PENETRATION OF FRAGMENTS INTO AIRCRAFT COMPOSITE STRUCTURES.

G. Jenaro, F.Rey, G.Rosado and P. García

Laboratorio Químico Central de Armamento (LQCA) P.O.Box 1105, 28080 Madrid, SPAIN

Aircraft structures use different kind of lightweight materials. There is a tendency to replace aluminium structures by composite structures, and as a consequence the vulnerability of the aerial platform is affected. The aim of this paper is to study the impact of fragments against carbon fibre reinforced plastic (CFRP). One specimen simulating the wing of a generic aircraft structure were designed and manufactured. It included internal walls simulating the fuel tank. A previous analytical analysis was carried out in order to estimate the penetration and residual velocities. The test involved the detonation of a fragment generator at close distance from the specimen. The aim of this paper is to assess the results, to apply some analytical models, estimate the ballistic limit velocity and the absorbed energy. A post-test analysis was done including the cracking pattern and the influence of the impact on the panel damage.

INTRODUCTION

The worldwide market for composite aerostructures is growing every year due to the good mechanical properties and potential to reduce the weight of aircrafts. Civil and military aircrafts are using more and more composite structures, and now it is usual to include Titanium, Aluminium and Carbon Fibre Reinforced Plastic (CFRP) as structural elements.

The aim of this work is to study the impact of fragments against aircraft composite structures.

One specimen simulating the wing of a generic aircraft structure was designed and manufactured. The specimen was made of CFRP and included internal walls simulating the fuel tank.

In order to prepare the test set-up a previous analysis was carried out, the analysis included the estimation of the ballistic limit and exit velocity for several types of fragments, equations taken from reference 1 were applied.

There were three main objectives, the first one was to assess an experimental anti-air warhead, the second one to check the validity of several analytical models to estimate the ballistic limit velocity for this and other configurations, and the third one was to measure the structure damage.

The fragmentation warhead (a kind of fragment generator) was detonated at such a distance that the expected fragments impacted at a velocity near the ballistic limit velocity of the specimen front panel.

The post-test analysis included to examine the impacts, the perforations, the cracking patterns, to calculate the ballistic limit velocity and the absorbed energy and to compare with analytical equations.

EXPERIMENTAL

The target was representative of a wing structure of a generic aircraft at the wing root. It was a kind of box, including front and rear panels, the panels were 16.46 mm thick, 595 mm x 595 mm, (laminates of 60% +-45º, 40% 0/90º) and were joined (Hi-lock de ¼`` bolts) by Aluminum alloy (Al 2024-T3 alloy) ribs. The complete box dimensions were 600 mm x 600mm x 169 mm. See Figure 1.

The fragment generator simulated a small ground to air warhead (mass < 1 Kg, outer diameter <90mm), it was placed at 4 m distance. The generator was mounted on a fixture that allowed its horizontal and vertical orientation to be adjusted.

Most of the fragments were cubes, each one 0.6 grams weight. Apart from that there were other kind of fragments but they are out of the scope of this paper.

Velocity Measuring Screens were placed to measure Fragments velocity.

The support fixture was designed to minimize the interference between the generator and the target.

The distance generator-target was chosen in order to get an impact velocity closed to the expected ballistic limit velocity.

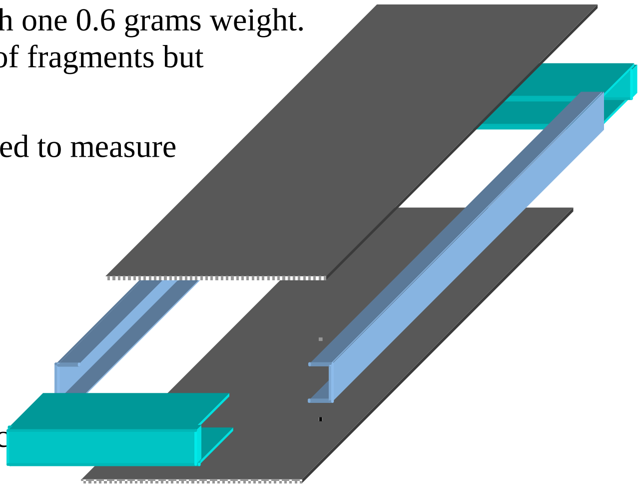

FIGURE 1: Wing Box Manufacturing Detail

The structure was rigidly fixed to a steel frame mounted on a steel support.

It was defined that a complete penetration occurred when a fragment had sufficient energy to damage at least 1 mm of the back panel, which acted as the witness panel.

The panel data are summarized in Table 1.

Property	**Value**
Laminate density	1445 Kg/m^3
Laminate thickness	16.5 mm
Area density	23.78 Kg/m^2

TABLE 1: Data of the laminate and impact.

PRELIMINARY ANALYSIS

Reference [2] shows a review of many analytical models, some of them are applied to carbon fiber composite laminates; despite the capabilities of numerical simulation, the simplified methods allow us to make initial estimations that may be useful.

Some calculations were done to adjust the projectile distance in such a way that the projectile impact velocity was close to the ballistic limit velocity of the front panel. It is known that the level of damage increases with the impact energy up to the ballistic limit velocity, so the damaged area will be maximized at this velocity, and will decrease at higher or lower velocities.

In order to get a first estimation of the ballistic limit, the analytical model of Wen was applied [see references 1, 4 and 5] assuming the projectile is flat with an equivalent area identical to the one used in the experiments.
Figure 1 shows the ballistic limit velocity versus laminate thickness.

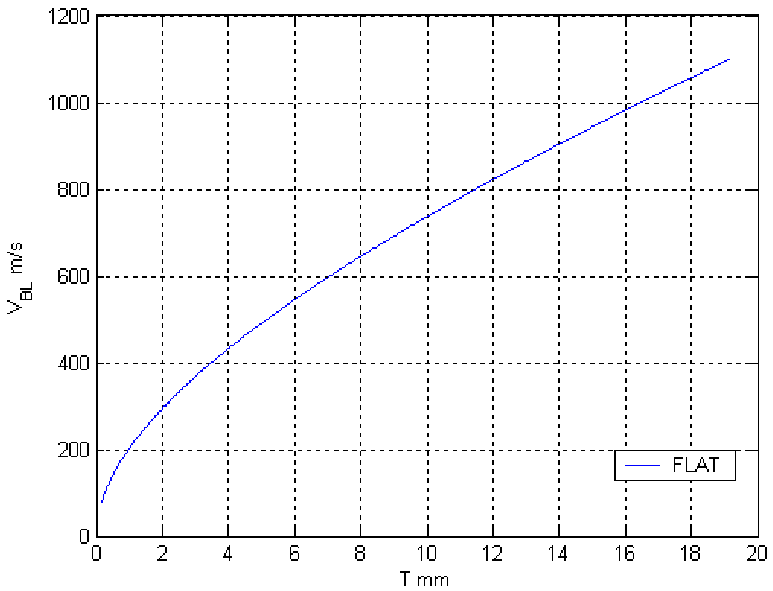

FIGURE 2: Estimated Ballistic Limit Velocity vs Laminate thickness

It was estimated that the ballistic limit velocity was close to 1030 m/s, and as a consequence the distance projectile-target was established around 4 m with an estimated impact velocity of 1050 m/s.

TEST RESULTS

The test was carried out as scheduled, and the investigation revealed that the effects of the generator on the front panel were:

- 48 impacts on the front panel (27 belong to the fragmented cubes and 21 to other kind of fragments).
- All fragmented cubes perforated the first panel. However, only 13 had penetrated in the back panel, other 5 had previously impacted on the rivet or on the edge of the front panel and did not impact on the back panel, and the last 9 had been significant hits but no complete penetration. All of them were easily recollected.
- The front face of the first ballistic panel displayed a smaller detached area than the corresponding back face detachment.
- The 13 out of 27 impacts with complete penetration have scored penetrations between 3 and 9 mm on the back panel.
- The fragments were not deformed as a consequence of the penetration.
- The spars were impacted and deformed but only locally, and provided enough protection to the back panel.

Table 2 presents the results. In this Table, d is the fragment size, d1 and d2 are the transverse and longitudinal crack dimensions in the front impact, CP and PP mean complete or partial penetration and alpha is the impact angle.

Fragment	d1/d	d2/d	CP or PP	Alpha (º)
1	1,77	1,29	**CP**	4.64
2	1,72	1,58	**CP**	11.22
3	1,81	1,82	**CP**	5.88
4	2	1,78	**CP**	0.61
5	1,76	1,87	**CP**	8.63
10	2,06	1,7	PP	
11	2,11	2,14	**CP**	9.14
12	1,44	1,49	**CP**	7.94
16	2,08	1,86	PP	
17	1,38	1,32	PP	
18	1,58	1,52	PP	
19	1,78	1,85	PP	
20	1,73	2,04	PP	
21	1,69	1,81	PP	

22	2,06	1,78	**CP**	6.70
23	2,17	1,77	**CP**	6.27
24	1,73	2,6	**CP**	28.95
25	2,06	1,99	**CP**	2.06
26	2,29	1,93	PP	3.43
28	2,08	1,88	**CP**	4.09
29	1,82	1,64	**CP**	4.03
30	1,64	1,81	PP	
31	1,79	2,07	PP	
34	1,79	2,15	PP	
35	1,25	1,72	PP	
38	1,77	1,79	PP	
47	2,34	1,89	PP	
average	1,84	1,82		

TABLE 2: Test results: Fragment, Transverse and longitudinal crack length, and angle of impact.

There are 13 complete penetrations and 14 partial penetrations. Then at a first glance it seems that the average impact velocity is just the ballistic limit velocity; but this is not true because 5 fragments had previously impacted on one rivet; discarding these 5 fragments, there are only 9 partial penetrations.

The measured average velocity was about 1040 m/s. This measurement is only an approximation because only the measurement of some fragments were available. The average residual velocity may be estimated by measuring the penetration on the second panel: the average thickness is equivalent to an impact velocity of 350 m/s, which is the residual velocity of the first panel. As a consequence the ballistic limit velocity is estimated by 979.3 m/s.

PHOTO 1: Front Panel after the Test.

PHOTO 2: Front Panel after the Test: Detail of impacts.

DISCUSSIONS

Two more analytical methods (Poncelet and Robins-Euler, see reference [5]) had also been applied (Figure 2). It is possible to see that the model of Poncelet seems to fit correctly.

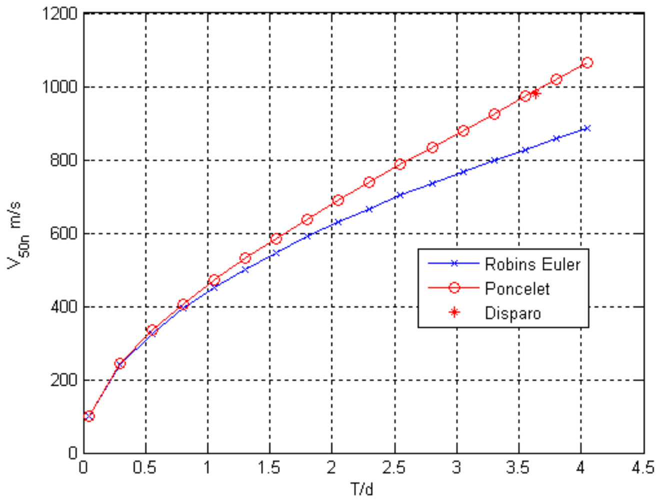

FIGURE 3: Estimated Ballistic Limit Velocity vs Laminate thickness/eq diameter

In the same way it is possible to study the relationship between the ballistic limit velocity and the areal density, even although it is only valid in a small interval (Figure 4).

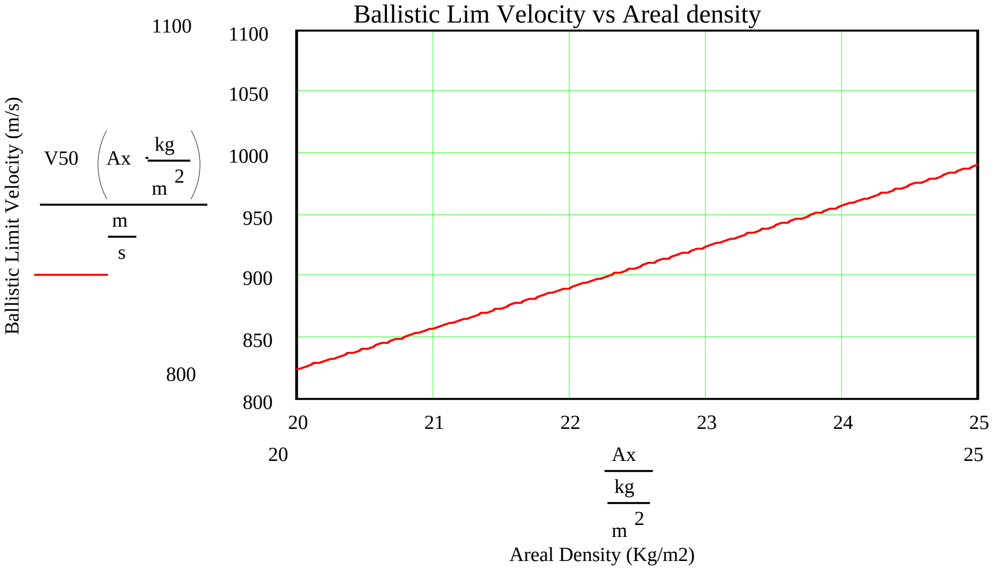

FIGURE 4: Estimated Ballistic Limit Velocity versus Areal Density

The post-test analysis showed that the cracking pattern is typical of the high velocity ballistic impact. It is known that the CFRP has poor resistance to high energy impact due to the low strain to failure and the low transverse shear strength of the graphite fibre, as much as the brittle characteristics of the epoxy matrix.

Photo 3 shows an impact (partially only) just in the edge of the panel, it is possible to see the shear plug near the front panel surface, the diameter of the shear plug is close to the diameter of the projectile on the first ply and increasing slightly with depth. The shear plug depth is close to 30% of the panel thickness.

The analysis of several impacts showed that the delamination between plies was larger on the first plies, reduced in the middle and increasing toward the back face. Delamination extended a bit away from the point of impact and the damage on both the upper and lower surfaces of the front panel was clearly visible.

High velocity impact loading by a light projectile tends to induce a more localized form of target response, resulting in the dissipation of energy over a comparatively small region. Most of the energy is dissipated over a small zone immediate to the point of impact.

Results of the Ultrasounds Test was not available at the time of printing.

CONCLUSIONS

A specimen simulating the wing of a generic aircraft has been tested. A fragment generator was applied to get the fragments at the desired velocity. Several analytical models have been applied with acceptable agreement. The cracking pattern is typical of fragment impacts at high velocity.

REFERENCES

1. Hosur, Mahes V et al; "Survivability of Affordable Aircraft Composite Structures. Vol 1: Overview and Ballistic Impact Testing of Affordable Woven Carbon/Epoxy Composites". AFRL-VA-WP-TR-2003-3071.Tuskegee Univ (2003).
2. G.Ben-Dor, A.Dubinsky and T.Elperin, "Ballistic Impact: Recent Advances in Analytical Modelling of Plate Penetration Dynamics-A Review", Applied Mechanics Reviews, November 2005, Vol 58pp.355-371.
3. Wen,H.M., "Predicting the Penetration and Perforation of FRP Laminates Struck Normally by Projectiles with Different Nose Shapes", Composite Structures, Vol 49, Nº 3, pp.321-329, 2000.
4. Wen,H.M., "Penetration and Perforation of ThickFRP Laminates", Composites Science and Technology",Vol 61, pp1163-1172, 2001.
5. J.A.Zucas,"High Velocity Impact dynamics", Edited by J.A.Zucas, 1990, John Wiley and Sons.