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Structural Health Monitoring Methods for Flight Safety

Manufacturers of material and structural systems such as commercial vehicles are striving to improve their competitive advantage by decreasing design conservatism and increasing product aftermarket profit margins in maintenance, warranty, and performance. Defense agencies are also working to transform the military infrastructure to reduce conservatism, weight, and vulnerability in their vehicle and weapon systems.

Structural Health Monitoring (SHM) is an important technology because it could help to increase safety, decrease life-cycle costs for maintenance, and reduce design conservatism by identifying loads, damage, and remaining life in real time as systems evolve. Structural Health Monitoring is the interdisciplinary engineering process of blending different kinds of models and data interrogation techniques with integrated sensory networks to identify loads, the damage they cause, and the evolution of that damage in material and structural systems. The principle advantages of SHM over conventional nondestructive testing methods are that SHM requires less time to carry out and is conducted online when systems are loaded, making loads and certain forms of damage more apparent.

Researchers from the Ray W. Herrick Laboratories at Purdue University recently demonstrated three complementary methodologies in SHM for aircraft and spacecraft materials and structures at the *Second European Workshop on Structural Health Monitoring* in Munich, Germany.

First, the quality of manual riveting processes, which are used exclusively for commercial and military aircraft repair work, was examined. Quality assurance indicators were developed based on the loads acting across the rivet gun-part interface to identify riveting processes with skewed delivery (gun or bar), circular indentations, and bucking bar slip to define susceptibility to future damage in fuselage structures. Such riveting errors can set up harmful residual stresses near rivet holes, leading to future corrosion, fatigue, or exfoliation damage. This work was performed in collaboration with Kumar Jata, a technical adviser in the Metals, Ceramics and Nondestructive Evaluation (NDE) Division of the U.S. Air Force Research Laboratory/Materials and Manufacturing Directorate (AFRL/ML) at Wright-Patterson Air Force Base (WPAFB) in Ohio.

Second, using a semi-realistic combined thermo-acoustic testing apparatus, it was demonstrated that certain types of local damage in mechanically attached thermal barriers in spacecraft are less apparent offline than online when operating temperatures are acting. Damage indicators developed using passive response data were shown in experiments to be effective at detecting and locating damaged standoff bolts in metallic panels. Such a SHM methodology could be used to reduce the service and turnaround times of vehicles equipped with such panels. Current thermal barriers on the *Space Shuttle* orbiter take several months to inspect and replace. This work was performed for Mark Derriso in the U.S. AFRL Air Vehicles Directorate.

Third, beamforming methods for steering elastic waveforms and processing phased sensor array data were used to identify low-level incipient damage in large friction stir welded metal tank structures. This type of global damage is difficult to find in such unitized structures, so guided elastic waves provide a means to quickly inspect large areas. This active diagnostic method was previously applied to detect and locate damage in metal and laminated composite types of armor. This work was performed for the U.S. AFRL/ML.

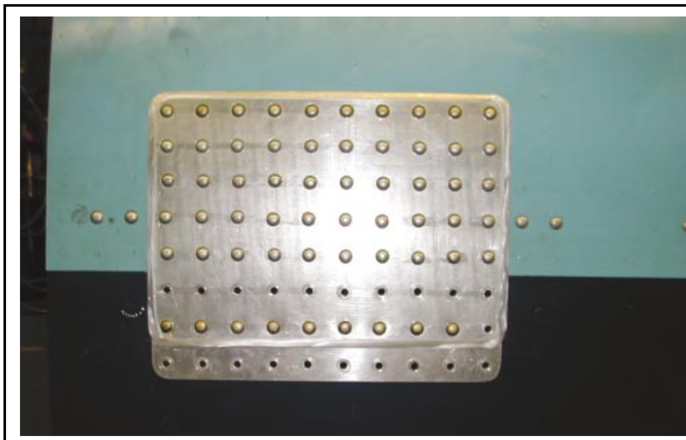

Fig. 1 Structural component with rivets

Commercial Airliners—A Riveting Idea

Commercial airliners have up to a million rivets (Fig. 1), some of which are unavoidably created with imperfections that make them more susceptible to corrosion, leading to cracks that could result in serious failures.

"Corrosion and corrosion-fatigue cracks emanate from fastener holes and, therefore, are dominant problems in the aircraft industry," said Kumar Jata. "If the rivets are loose, for instance, your structure is going to start rattling. You don't want that because you are causing fatigue. As cracks develop and grow, they eventually link up and can cause catastrophic accidents in which the fuselage loses its strength and gives way."

Riveting in new aircraft is done with automated machines, whereas repairs to older aircraft are performed manually by two workers, one wielding the rivet gun while the other holds a "bucking bar" on the opposite side (Fig. 2). As the riveter pushes the rivet through the hole, the other worker positions the bucking bar on the opposite side of the hole so that the rivet hits the bar and is hammered snugly into place. "This happens very quickly, roughly three seconds for each rivet, in rapid-fire succession," said Douglas Adams, an assistant professor of mechanical engineering at Purdue. "Inevitably, some of the rivets are created with flaws." Sometimes a worker holds the rivet gun at the wrong angle, causing the rivet to go in sideways. At other times, the riveter holds the trigger of the gun a few seconds too long or pushes too hard on the gun, creating indentations around the rivet in the skin of the aircraft's fuselage, or the worker holding the bucking bar sometimes pulls it away prematurely, preventing the rivet from forming completely. "Even the automated machines can introduce flaws that are not detected," Adams said.

Engineers and technicians currently have no way of knowing which rivets are inferior, so Adams is collaborating with the AFRL/ML and researchers in Purdue's School of Aviation Technology to develop a system that tracks the quality of every rivet. Accelerometers attached to a rivet gun (Fig. 3) record information as each rivet is created. The data is later interpreted by a computer to determine the quality of the rivets.

Fig. 2 Two-person riveting team

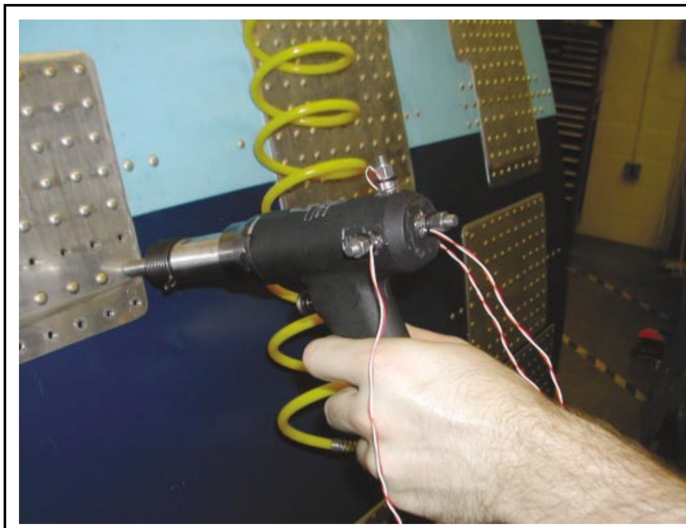

Fig. 3 Instrumented rivet gun

As larger commercial aircraft are being built, the ability to monitor the quality of rivets is becoming increasingly important, Adams said. "One of the great challenges when you've got something with a million rivets is, 'How in the world do you identify the bad ones?' Talk about a hard problem! One quick way to observe obvious surface corrosion is to walk around the aircraft and visually inspect it. You often see a pilot walking around an aircraft before takeoff. One thing pilots look for is signs of corrosion and other defects around rivet holes. To find hidden corrosion requires many labor hours and sophisticated nondestructive evaluation methods. The likelihood of catching corrosion sites before they become dangerous should not be left up to visual inspections and other conventional methods."

"We are trying to use a technique like this to make a map that shows where the sub-par rivets are," Adams explained. "Such maps would help to guide the ground inspections by alerting technicians to locations that are more susceptible to corrosion." Ground crews could focus on these areas when inspecting aircraft.

After more development

and commercialization of this technique, such a system could be used for military aircraft as well.

Spacecraft Heat Panel Monitors that Work Best Under Pressure

With a technique that employs vibration and sound measurements to detect subtle damage in structures, heat-shielding panels on spacecraft could be constantly monitored from liftoff to landing to ensure safety.

"Future space vehicles and hypersonic aircraft may be equipped with a structural health monitoring system that constantly records how vibration and sound waves travel through materials and structures to detect damage as it occurs in real time," said Adams. "Otherwise, large numbers of ground inspectors would need to spend a great deal of time looking for damage between flights. There is also a possibility that subtle damage just beginning to form, which could later lead to accidents, will not be detected."

Moreover, his research shows that such a detection system would be most effective during periods of highest stress—while the vehicle is taking off and reentering the atmosphere—when it is subject to the greatest pressures and temperatures. During those times, because of the way vibrations travel through the heated metal panels, certain kinds of damage are easier to detect in flight than while the spacecraft is sitting on the ground.

"The fundamental advance we have made is that we have shown that unless you monitor for damage and loads while the vehicle is in the most severe part of the mission, you will likely miss incipient damage," Adams stated. "We are developing mathematical models and data-analysis methods that overcome challenges to identify damage in real time. It's very important to note that damage is much easier to detect while the metal panels are heated during flight. That's because extremely hot temperatures reduce the stiffness of the metal, changing how the panels vibrate and making the flaws easier to detect with our techniques."

"...unless you monitor for damage and loads while the vehicle is in the most severe part of the mission, you will likely miss incipient damage."

The panels have to withstand temperatures ranging from roughly –250 °F in space to 1800 °F during reentry. "And you are talking about that change occurring in a relatively short period of time," Adams continued. "On top of those rapid temperature changes, you have extreme acoustic loads—noise loud enough to burst your ear drums. These sound levels are much higher than at a rock concert. The loud noise causes vibration and sound pressure that continuously pulsate and produce forces on the panel."

A new generation of metal thermal-protection panels, developed by Goodrich Corp's Aerostructures Group (Chula Vista, Calif.), are made of a "metallic sandwich" material capable of withstanding high temperatures and pressures. Each panel consists of two outer face sheets bonded to an inner honeycomb core (Fig. 4). Adams is helping the U.S. Air Force and the National Aeronautics and Space Administration (NASA) develop a SHM system for the panels, using sensors to record the different responses of vibration and sound waves passing through damage caused by cracks and other flaws.

Researchers used the monitoring system to detect impact forces such as those exerted by a heavy tool being dropped on a panel—simulating and identifying resulting damage to bolts and the panel itself (Fig. 5). "If a micro-meteoroid or other form of debris strikes a panel, we want to identify how hard it hit that panel, because designers know how much force the panels can withstand," Adams said. "If a force goes above a certain level, then we know that we ought to replace that panel the next time around."

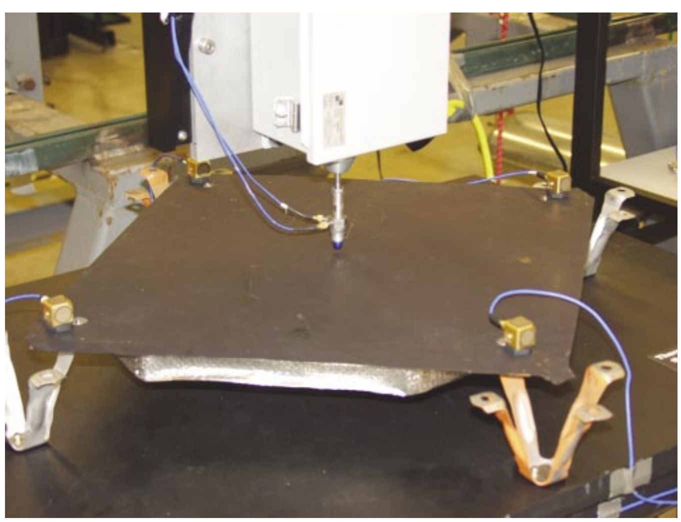

Fig. 4 *Three-layer sandwich-type honeycomb composite mechanically attaches to airframe with standoffs*

Unlike the current space shuttles' ceramic tiles, the metallic panels could be easily replaced within minutes. Tiles on the *Space Shuttle* must be glued onto the orbiter using strain-isolation pads in a process that takes days. Future spacecraft and hypersonic aircraft that travel several times the speed of sound will likely have heat panels that are bolted in place. Replacing the panels would be simply a matter of unbolting the old panel and attaching a new one, said Mark Derriso, an engineer leading the work in SHM at the AFRL.

Fig. 5 *Purdue researcher Douglas Adams strikes a spacecraft heat-shielding panel with a special hammer equipped with a sensor, while a graduate student, foreground, watches data showing how the panel responds to the vibration caused by the impact. Purdue News Service photo/David Umberger*

The Air Force is developing technologies for a proposed "space operations vehicle," which will need a new kind of thermal protection system for reentering the atmosphere. "One of the main goals is for this new vehicle to have a fast turnaround time from one mission to the next," said Derriso. "Obviously, a critical advantage of these heat panels is that they are mechanically attached. Right now the shuttle uses an adhesive to bond the tiles onto the airframe. Even if you detect damage in a particular tile, it's going to take a long time to replace that tile because you have to clean and prep the surface and re-glue these tiles back on—all of which takes time."

The innovative metallic heat-protecting panels were tested as part of NASA's experimental X-33 spacecraft program, one early concept for a space operations vehicle. The proposed spacecraft never flew but was tested in specialized chambers that recreate the extreme conditions of launch, space flight, and reentry. The chambers, located at WPAFB, are the only ones capable of simultaneously simulating all of the conditions, including extreme pressures, temperatures, and noise.

Goodrich Aerostructures created approximately 1300 of the special panels for the X-33. The panels performed well and are available for future space vehicle applications, said Paul Kukuchek, an engineers for Goodrich.

Another advantage of the panels is that they could be replaced in space. However, because many of the panels have unique shapes, the crew would have to haul hundreds of replacement panels to ensure a match for a specific damaged panel. A more practical approach, Kukuchek said, might be for crew members to repair damaged panels in space and reattach them before reentry.

Keeping Spacecraft Fuel Tanks Coming Back for More

A SHM system will likely be used to pinpoint damage in a new class of large metal fuel tanks for the previously described space operations vehicles, which would fly many more missions than the current space shuttles. "If you are going to be performing many missions, that means the tank is going to be used over and over again, so it's critical to have a health monitoring system that constantly checks for damage," said Jata.

The system uses a high-frequency actuator (miniature loudspeaker) to produce sound waves that travel through a material. The sound creates vibration waves that are picked up by an array of sensors. An onboard monitoring system that looks for signs of damage in vibration wave patterns would be critical, said Adams, because the fuel tanks would undergo extreme changes in pressure and acceleration during launch and while re-entering the Earth's atmosphere.

Engineers have recently demonstrated that the system effectively detects and locates subtle damage in a new lightweight alloy that will likely be used to create fuel tanks (Fig. 6a)

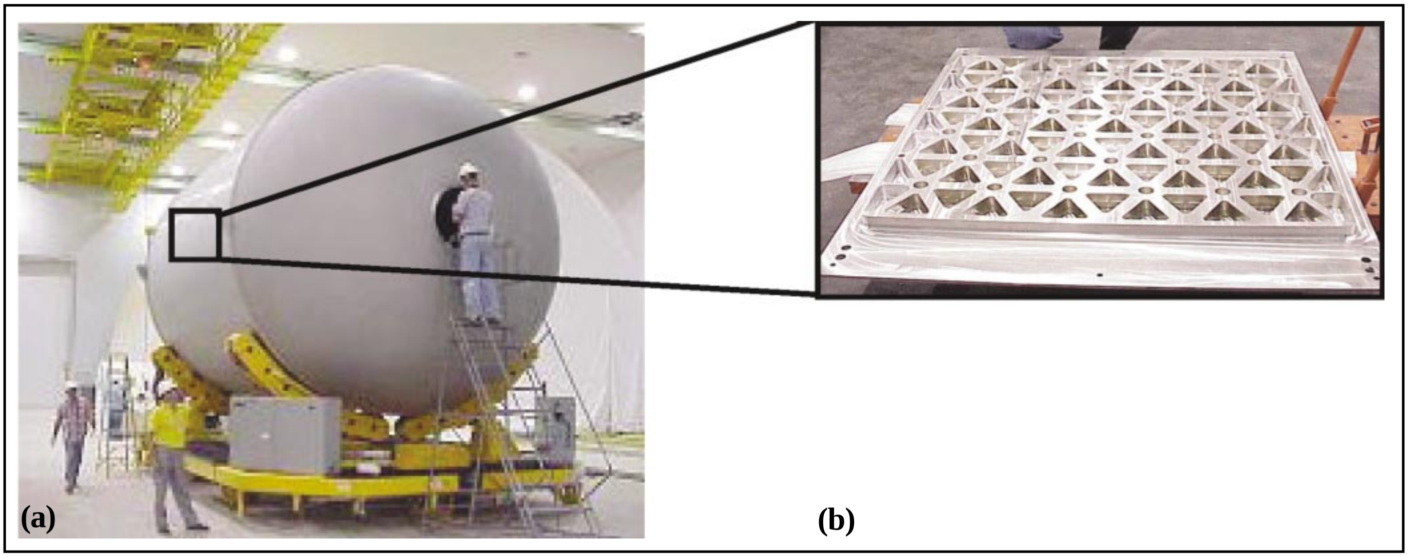

Fig. 6 (a) Aluminum-lithium friction stir welded tanks. (b) Isogrid stiffeners

for future spacecraft and satellites. Adams explains, “The tanks, made from a very lightweight aluminum-lithium alloy, will hold cryogenically cooled fuel and/or liquid oxygen for rocket motors. These tanks are enormous and they are quite thin-walled, which means they are quite flexible. They flex, squeeze, and undergo acoustic loads from the extremely loud noise of rocket launches.”

The tank walls contain a machined grid (Fig. 6b) that looks like a continuous pattern of adjacent, rib-like triangles that provide extra strength without adding much weight to the structure. Jata helped develop the alloy, working with the Alcoa Technical Center near Pittsburgh. “The Air Force has been the driving force behind that material, because it provides you with a lot of weight savings,” Jata said.

The experimental fuel tanks are manufactured using a new type of welding in which a rotating pin “stirs” the metal from opposing plates (Fig. 7) until they form into a single piece. The method, called friction-stir welding, creates welds many times stronger than conventional welds, which weaken materials by melting them, Adams said. “The rotating pin causes the metal to plastically deform, and it stirs it, literally. It looks like you’re making a milkshake. As you make this milkshake along the weld, the material comes together and joins.” Unlike conventional welding, the two plates being welded are not heated to the point of melting. “When you melt a

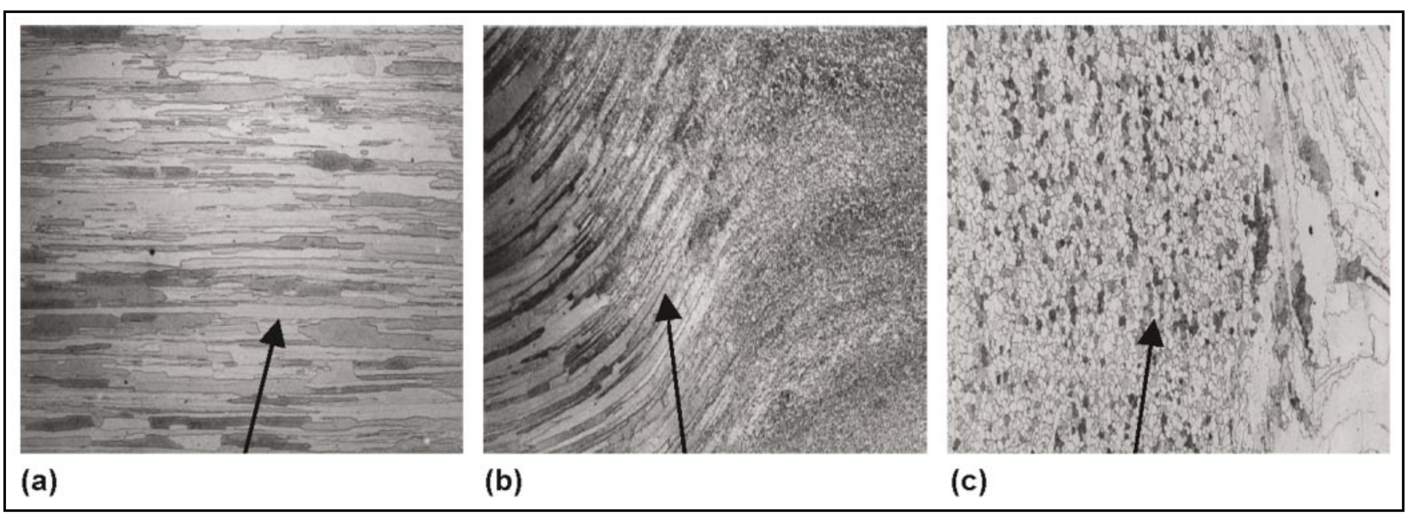

Fig. 7 Microstructure across weld from: (a) outside, (b) thermomechanically affected zone, and (c) nugget region/stir zone

material and it recrystallizes, you are weakening the material," Adams said. "You can get voids, and when something breaks, very often it breaks at a weld. The new friction-stir welding method gives you much better strength and toughness than competing welding methods that have been in existence for many years."

Adams said the onboard monitoring system could save time and money by telling technicians when a part was damaged or worn out, cutting down on unnecessary scheduled maintenance. Technicians would still have to perform routine NDE on the spacecraft after each flight. Such tests include using a dye that changes color if damage is present in a material, handheld devices that use high-frequency sound waves to detect damage, and eddy current sensors that use electromagnetic fields to analyze material. "We have very reliable NDE techniques, but they take time and increase the operations costs," Jata said. "If you have a good, robust health monitoring system in place, then perhaps you could reduce the inspection time after each flight."

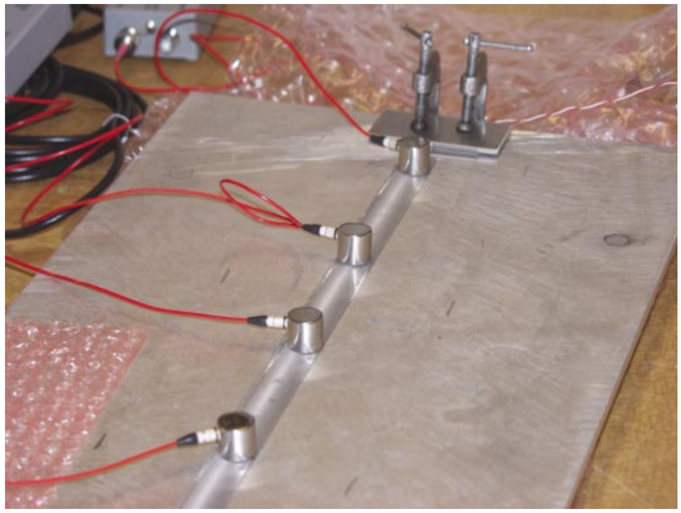

Fig. 8 *Aluminum-lithium friction stir welded coupon for tests with acoustic emission sensors and piezo actuator*

Findings from the research show the system was able to not only detect incipient damage, but also to pinpoint its location on a flat piece of the alloy (Fig. 8). Adams developed an algorithm, or software that uses mathematics to analyze vibration patterns with "wavelet transformations," that breaks data into pieces to help detect and pinpoint tiny changes in the signals.

"The incipient damage is smaller than a crack but, if left undetected, could eventually become larger and pose a safety threat," Adams said. "We simulate this sort of damage by heating a very small spot of material with a localized heat source. The heating is not high enough to melt the metal, but it temporarily creates changes in the microscopic structure of the metal—the same kind of changes seen in incipient damage. The heating does not create permanent damage, so we are able to conduct numerous tests in different locations simply by applying the heat source to those locations."

Jata said such metallic cryogenic tanks with onboard health monitoring systems could be used within the next 10 to 15 years in the military spacecraft.

The next step in the research will be to test the monitoring system on curved pieces of the alloy, instead of the flat pieces used in the current work. The curved segments will be similar to the curved walls of actual tanks, said Jata.

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