SPACE STRUCTURES: LESSONS FOR EVERYONE

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The origins of the Columbia disaster

The board investigating the Columbia Space Shuttle accident has recently (April 17, 2003) announced their preliminary findings and recommendations. Just as most people suspected, the breakup of the Columbia was related to the loss of or damage to a few carbon-carbon areas that are an integral part of the thermal protection system (TPS). (See Figure 1 which shows the carbon-carbon areas.) Even though other missions have flown and landed successfully with some damage to the TPS, those were damages to some other part of the TPS system rather than the carbon-carbon areas. Clearly, something tragically different occurred with the Columbia's last flight. We believe that a careful consideration of this disaster leads to important lessons for NASA and even to the more mundane manufacturing of typical FRP.

Lesson 1: History tells us why this flight was unique

Let us consider a story from World War II. During the middle part of the war (1942-1943), the Royal Air Force was flying daily bombing runs over German-occupied territory and airplane losses were devastatingly high. The German anti-aircraft fire was so intense that on almost every run most airplanes were receiving damage and about twenty percent of the planes were shot down. The RAF could not continue to sustain that level of losses but the suggestions on reducing the losses all seemed to have some problems. For instance, the planes could not fly higher because they were not pressurized and, moreover, they had some inherent limitations on altitude. The RAF couldn't cover the bottom of the plane with armor plate because the planes would be too heavy to take off.

Finally, a mathematician known for his ability to carefully analyze problems was asked to help. The mathematician began his analysis by examining the planes that were returning. After several days of these examinations, the mathematician made a brilliant discovery which led to a suggestion that resulted in a significant reduction in the number of planes that were lost.

What was the brilliant discovery? The mathematician reasoned that, taking the entire squadron as a whole, the anti-aircraft damage would be random over the entire under-surface of the airplanes. But, that is not what he saw. He found that there were some areas on the planes that were not damaged. How could that be? He then realized that he was looking at only the planes that had survived the flights. The planes that did not survive must have been those planes that received damage in the areas where he had not seen damage. Those areas, he reasoned, must have been the critical areas of the plane and when damage was received there, the plane would be lost.

His suggestion was, therefore, quite simple. He suggested that the RAF put armor only in the areas of the planes where no damage had been observed on the surviving planes. These were the critical areas for survival of the aircraft. The areas to be armored were not so many that the weight was excessive and the number of airplane losses was cut in half.

What does that have to do with the Columbia accident? We think that it is logical that the areas on the Columbia where damage occurred were critical areas. Previous TPS damage on other flights was obviously not critical and so those flights survived. Why didn=t NASA realize how critical the performance of a these specific areas of the TPS could be? The probably answer is that NASA hadn=t really tested for criticality of various areas (although some critical areas would be obvious).

What does that lesson have to do with FRP manufacturing? Some combinations of manufacturing defects and end use environments produce unanticipated results. Manufacturers should take the effort to clearly identify the areas or the properties of their products that are critical to its success. These critical product characteristics should be protected with special care and robustness. That protection should include testing and a determination to never compromise on the integrity of the critical characteristics.

Lesson 2: The broken window theory

This theory grew out of an observation made in New York City in the 1990's and it has direct application to both the Columbia accident and your FRP business. As discussed in the book *The Tipping Point* by Malcolm Gladwell, according to this theory, if a window is broken and left unrepaired, people walking by will conclude that no one cares and no one is in charge. Soon, more windows will be broken, and the sense of anarchy will spread from the building to the street on which it faces, sending a signal that anything goes. In a city, relatively minor problems like graffiti, public disorder, and aggressive panhandling are all the equivalent of broken windows and are invitations to more serious crimes.

When the officials of New York City began to immediately repair broken windows, remove graffiti, stop people from jumping the turnstiles in subways, clamp down on muggers and various other relatively minor crimes, the incidence of major crimes also declined dramatically. The criminals realized that someone was in control. Even more important, an attitude was developed among the City officials and among the populace that even the smallest problem needs to be fixed and everyone has the responsibility to do their best to fix it.

NASA engineers and officials had become accustomed to seeing missing or damaged TPS on returning the space shuttles. Given that the design was qualified (tested to be sure that the design was able to meet all requirements), the missing/damaged TPS was considered to be either evidence of a combination of circumstances not tested or manufacturing/installation defects.

Given that the TPS has long been an area of concern based on a combination of the extreme temperatures of operation, the generally brittle nature of the materials, the complexity of the fabrication processes, human-intensive installation, complex assessment, refurbishment and repair processes, and custom tailored installation to accommodate the curved surfaces of the vehicle, the opportunities for a problem to develop are many.

A combination of declining budgets and the growing body of data that indicated that some loss of TPS does not cause catastrophic failures induced some measure of tolerance for little problems.

For the FRP manufacturer, the lesson is simply this: The company will work better if the small problems are taken care of. Furthermore, problems that seem to be inherent in the system should be solved because the ultimate result might be a disaster (such as a massive product recall). In summary, don't be satisfied or even resigned to a situation where a problem persists.

Lesson 3: Testing and quality control are critical

The Columbia Accident Investigation Board suggested that NASA should now implement a strong program of testing of the reinforced carbon-carbon composite TPS components of the shuttle, making use of both non-destructive testing on the actual shuttle and destructive testing on a control panel that is made parallel to the actual shuttle parts. Some of the testing methods currently employed include: physical tap, ultrasonic, radiographic, eddy current, weight gain, and visual tests. These should be upgraded and new methods identified to assess the structural integrity of the composite supporting structure and attaching hardware. Tests of the shuttle after each flight should be improved and should be directed toward evaluating the longevity and performance of each of the components, especially those made of composites, so that routine maintenance and replacement can be initiated.

The Investigation Board also noted that the U.S. Government has the capability of imaging the shuttle while it is in orbit. Such imaging is to be required on each future flight.

What was the problem with the testing done before the accident? Maybe nothing, but the Board's report points out potential improvements that may have prevented this accident. We have seen similar cases where testing has been considered to be merely a method of assuring compliance rather than a method of ensuring performance. Every manufacturer should remember that quality testing is a method to assist in making sure that the part will perform as intended and to monitor with ongoing vigilance the capability of the manufacturing process. Testing and quality control are not just a series of hoops to be blindly jumped through.

Lesson 4: Materials are critical to success

An old saying asserts: Everything is made out of something. Clearly the Columbia's accident occurred because of the failure of the materials it was made of. Our guess at the scenario of failure was that some of the thermal insulation on the structure that holds the external tank to the Shuttle hit the Shuttle=s leading edge (reinforced carbon-carbon composite) causing damage to the brittle carbon-carbon areas. This may have been of sufficient severity that a path was created for the re-entry heat to reach unprotected and critical subsurface elements.

In the case of materials for space vehicles, including Columbia, selecting materials and understanding their behavior in the many environments to which they are exposed provides special challenges. Much of the work that underlies the exploration and use of space is directed toward the development of materials that can meet the stringent requirements of survivability in space and, at the same time, be light enough that they can be launched economically. The space environment includes the following:

Vacuum. Even though the vacuum of space increases with altitude, the effects of vacuum are evident at all orbits over about 30km. One major problem with a vacuum environment is the inability to transfer heat through convection, the most efficient of the heat transfer mechanisms. Therefore, space structures often have very large surface areas to facilitate heat dissipation through radiation. Vacuum is also and environment which encourages outgassing of the plastic. This is the loss of small molecules (such as unreacted monomer or co-reactant) that are often present in the resins. The scarcity of all molecules in the vacuum means that the outgassed molecules are able to travel for significant distances without diversion. These molecules can then be captured by and deposited on another surface, sometimes one that is sensitive to the contamination (such as optics or solar arrays).

Neutral atoms and atomic oxygen. The neutral environment consists of a variety of gases, some of which exist as single-atom species rather than the more common double-atom molecules found on earth. The most important of these atomic species is oxygen, which is highly reactive with many organic materials. As can be seen in Table 1, the reaction efficiency (that is, the tendency to react with atomic oxygen) is nearly no reaction (designated as 0 in the table) for metals. However, for polymeric materials, the reaction efficiency can range from 0.03 for Teflon7 to 3.9 for Mylar7 (a polyester).

Plasma. Plasma is an environment of electrons and protons that causes uncontrolled electrical charging and discharging as well as the dielectric breakdown of the materials. These effects are diminished by coating materials with stable conductive coatings such as indium tin oxide and special efforts to ensure grounding of the devices.

Radiation. Although radiation has a degradation effect on polymers similar to the aging effects observed on earth, the most serious problems from radiation (at least short term) are with electronic components. The solutions that are applied are to build the components to be radiation hardened, to design in fault tolerance, and/or to provide shielding with a metal such as aluminum.

Micrometeoroids/debris. Natural space materials and man-made debris can impact the space structure as it flies through space. The possibility of encountering debris is expanding rapidly as the number of launches continues and as the satellites now in the orbit fall apart. The Shuttle windows have sustained multiple impacts and are periodically replaced.

Launch environment. The highest structural loads a space structure normally encounters are during the launch (or in the case of the Shuttle, launch and landing). Designing for reduced weight to improve performance (payload to orbit) puts special emphasis on making the structure only just strong enough (with margin) to withstand the expected environment.

Even though these special environments are for space vehicles where much of the testing cannot be duplicated on the ground, the importance of understanding the material properties and behaviors when exposed to a wide variety of environments, even environments not anticipated, provides significant insight into the initiation of potentially catastrophic events. This insight should lead to an early evaluation of consequences and contingencies, something every FRP manufacturer should also explicitly include in their planning.

In addition, the importance of maintaining the properties of the materials cannot be overemphasized at NASA or at any FRP manufacturing site. We use composites for many applications, including space applications, because of their desirable properties; and so we should guard those properties with great care.

Conclusion

Though space vehicles are specialty items, the space program is a rich source of information that can be applied in many other areas. Not only can we obtain knowledge from actual excursions into space (generally with great difficulty, cost and time), but we can also gain valuable knowledge because space hardware must first be tested as components, subsystems and then as a part of a system and finally in orbit., The development cycle for these complex vehicles averages about 10 years and the operational cycle is 5-15 years in addition. Hence, the investment for a space vehicle can be very high. A typical satellite investment is $400 million and a launch vehicle adds to this price tag. Estimates of the cost per pound of cargo are as high as $20,000.

These investments are at risk when we consider the things that can go wrong and wipe out the investment with a single detail gone awry. Space vehicles might self destroy (usually due to a propulsion problem). They might veer off course with potential to hit land and are therefore destroyed in flight to preserve public safety. They might be launched into an incorrect orbit. Even if they achieve the right orbit, they might not work as planned. Each of these failure modes is real and, sadly, possible.

Nevertheless, space vehicles continue to be made in ever increasing numbers. They are low volume products, but the potential for profit has proven to be very high. For NASA, the contributions to the nation via the products developed initially to meet the unique challenges of space and subsequently passed into the general economy (commercialized) have been many. These collateral applications are important to NASA, as reflected in the NASA mission and goals (see sidebar). Space vehicles continue to be very important for the military as was evident in the war in Iraq. Hence, space vehicles have a place in the future and composites have an important place as components of space vehicles.

Though there are many applications whose designs, materials and manufacturing will never produce the highly dramatic and catastrophic failure of the Columbia, there are nevertheless some lessons we can derive from this tragedy.

1- Anticipate and plan for all of the potential consequences of combinations of environments and the results of less than perfect manufacturing process.

2- Take care of the small problems as they come along

3- Stay vigilant that the testing and quality control processes do not become rote. They can be harbingers of bigger things to come.

4- Materials are critical; their selection, design, and manufacturing are key to a product=s ability to perform in not only the anticipated environment, but in ways never intended.

Finally, as composites are developed and modified for application to space vehicles, we should be alert for the potential value to our own businesses. New materials, processes, designs, quality control and testing methods could all be key to remaining competetive.

References

Gladwell, Malcolm, *The Tipping Point*, Boston: Little, Brown and Company, 2002, p. 141.

Harris, Charles E., Mark J. Shuart, and Hugh R. Gray, "Emerging Materials For Revolutionary Aerospace Vehicle Structures and Propulsion Systems," *SAMPE Journal*, Vol. 38, No. 6, November/December 2002, p. 33-43.

www.nasa.gov

Critics Scrutinize Cost of Shuttle, The Associated Press, http://www.usatoday.com/news/nation/2003-02-04-shuttle-critics_x.htm

Tribble, Alan, The Space Environment, Implications for Spacecraft Design, Princeton, NJ: Princeton University Press, 1995

Sidebar

The mission of NASA is to:

Advance and communicate scientific knowledge and understanding of Earth, the solar system, and the universe;

- To advance human exploration, use, and development of space; and
- To research, develop, verify, and transfer advanced aeronautics, space, and related technologies.

To fulfill this bold mission, NASA has adopted the following long-term goals:

1. Create a virtual presence throughout our solar system and probe deeper into the mysteries of the universe and life on Earth and beyond,
2. Use our understanding of nature's processes in space to support research endeavors in space and on Earth,
3. Conduct human and robotic missions to planets and other bodies in our solar system to enable human expansion,
4. Provide safe and affordable space access, orbital transfer, and interplanetary transportation capabilities to enable research, human exploratiokn, and the commercial development of space, and
5. Develop cutting-edge aeronautics and space systems technologies to support highway in the sky, smart aircraft, and revolutionary space vehicles.

–Adapted from "Emerging Materials For Revolutionary Aerospace Vehicle Structures and Propulsion Systems" by Harris, et. al. (See references)

Table 1 Atomic Oxygen Reaction Efficiencies for Common Materials

Material	Reaction Efficiency (Tendency to React)
Aluminum	0
Gold	0
PTFE (Teflon7)	0.03-0.5
Carbon	0.9-1.7
Silicone (RTV)	0.443
Polyimide (Kapton7)	1.4-2.5
Epoxy	1.7-2.5
Polyester (Mylar7)	1.5-3.9

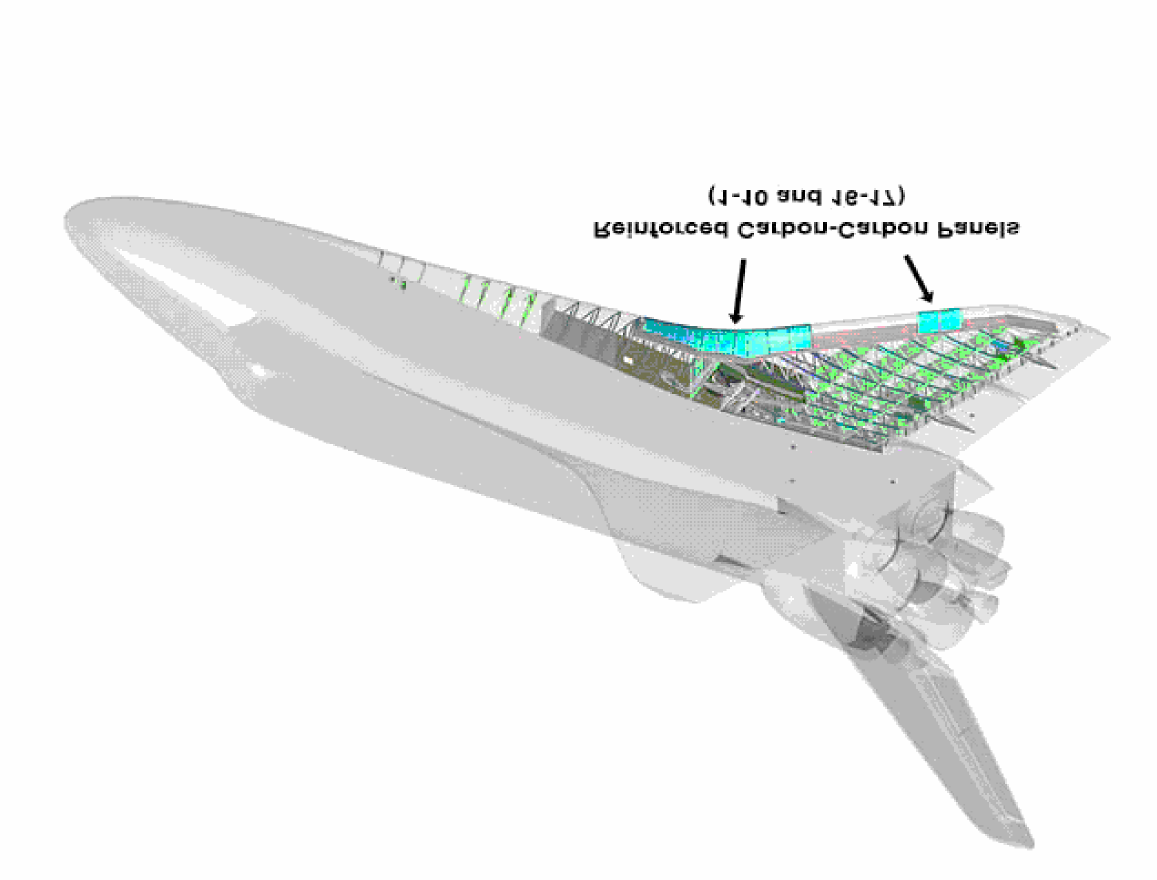

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Figure 1 Diagram of the Space Shuttle showing the areas of reinforced carbon-carbon material

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