloud moves away from the wall while others move in-line and normal to the surface of spacecraft plate. The results from LS-DYNA over predict the behavior being no compensation for the air drag, no account of energy dissipation as heat and there is no loss accounted for the acoustic energy. Although it's not been accounted for experimental data but energy loss is there because of these factors, which actually not in case of simulations a result.

## 5 Discussion

The LEO space environment severely effects on spacecraft wall from surface erosion, mass loss to degradation in properties because of AO attack and lastly the space debris attack. These debris impacts catastrophically effect on spacecraft life and its different subsystems. In this work the spacecraft outer wall composed of carbon-epoxy composites had been proposed and then tested with the real time simulation facilities available in the Smart Structure and Composite Lab, KAIST. The composite wall was the outermost part of hybrid composite shielding system which were earlier tested for normal impacts [9] and has to be exploited for oblique impacts. In case of using the Composites over Aluminuim alloys many advantages are there, being less in weight, having high strength to stiffness ratio in comparison to Aluminuim alloys. The usage of composite materials for spacecraft results in less secondary debris clouds in comparison to Aluminium shields. In case of Aluminuim alloys only plate absorbed the energy while in case of composites, Fiber breakage and deformation, matrix fracture, delamination and friction to projectile plays a combined role in dissipating the energy of impacting projectile. As the fibers are continuous so they resulted in less secondary debris cloud being attached to rest of fiber.

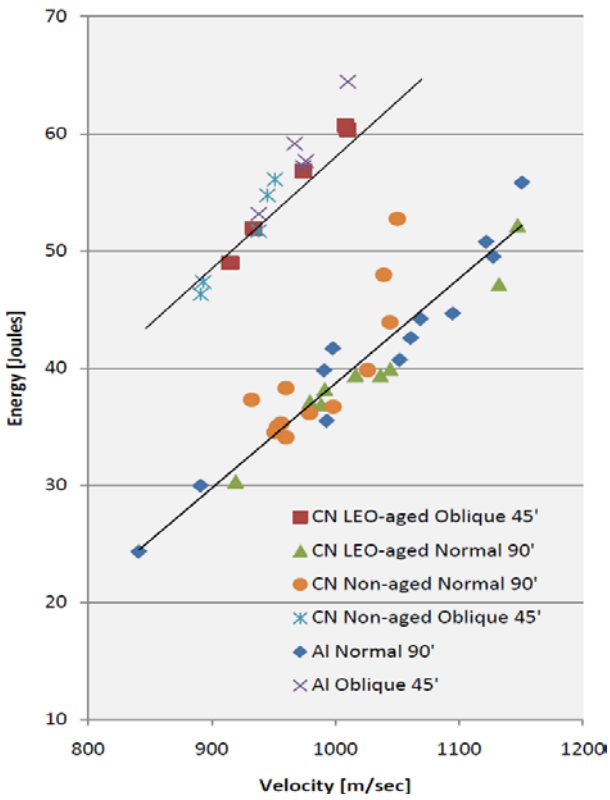


*Figure 7 : Comparison of Aluminuim alloys and composite wall in different scenarios.*

The oblique impact on spacecraft composite wall showed one third folds around 35% more energy absorption then in case of normal impacts of the same. The comparison of Aluminuim alloy and non-aged specimen with LEO simulated composite specimen is shown in Figure 7. The oblique impacts always had more energy absorption and it went on increasing with the increase of velocity. The energy absorbed per unit weight found to be 1.561217 J/gram for composite laminate which is 1.85% more than that of Aluminium specimen of same

dimensions in the same conditions. For the oblique impact the secondary debris cloud had less energy to affect the remaining damper plates because of many reasons. Firstly more energy is being absorbed by the first composite plate and secondly the oblique debris has three types of cloud and impacting cloud get decreasing in energy after every impact. This is due to the fact that a component is acting on next shielding plate instead on normal impact. The difference on the surface of composite can easily be seen in Figure 8. In front view the impact is of oval shape due to oblique impact while at the rear side the breakage, delamination and fiber separation is obvious.

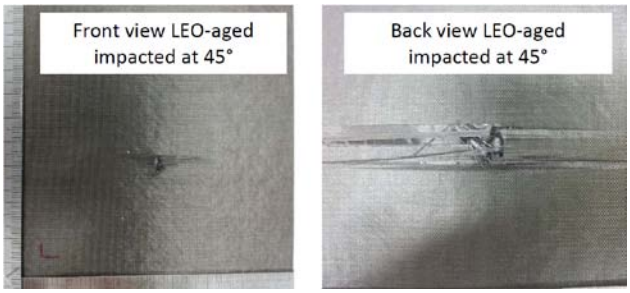


*Figure 8 : Oblique impact on specimen (Front and rear views).*

## 6 Conclusions

The results show the dominancy of carbon-epoxy composite towards impact handling at oblique angles with itself at normal angles and with Aluminuim alloy (6061-T6) plate as well. The energy absorbed at oblique angle is one third folds is more than that of normal impact and it goes on increasing with the increase of Initial velocity. The comparison resulted in 35% more absorption of energy at oblique angle of 45° and the energy absorption by composite at oblique angles is almost 1.85% more than that of its Aluminium alloy counterpart in LEO. Concluding all, the shielding system design at oblique angle has much potential to absorb more energy by keeping its weight minimum. In the future these will be utilized to get the more detailed HCS system for spacecraft shielding which will have better strength with less in weight.

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