CERAMIC COMPOSITE PROTECTION FOR TURBINE DISC BURSTS

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INTRODUCTION

Imagine yourself boarding an airbus with 300 other passengers heading off for a vacation trip when suddenly the in-flight certified auxiliary power unit bursts a turbine rotor during the take-off roll. Not a very happy start for your vacation is it?

This is what the civil authorities in Europe were concerned about prior to European certification of the A300B Airbus Commercial Transport.

The Hamburger Flugzeugbau Division of Messerschmitt-Bolkow-Blohm went to work on a solution to this potential problem since they had the installation responsibility for the Garrett supplied Auxiliary Power Unit (APU) for the A300B. In a program with Norton Company, a viable lightweight rotor containment system was developed and qualified for use in the production A300B aircraft.

The ceramic composite rotor containment system for the A300B application was totally developed and qualified for close to $60,000 with an addition to the aircraft weight of about 50 pounds. The cost per aircraft set is close to $2300. Compared to the integral containment system used on the L-1011 APU which cost close to 2 million dollars to develop at an increased unit cost per PT-6 engine much greater than the cost of the A300B panels, it can be readily determined that the ceramic composite rotor containment system provides an economical solution to the APU disc containment problem.

BACKGROUND

The Garrett TSCP 700-4 APU for the Airbus is the identical unit used in the Douglas DC-10. Unlike the L-1011 APU which Lockheed specified both integral blade and rotor disc protection for, the DC-10 unit was not designed to withstand rotor disc failures since the FAA TSO only required blade containment. Both the DC-10 and L-1011 APU's have high degrees of reliability, but Lockheed wanted the extra measure of safety provided with an integrally contained APU. Over two million dollars was spent to develop and qualify the L-1011 APU for this protection level.

The Garrett unit in the DC-10 installation apparently does not constitute a hazard to flight critical equipment in the immediate proximity of the tail installation, but with the A300B location there could be some severe consequences from a turbine burst. Immediately beside the APU the triply redundant hydraulic actuators for the horizontal stabilizer surfaces are located. The rotating plane of the high energy rotors can be shown to pass through the flight control actuator locations. It was in these areas that MBB selected to locate rotor containment protection panels.

MATERIALS SEARCH

Having made the decision to provide protection with guards or panels located in the plane of the high energy compressor section of the APU, the next obvious task was to find a lightweight material capable of stopping pieces of the high or low pressure compressor rotor discs.

This turned out to be a much greater task than originally anticipated by MBB. Their tests were conducted on over 25 different materials without success. In utter frustration, even reinforced concrete slabs were tested without success. Some limited success was obtained using rubber/metal composite laminates but not so much success as to allow their consideration for production. Finally, MBB contacted the ceramic composite armor manufacturers for information and selected Norton to work with them on a developmental effort to see if a modified ceramic composite armor system could do the job.

Norton's engineers determined analytically that a slight modification to the Armor System could possibly provide the high energy level protection required and various ceramic to backing ratios were proposed for testing to prove out the system design.

Essentially, four configurations were finally selected for testing against the high pressure and the low pressure wheels. Samples were provided to MBB and successful containment tests were conducted on the first try! All of the selected configurations passed the impact tests, and a final design was then optimized to combine both high pressure and low pressure protection in the same panel.

Final qualification impact and environmental testing was then jointly conducted and the Norton supplied rotor containment system was certified for use on the A300B aircraft against the FAA special conditions which required complete APU containment against rotor bursts to protect the complete aircraft.

PANEL DESIGN

As previously mentioned, Norton provided a modified Armor System design for the rotor containment panels. Basically, the modification of the design consisted of increasing the thickness of the fiberglass reinforced plastic backing material to achieve an optimum ratio of ceramic thickness to backing thickness for the different ballistic defeat condition.

CERAMIC COMPOSITE ARMOR SYSTEMS

Conventional Armor Systems of ceramic composites for Armor piercing projectile protection have been around for about 15 years. Much of the preliminary design of these systems was done on an empirical basis in ballistic test laboratories by both government and industry researchers.

The first lightweight Armor Systems to provide protection against ballistic projectiles were composed of a sintered aluminum oxide ceramic tile approximately one-third of an inch thick bonded to a ductile backing panel, usually aluminum or fiberglass reinforced plastic. In the early

1960's, the Norton Company entered the field of ceramic armor development with the hot pressed boron carbide armor system. Both the alumina and the boron carbide systems are similar in construction - the tile composition being the only difference, but the lower specific gravity of the boron carbide ceramic yields an armor system weighing approximately 30 percent less than the aluminum oxide system.

The most common lightweight armor systems, listed in the order of decreasing areal density (the weight per square foot necessary to provide a given ballistic protection level) follow:

- -Dual Hardness Steel (also identified as DPSA, or dual property steel armor)
- -Alumina (Aluminum Oxide, or Al_2O_3)/GRP Backing
- -Silicon/Boron Carbide/Silicon Carbide ($Si/B_4C/SiC$-Sintered/Impregnated)/GRP Backing
- -Boron Carbide (B_4C, also identified as SF B_4C, or silicon-free boron carbide - hot pressed)/GRP backing

All of the ceramic armor systems have one feature in common. Each is a two-component system consisting of a facing of hard brittle material and a backing of soft, deformable material such as fiberglass reinforced plastic. For dual hardness steel armor, the facing is a hardened austenitic steel, while the backing is a mild steel.

When either armor system is struck by an armor-piercing projectile, the core or penetrator is broken upon impact with the facing in the first few microseconds. The residual energy is then absorbed by the backing material. The role of the backing has been likened to that of a "catcher's mitt" in this situation.

What was desired in the rotor containment application was to optimize the design to obtain a bigger "catcher's mitt" to contain the much greater kinetic energy of the impacting disc fragment. Unlike the piercing projectile situation, the impact "footprint" is very much larger for the disc fragment. The boron carbide ceramic acts to break-up the impacting disc fragment much like the armor piercing projectile, but the backing material plays a much greater role in absorbing the kinetic energy. Without the ceramic facing, the disc fragment's sharp edges would easily cut through the various plies of fiberglass causing easy defeat of the backing plate.

MODIFICATION OF THE DESIGN

By increasing the backing thickness of the rotor containment system to achieve a nearly 1/1 ratio of ceramic thickness to backing thickness, as opposed to the conventional projectile armor system which utilizes close to a 1.75/1 ceramic to backing ratio, a two-to-three fold increase in the kinetic energy protection level can be obtained for the same areal density system. For comparison purposes, an armor system for 50 caliber AP projectiles with an areal density of 13 pounds per square foot protects against 12,500 ft-lbs of energy whereas the rotor containment system of 13.5 pounds per square foot protects against 26,000 ft-lbs of energy.

BALLISTIC TEST PROGRAM

In order to develop the rotor containment system, Norton Company in conjunction with Hamburger Flugzeugbau in Hamburg, Germany, conducted an extensive test program utilizing an air cannon test rig. A plenum chamber was connected to the air cannon barrel by a fast acting pressure valve. The plenum chamber could be pressurized to varying levels to produce different impact velocities at the test panels.

The test fragments were unmachined 120° segments of the actual compressor discs weighing 1.25 Kg each. Impact velocities from 175 m/sec to 260 m/sec were used in the test program with the test criteria for success being total containment.

The test fragments were mounted in hard foam plugs which exposed the sharp edge of the disc fragment. These hard foam plugs are called sabots, and this is a common method for mounting test fragments of varying sizes for impact testing.

The test panels were rigidly mounted to an impact frame and subjected to a variety of impact tests which simulated various energy levels associated with the high and low pressure discs of the engine compressor.

The initial tests were conducted with the panels bolted directly to the impact frame, but the impact energy transmitted to the frame was so great that the mounting bolts were all sheared completely off. A revised mounting technique was then designed utilizing four straps which mounted the panel to the test frame. This mounting method was very successful and has been incorporated in the actual aircraft installation.

This transmitted energy to the mounting structure is a particularly troublesome problem for projectile armor systems as well. On the higher level kinetic energy threats such as the 50 caliber AP round, it can be a tough problem to solve. LTV Corporation spent considerable time and effort designing deformable bracketry to mount the armor panels on the USAF A-7D aircraft just to attenuate the energy levels transmitted to the aircraft structure. The Army's Natick Laboratories have also fretted over the problem in the design of a ballistic infantry helmet. Their problem is a bit tougher, however, because if they stop the round, the transmitted energy is great enough to break the helmet wearer's neck, and a helmet suspension system capable of attenuating the energy is also much too heavy to wear! For these reasons, the U. S. Army Infantry is still using the old "steel pot" helmet which makes a good coffee pot but not much else!

THE A300B APU INSTALLATION

In the absence of firm requirements for rotor disc containment and the fact that the APU compressor is not secured against the egress of debris; Hamburger Flugzeugbau required additional shielding over a given area. This shielding is installed between the adjacent fire walls and the airframe structure of the APU compartment. The shielding protects both the hydraulic systems and the airframe structure from damage, so that the free operation of the horizontal elevators remains unimpaired.

THE FINALIZED DESIGN - DUAL PROTECTION

After the complete survey of ballistic impact tests were conducted, it was determined that a single panel design could be provided to protect both the low pressure and high pressure disc fragments. Norton designed this system using a constant thickness backing with two different boron carbide ceramic thicknesses. The total thicknesses of the two segments are 25 mm and 30 mm respectively.

The backing material consists of various plies of armor grade woven roving fiberglass in a special high temperature resistant polyester resin. The high temperature resin was used since the panels are subjected to the high temperature levels of the APU compartment during operation.

This panel design was then subjected to full environmental testing per MIL-STD-810 which included the following tests:

-Structural Performance Load Tests

-Fungus Resistance

-Humidity Test

-Salt Fog Test

-Fluid Resistance (Hydraulic oil, fuel, lubricating oil and Halon 1301 fire extinguishant)

-High and Low Temperature (-60°C to +150°C)

-Acceleration (-4.5G to +9G)

-Vibration Test (Method 514, Procedure I, MIL-STD-810B)

Following the successful completion of the environmental test program, the rotor containment system was certified for use on the A300B Aircraft. The A300B aircraft entered commercial service in 1974 and over 50 aircraft are now in service with the European carriers.

RECENT ADVANCES IN ARMOR TECHNOLOGY - WEIGHT SAVINGS POTENTIAL

There has been a significant improvement made in the performance of ceramic composite armor systems since the rotor containment system was developed and qualified for the A300B APU. This improvement could be directly applicable to this system to achieve an areal density savings of about 12%. This could translate directly to a weight reduction of 7.0 pounds per aircraft set of panels today with a minimum of requalification testing required. This improvement involves the replacement of the woven roving fiberglass backing with DuPont's Kevlar-49 organic fiber. Norton Company is considered the pioneer in the development of advanced design ceramic composite armor systems utilizing Kevlar-49 backing materials, and a summary of this development work applicable to crashworthy armored seats is discussed below.

BACKING MATERIAL IMPROVEMENTS

With the advent of the U. S. Army's request for proposals to industry for the Advanced Attack Helicopter, much emphasis was placed on eliminating parasitic armor completely or reducing the current areal densities required to defeat the specified ballistic projectile threats.

Theoretical penetration analysis techniques (THOR) indicated that a significant weight savings could be realized by replacing the conventional woven roving fiberglass (E-Glass) reinforced plastic with a newly developed synthetic fiber recently developed by DuPont.

Initial consultations began and soon various tests were underway by Norton to evaluate the validity of the hypothesis that a potential (7-8%) savings could be achieved by utilizing this material as a backing for the then "best" B_4C/E-Glass armor system.

Initially, the test results were not entirely encouraging, but inspired by DuPont, Norton attempted to reduce the variables affecting the performance of the backing to a minimum by utilizing essentially a one-for-one replacement of the E-Glass fibers alone by the Kevlar-49.

In a self-funded program, a comparable backing material was developed to the conventional E-Glass system with a resultant weight savings of about 30% over the E-Glass system. This program gained extreme interest and eventual further funding for ballistic verification by the U. S. Army's Natick Laboratories.

A number of ballistic verification tests were conducted to establish the validity of the initially encouraging results and the B_4C/Kevlar-49 system was approved by the Army for use as the armor system on the new advanced attack helicopter, thereby enabling the potential contractors a significant 10-12% weight savings in the Armor System.

The Kevlar-49 backing works well as an armor because of its outstanding physical properties as compared to E-Glass. As suggested by Wilkins et al, the synthesis of a new backing material that would be stiffer to more adequately support the ceramic and delay the onset of ceramic tensile failure is accomplished with the Kevlar laminates. At 19 million psi, it has the highest modulus of elasticity of any synthetic fiber, and is twice as stiff as E-Glass the most commonly used reinforcing fiber. Its high tensile strength and high modulus combined with its extremely low weight (1.45 g/cc - 40% less than the weight of glass), along with low elongation (2.8% at break vs. 4.0% at break for glass), high stress rupture, excellent impact strength and good vibration damping characteristics make it a natural for use as an armor backing.

SUMMARY

The development of the ceramic composite turbine disc protection panels for the A300B was a direct application of Norton's armor technology to a commercial application. In this case, the analytical predictions for modifying the ballistic projectile armor system were more than verified by the test program conducted to qualify the rotor containment system. In fact, with only a slight change in the areal density of the armor system a more than two-fold increase in kinetic energy protection level was achieved.

The assumption that guards used to protect against disc fragment damage to either the engine or aircraft components from failed turbine discs would impose intolerable weight and cost penalties upon the aircraft is disputed by this design. In fact, this concept is only slightly heavier than an integrally contained turbine engine but significantly less expensive on both a recurring and non-recurring cost basis.

Additional improvements in the state-of-the-art of armor technology also can now be incorporated into the rotor containment system to make this alternative even more attractive on a weight comparison basis to integral containment. The use of Kevlar-49 as a backing for the boron carbide ceramic has already been proven and qualified for use in the projectile armor systems, and its use for the rotor containment system could achieve a 12% weight savings over the current system.

Based on the successful application of Norton's Armor technology to this commercial application, and the significant increase in protection level that has been achieved, Norton has filed for patent rights in the U. S. and several foreign countries under Application Number 329,046. Patents rights are now pending in the U.S., U.K., France, Germany and Japan. This application is also covered in Italy under Patent Number 1004855.

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ABOUT THE AUTHOR

Paul B. Gardner is currently Business Manager for Armor and Spectramic Products in Norton Company's Industrial Ceramics Division. He joined the company in 1971 as a Project Engineer in Ceramic Components and in 1972 he was named Product Manager for the Armor Products Department. In his current position since late 1974, he has the responsibility for the business planning, marketing, sales and engineering of the Company's ARMOR, CRYSTAR and NORBIDE Product Lines. Prior to 1971 he held Experimental and Senior Experimental Engineering positions in Hamilton Standard Division of United Technologies' Aircraft Systems Department.

He received a BSME from the University of Rhode Island and an MSME from the Rensselaer Polytechnic Institute. He is currently a candidate for a Master of Science Degree in Management Science from the Worcester Polytechnic Institute. He holds a Registered Professional Engineers License in the Commonwealth of Massachusetts and is a member of the American Helicopter Society.

DISCUSSION

P. Gardner, Norton Co.

The compressor segment weight was 1.25 kilograms and the velocities varied from 175 to 260 meters per second.

G.J. Mangano, NAPTC

Paul, you made reference to high temperature. Could you tell me what the temperature was, how high?

P. Gardner, Norton Co.

We qualified the system at 300°F.

Question

How was the shield supported?

P. Gardner, Norton Co.

Only the four straps that I showed on the viewgraph supported the shield. These straps were attached to the aircraft structure at the Z-frame inside the firewall. The system weighed about 50 pounds, not including the weight of the straps. I do not recall the weight of the straps.

D. McCarthy, Rolls-Royce

Did you test a titanium shield mounted on the straps in exactly the same way?

P. Gardner, Norton Co.

No, we did not do any of the testing, it was done by Air Bus Industry, Hamburger, Flugzeugbau. Their test report indicates that they tested over 25 different materials, and had very little success, or had some very little success they could afford the weight for.

D. McCarthy, Rolls-Royce

I had the impression that the straps made quite a difference to the results.

P. Gardner, Norton Co.

The straps made some difference in the results. The initial test work was done with the armor panels mounted directly to the Z-frame of the simulated aircraft structure. The panels stopped the rotor segment, but the transmitted energy into the structure sheared the bolts off and the panel dropped away. So the straps were there to distribute that load more uniformly into the structure. That was not our design, that was designed by Hamburger Flugzeubau. If the actuators had not been in the wrong position relative to the APU, we probably wouldn't have had to contain anything.

C-4.