JET ENGINE ROTOR FRAGMENT IMPACT ON COMPOSITE PANELS

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ABSTRACT

Ballistic impact on composite panels is studied in this paper. Spherical projectiles ware shot against composite plates, impact damage was observed, and the initial and exit speeds were measured. Explicit finite element program LS-DYNA, with some enhancements was used to simulate the impact event. An analysis process has been developed and the simulated results were compared with the tests results. Each ply in the panels was modeled with 8-node solid elements with material model allowing complete three dimensional progressive failure. Fracture mechanics based contact definition was modeled between plies with full delamination capability between each ply.

INTRODUCTION

Modern jet airplane is a remarkably safe transportation machine. A two engine aircraft can now fly non-stop virtually from any airport to any other airport in the world. However, because the engine rotors spin at high speed and are designed for the minimum weight, the blades occasionally break with catastrophic consequences. The worst accident caused by rotor failure happened at Sioux City, Iowa in 1989. A DC-10 tail engine had a massive in-flight failure, the main rotor disk failed, the pieces cut all the hydraulic lines, the aircraft was rendered uncontrollable and crashed killing 123 people. The failure was caused by a small manufacturing defect in the disk. Several other accidents have occurred over the years, but the good news is that fatal accidents are getting less frequent. To put this in perspective, the probability of a massive engine failure on any given flight is about 1.e-09. On the other hand, the probability of hitting the jackpot on the Washington State Lottery is about 1.0e-07. The improved aviation safety is due to better maintenance, better manufacturing quality and better designs. The aviation authorities impose strict design requirements and the aircraft companies are making a great effort to make the airplanes safe. The electrical and hydraulic lines have to be adequately protected, the fuel tanks have to be able to stand a specified impact without leaking and a fragment from one engine cannot disable the other engine, etc.

Over the past several years The Boeing Company in cooperation with the Federal Aviation Administration (FAA) and University California, Berkeley (UCB) and other research facilities has conducted material testing and numerical computations on ballistic impact on various airplane structures. FAA has funded and administered the work, UCB performed mainly the testing and Boeing the computations. The purpose has been to develop computational methods to analyze a high speed fragment impacting on the chosen targets. Material testing had two aspects: small coupon tests to determine the material properties needed as input to the computer program and ballistic testing where a projectile was shot against a target specimen and penetration was measured. Then finite element (FE) models were created and analyzed and the computational results compared with the test results. Once a reliable computational tool is available then it is much cheaper to use it than laboratory testing. In addition, computer analysis yields much more information than a test and makes it possible to understand the underlying physics better, which in turn makes the design process more accurate and faster. Commercially available explicit finite element program LS-DYNA, developed by Livermore Software Technology Corporation (LSTC), was chosen as the computational tool [2, 3].

Fig. 1. Massive jet engine failure.

BALLISTIC TESTING

Test Setup: One of many Boeing composite materials was used in the study [4]. Flat panels with three different thicknesses, 0.06 in, 0.12 in and 0.24 in were tested. The nominal ply thickness is about 0.0075 in and so the panels had 8, 16, and 32 plies, respectively. The stacking sequence, for the 16 ply panel, starting from the bottom is: 45, 90, -45, 0, 45, 90, -45, 0, (center) 0, -45, 90, 45, 0, -45,90, 45 degrees. I.e. these are the ply rotations from the reference axis. The stacking is symmetric about the center plane. In addition, the 4-ply (0, -45, 90, 45)-sequence repeats itself around the center plane. The 32-ply panel has four 4-ply stacks both above and below the center plane in the same pattern. The overall panel with all three thicknesses with this stacking sequence has almost isotropic bending and in-plane stiffness properties (therefore called "quasi-isotropic") and is a common design. Due to the symmetric lay-up, the bending and in-plane stiffness are also uncoupled. The total size of each panel was 12x12 inches and when mounted onto a steel test frame, the clear test area was 10x10 inches. Several panels for each of the three thicknesses were tested to get some statistical reliability. The mounting steel frame was stiff enough so that the plate boundary was considered clamped. It takes 1 to 3 milliseconds for the projectile to penetrate the plate depending on the impact velocity and thickness. This is long enough time for waves to travel from impact point to the plate boundary and back before the event is over. This means that the reflecting waves interfere with the penetration. The finite element model has clamped boundaries and accounts for the reflecting waves. This was considered acceptable although not ideal.

A nitrogen gas gun with half-inch diameter spherical steel projectiles was used in all the tests shots. The spheres were one half inch in diameter and weighed 0.018 pounds (8.2 grams). The gun used industrial grade compressed nitrogen with a maximum pressure of 1500 psi. The gun barrel was approximately 52 in long. After 39 in of smooth barrel, there were slits in the barrel downstream that relieved the pressure behind the projectile. A regulator controlling the pressure could be set for any value between 25 and 1500 psi. The solenoid valve that released the pressure was controlled by an electronic control box and triggered from the adjacent room. The gun was able to propel the projectiles up to 1000 ft/s speed. This was high enough for complete penetration with the 32-ply panels. In this study all the shots were perpendicular and at the center of the plate. The advantage of using gas gun over powder gun is that the pressure and the projectile velocity can be controlled more precisely. The impact and exit (residual, after penetration) velocities were measured. Each shot was videotaped with a high speed camera and the damage and hole to the panels were photographed. Two light beams in the front of the panels were used to measure the impact velocity while the exit velocity was determined from the high speed video.

Ballistic Limit: The impact and exit velocities are usually plotted on an x-y scale: impact velocity on the horizontal axis and the exit velocity on the vertical axis. A typical ballistic event is shown in Fig. 3 [1]. The shape of this plot is approximately the same regardless of ballistic conditions, material target thickness, etc. The point where the exit velocity becomes greater than zero is called the ballistic limit. After the limit, first there is steep rise in the exit velocity plot and then it flattens out to a 45-degree slope and stays approximately at constant slope indefinitely. To illustrate further, 45-degree reference line is drawn, i.e. this has the same impact and exit velocities. The difference between the 45-degree reference line and the real impact/exit velocity plot represents the velocity (and kinetic energy) that the projectile looses in the penetration. The sharp rise in the plot comes from material ductility and then at higher velocities the projectile velocity loss is practically constant.

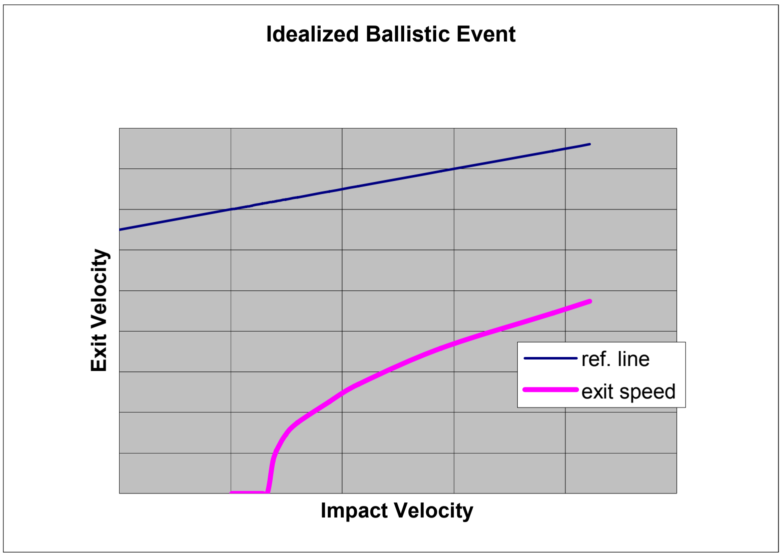

Fig. 2. Ballistic impact characteristics.

Test Results: Typical entry and exit holes for the spherical projectiles are shown in Fig. 3. The entry side hole (on the left) is always cleaner than the exit side hole. Exit side always has visible delamination. Inspection shows that it is mostly on the last few plies and extends several inches away from the hole mainly in the fiber direction. However, it was impossible with the available equipment to quantify exactly how much delamination there was between each ply inside the plate and how much energy was dissipated in total delamination.

The impact and exit velocities were plotted for all the test points for the three plate thicknesses and are shown in Fig. 4. The thinnest, 8-ply panel (blue squares) has the lowest ballistic limit, about 200 ft/sec, and takes the least amount energy for penetration, the 16-ply ballistic limit is about 300 ft/sec (red triangles) and the 32-ply panel ballistic limit is 450 ft/sec. The dots form the same overall shape as shown in Fig. 2. The rise after the ballistic limit is relatively low since composites lack ductility compared to aluminum, for example

The initial kinetic energy vs. dissipated energy is plotted in Fig. 5. It shows that the dissipated energy is approximately constant with each plate thickness over the velocity range considered here. In Fig 6 the absorbed energy is plotted per one ply. The thicker plate gives some advantage. Is seen that in the dissipated energy per ply increases somewhat with the increased number of plies.

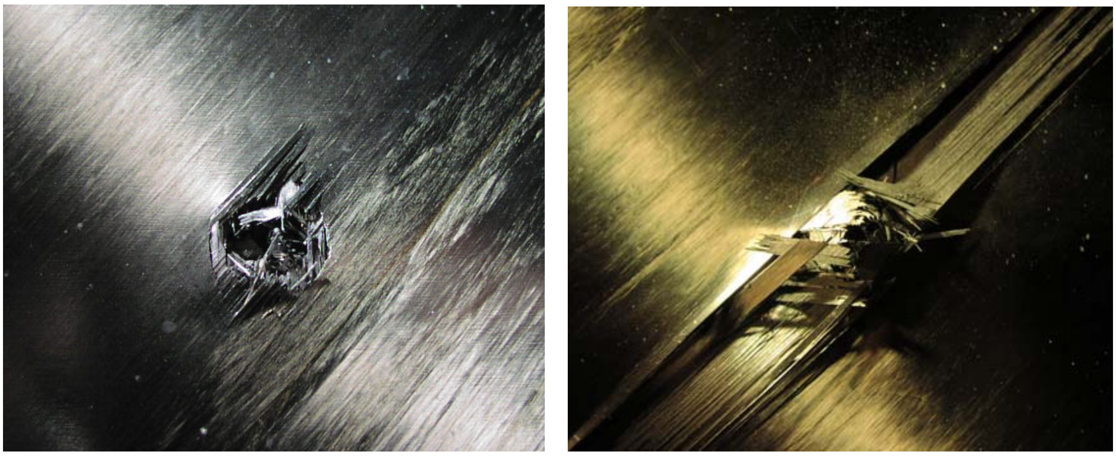

Fig. 3. Damage from spherical projectile impact; entry hole on the left, exit hole on the right.

Coupon Tests: Most of the required material data [3] have been tested in the Boeing Materials Labs and was available in the Boeing database. Fig 7 shows a typical force-deflection curve for one ply from a static tension test. First there is a linear elastic region and then a smooth round transition and then finally a sudden drop with the complete failure. The shape would be very similar for compression and shear also. Tension in fiber direction is by far the strongest direction. Unlike with metals, there is no long plastic region before failure and the total failure energy is low.

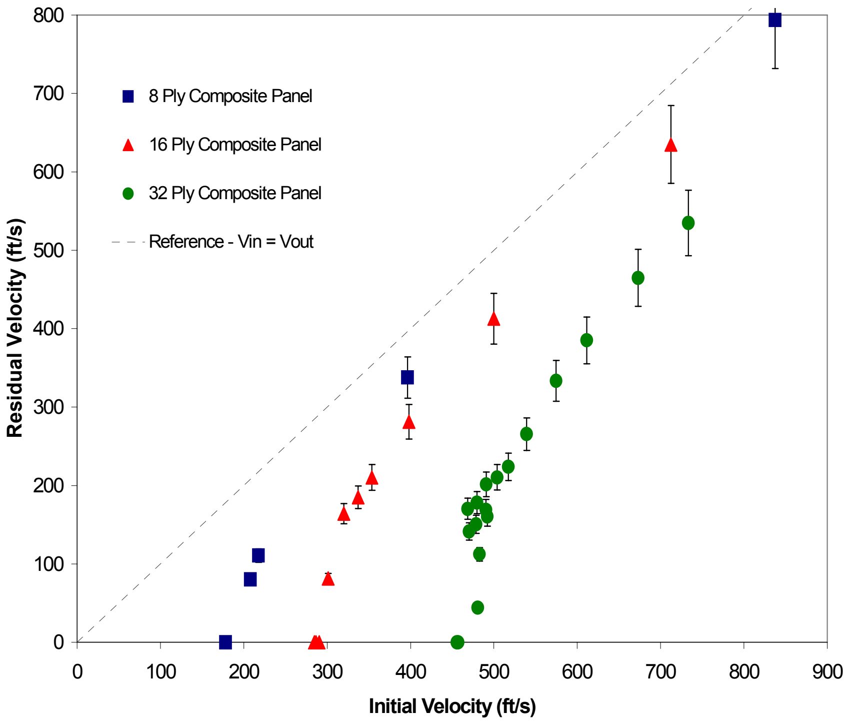

Fig. 4. Ballistic velocities.

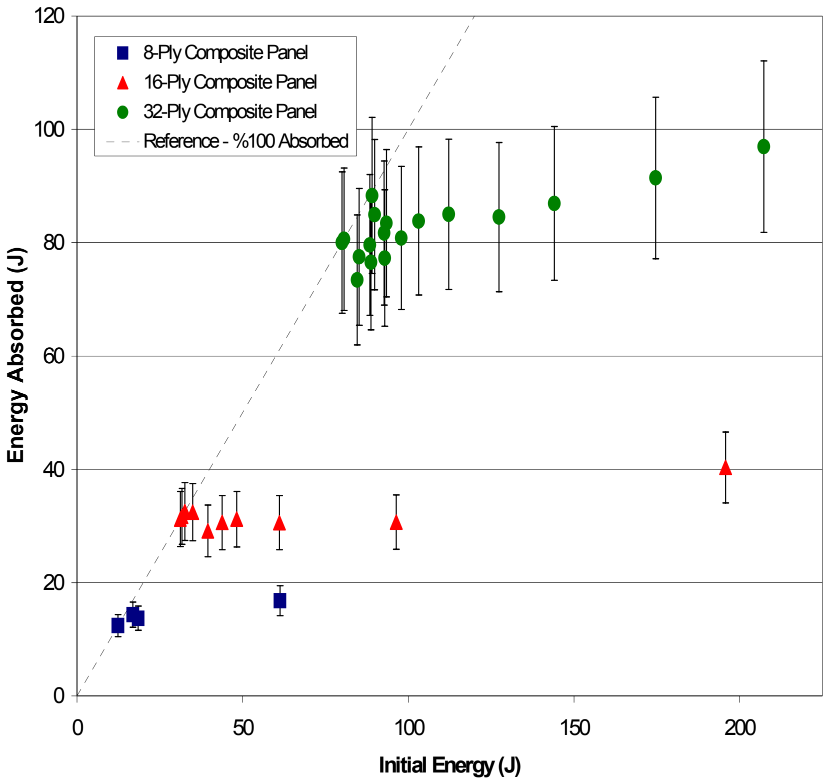

Fig. 5. Absorbed energy.

COMPUTATIONS

Description of the Event: Fragment impact and penetration into a laminated composite plate is difficult to compute correctly. As the projectile pushes against the plate, the contact force between them builds up, the plies break one by one and the shear and normal stresses between the plies will separate them from each others (plies delaminate). The deformation around the projectile is localized and therefore it is necessary to consider a three dimensional stress and strain state. Fiber is brittle with high tension strength but has almost no strength in the other directions. Resin is viscoplastic with ductile failure and heavily rate dependent. Since there is practically no plastic deformation before failure, the energy required to fail the material is small. This makes composites weak under transverse impact loading. The plies fail mainly in shear and compression. The hydrostatic component has a significant part in the failure, but is not well captured in the available material models. The resin and fibers break at different strain levels, but is not accounted for in the present material model. The available material models simply combine the fiber and resin into one homogenous orthotropic material.

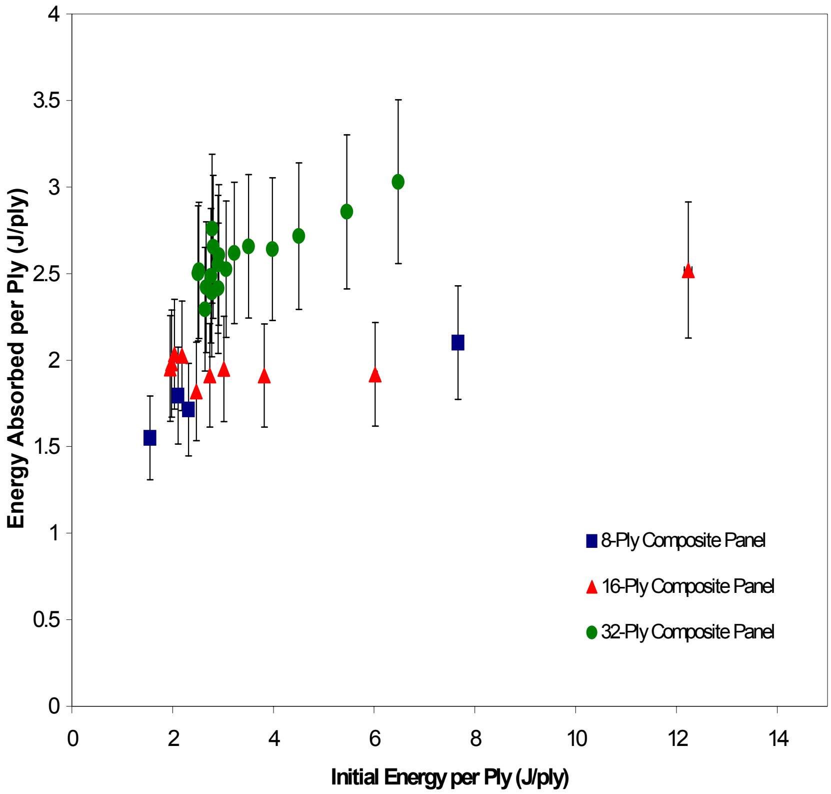

Fig. 6. Energy absorbed per ply.

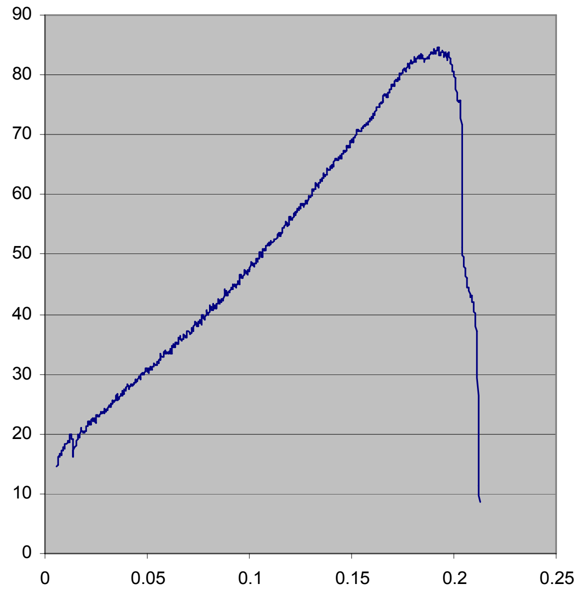

Fig. 7. Force vs. deflection for one ply.

The ply delamination (debonding, decohesion) is caused by in-plane shear (Mode II) and normal tension (Mode I) between the pies. The crack tip runs in the direction of least resistance between two plies. The energy released in the process is measured by the dynamic fracture toughness, which is determined by testing. Fracture toughness is different between Mode I and Mode II and is considered in the present material models. It is also different between the fiber and perpendicular to fiber directions, which is not considered in the present models. The two shear directions are lumped into one.

Computational Models: In the explicit FE analysis the mass matrix is uncoupled which allows the equations to be solved explicitly without assembly and decomposition of the global matrices. The stability condition requires that the time step is smaller than the time it takes for acoustic wave to travel across one element. Wave speed is related to the largest eigenvalue in the model, which in turn comes from the smallest element in the system [6]. Typical time step in explicit FE runs is 0.5e-7 to 1.0e-07 seconds and analysis up to 5 milliseconds requires some 50000 steps. For the best accuracy and computer economy, the finite element mesh needs to be as uniform and smooth as possible.

Figure 8 shows a typical FE mesh for the 32-ply plate and spherical projectile. Only one half of the model was considered in the computer analyses, although the model is not strictly symmetric.

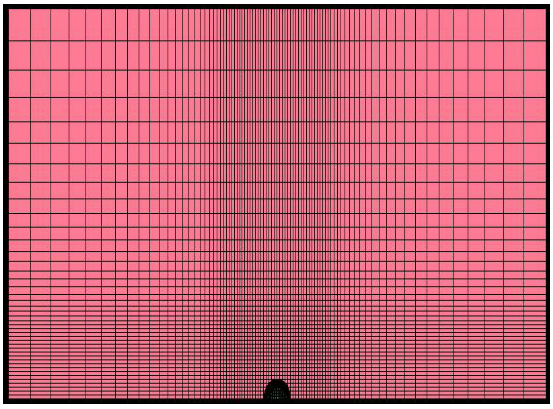
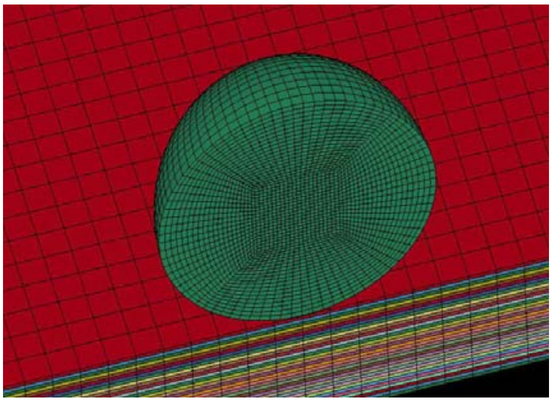

Fig. 8. Top view of the FE mesh on the left, side view on the right.

One 8-node solid element was used through each ply. The element size under the projectile was 0.05 by 0.05 by 0.0075 in (ply thickness is 0.0075 in) and all the elements had rectangular shape. A typical model had about 200000 elements. The bonding between the plies was modeled with “contact tiebreak surfaces” which has the facture mechanics based delamination capability and requires fracture toughness input. The contact was defined between each ply allowing them to delaminate from each other. The impact force between the projectile and the plate was modeled with “eroding contact surfaces”. The contact surface redefines itself after an element fails and is removed from the model, thus tracking correctly the force between the projectile and the plate

“Composite progressive damage and failure” material model was chosen for the composite ply material. This model requires the normal and shear stiffness in all three directions with the corresponding Poisson’s Ratios. The material strength in each direction, 9 in total, is required as input. The model uses the material strength as the start of progressive failure and the progressive failure then follows an exponential curve with user defined slope (m). The test data (Fig 7) should match closely with the exponential unloading curve shown in Fig. 9

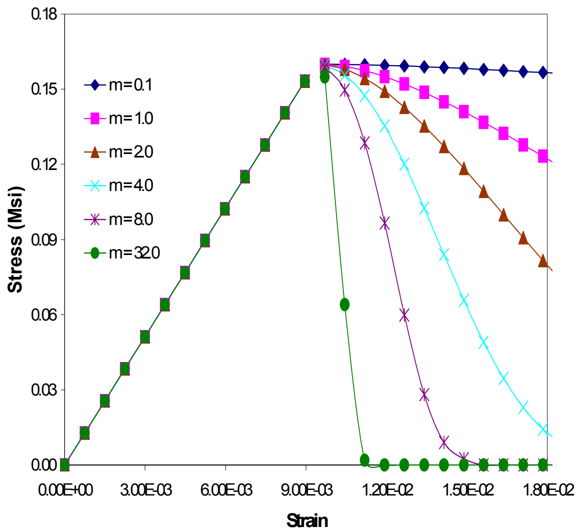

Fig. 9. Idealized ply stress-strain response.

Computational Results: Fig 10 shows the penetration and failure of the 32-ply plate for initial velocity of 574 ft/sec.

Some elements fail and are deleted, some elements are pushed forward under the projectile and all the plies delaminate around the hole. Fig 11 has a typical projectile velocity profile during penetration. The exit velocity was the primary unknown in the computer simulations. Fig 12 has the summary of both the computed and experimentally determined exit velocities for the 32-ply, 16-ply, and 8-ply plates for all the shots.

The thicker the plate, the more errors have chance to accumulate and more difficult it is to get an accurate simulation because the time integration requires more steps. Furthermore when the impact velocity is close the ballistic limit the impact event takes longer, the program has to take more time steps and the programs requires more time steps and the results tend to be less accurate.

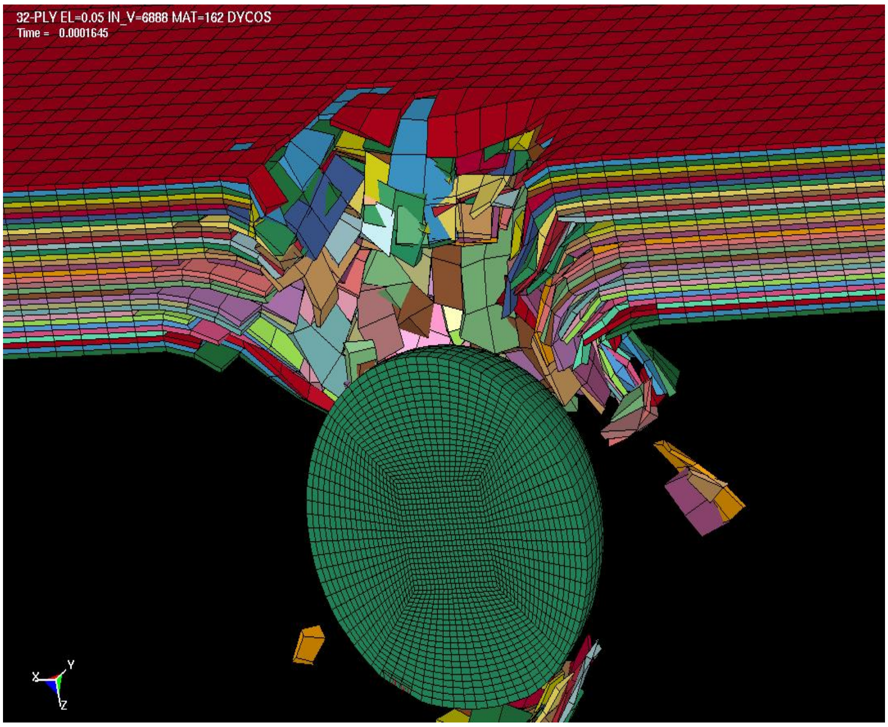

Fig. 10. Penetration and failure.

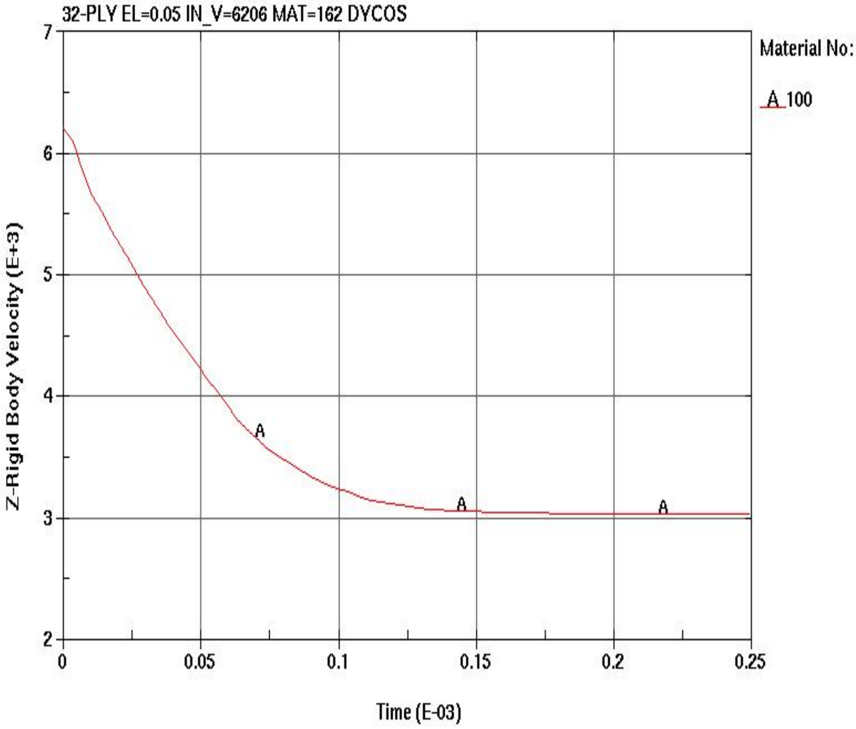

Fig. 11. .Projectile velocity profile.

4 Discussion

Jet engine rotor fragment impact on composite structures has been studied both experimentally and computationally. The computer hardware and software have reached maturity so that reliable ballistic simulations are now possible, provided that accurate material data is available and the analyst has some experience with the software. The available composite material models have deficiencies which are corrected presently. Simulation of the ply failure and delamination require very specialized material data and require special testing. The numerical simulations are computationally intensive. A typical simulation run takes at least overnight. Nevertheless the computer simulations are substantially less expensive and yield more information than laboratory testing.

Finite element analysis of material failure does not converge to anything when the mesh is refined. Too coarse a mesh (elements too large) can grossly overestimate the energy required to fail the material (i.e. all materials, metals, composites, etc). When the mesh is refined (elements are made smaller) the required energy to fail the material decreases without bounds. When the elements are too small, the energy is underestimated and the projectile penetrates too easily. There does not seem to be any reliable way to determine the optimum mesh density without actually tuning the mesh with known test results. Researches are making efforts to minimize this effect, but so far no one is promising a complete cure.

Meanwhile, the present state is mature enough so that it can be used confidently for practical aircraft design work.

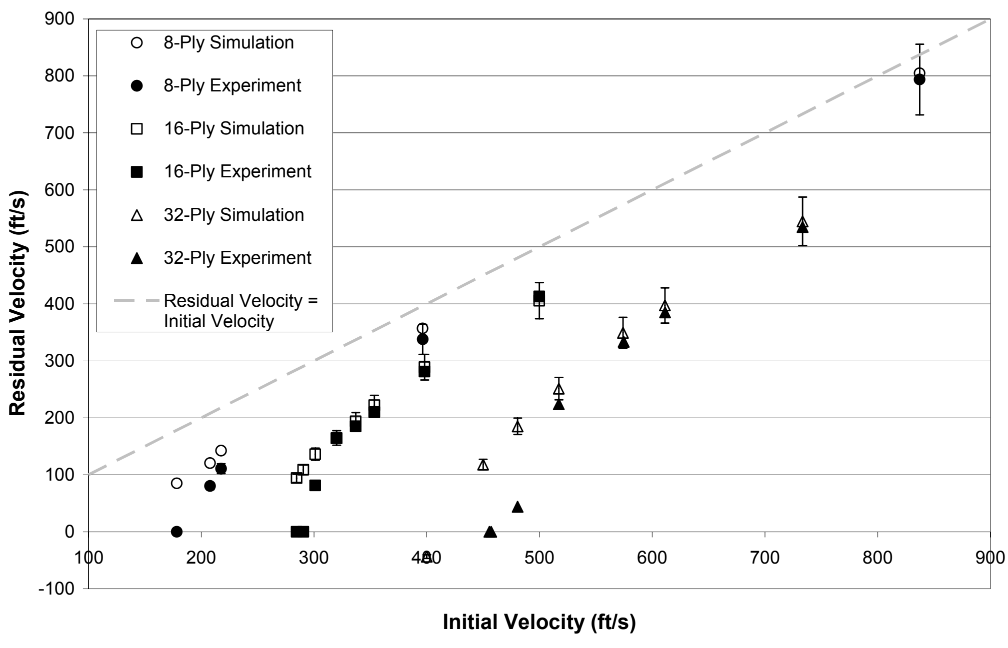

Fig. 12. Spherical projectile: computations vs. testing.

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