Structural Health Monitoring of Strategically Tuned Absolutely Resilient Structures (STARS)

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ABSTRACT

Strategically **T**uned **A**bsolutely **R**esilient **S**tructures (STARS) are being designed to store potential energy in the form of elastic deformation that can be released in a controlled fashion as work or kinetic energy. This paper outlines steps being taken to monitor the structural health of STARS by making modifications to a Remote Readiness Asset Prognostic and Diagnostic System (RRAPDS). The latter is being developed by the U.S. Army Aviation and Missile Command Research, Development and Engineering Center (AMRDEC)/U.S. Army Tank Automotive and Armaments Command, Armaments Research, Development and Engineering Center (TARDEC) to monitor health/condition and deliver advanced diagnostics/prognostics while an asset (i.e., missile) is tactically deployed, in storage, and/or being transported. As an example of this application, it is described how and why accelerometers are being redesigned to quantify the dynamic performance of "ConQuest," Team UAH's entry in the 2004 ASCE/MBT National Concrete Canoe Competition.

INTRODUCTION

The STARS concept makes it possible to build a structure capable of storing potential energy in the form of elastic deformation that can be released in a controlled fashion as work or kinetic energy [1]. As described below, composite sections made from a new class of **G**raphite **R**einforced **C**ementitious **C**omposite (GRCC) materials are being designed for this purpose based on the strength, stiffness, and the position of the component materials [2-5]. The ability to store and release energy depends upon a complex interaction between the shape, modal response, and the forcing function initiated to the structure. Since the method relies on energy recovery through elastic deformation, steps must be taken to prevent damage by monitoring the structure to insure that it remains absolutely resilient. The Remote Readiness Asset Prognostic and Diagnostic System (RRAPDS) has been targeted for this task [6].

RRAPDS

DoD leadership has recognized the importance of health monitoring and failure prediction in weapon systems as a goal towards successfully sustaining a combat effective fighting force. As a result, steps are being taken to include the tools for logistics situational awareness and embedded diagnostics and prognostics in all new weapon systems.

RRAPDS is being developed to provide an integrated system transparent to the war fighter that monitors health/condition and delivers advanced diagnostics/prognostics while an asset is tactically deployed, in storage, and/or being transported. As illustrated in Fig. 1, the RRAPDS concept consists of an assembly of low-power sensors located on the weapon system to collect environmental data, a processor termed the Asset Electronics Package to autonomously control RRAPDS operation, a power source capable of IO or more years of continuous system life, a capability to transmit real-time data, and the necessary tools to provide seamless users interface.

RRAPDS devices have the potential to monitor environmental conditions and collect temperature, humidity, and vibration/shock data to improve the reliability of STARS. The system allows for real-time access of source data and can provide critical information needed to monitor and control the structural response. Sensor data analyzed by data mining algorithms and predictive trending has the potential to extend life and save maintenance costs. All data can be time stamped to enhance the diagnostic and prognostic capability; and, over time, data collected can be used to refine composite designs and improve reliability, resulting in an improved overall life cycle.

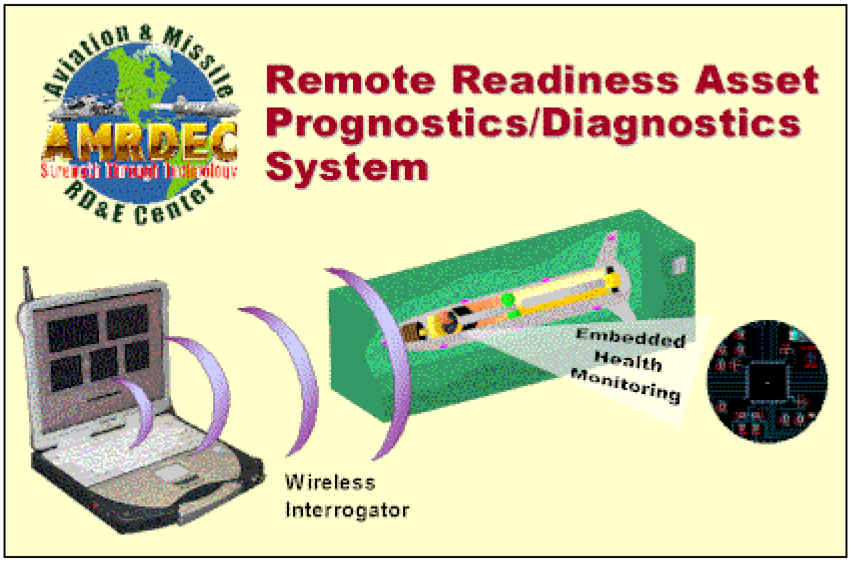

Figure 1. RRAPDS features wireless communication links and embedded sensors.

Significant variables and trends can be identified using data mining techniques. Data collected can be analyzed to update design parameters such as failure rate of components, test costs, environmental thresholds, etc., and to predict spare parts requirements.

For STARS applications, on-line health monitoring and smart diagnostics/prognostics strategies will lead to significant savings in the total life cycle costs by improving a structure's reliability, maintainability, and availability. RRAPDS will allow for real-time access of source data and, in military applications, provide critical information needed for reduced sustainment costs and enhanced readiness. Sensor data analyzed by data mining algorithms and predictive trending has the potential to extend life and save millions in maintenance costs. Over time, data collected can be used to refine structural designs and improve reliability, resulting in an improved overall life cycle.

STAR STRUCTURES

A STAR structure is unique in that the component materials are purposefully stressed and deformed to the largest extent possible in order to store the maximum amount of potential energy. They are much more complex and versatile than other more simple energy storage devices such as springs. In general, component materials that have very large differences in stiffness characterize STARS and the composite structure is designed to be absolutely resilient such that it can sustain very large deformations without compromising structural integrity.

Figure 2 illustrates that one method for achieving large deformations is to drive the STAR structure to controlled resonance by using a forcing function having a frequency close to the natural frequency.

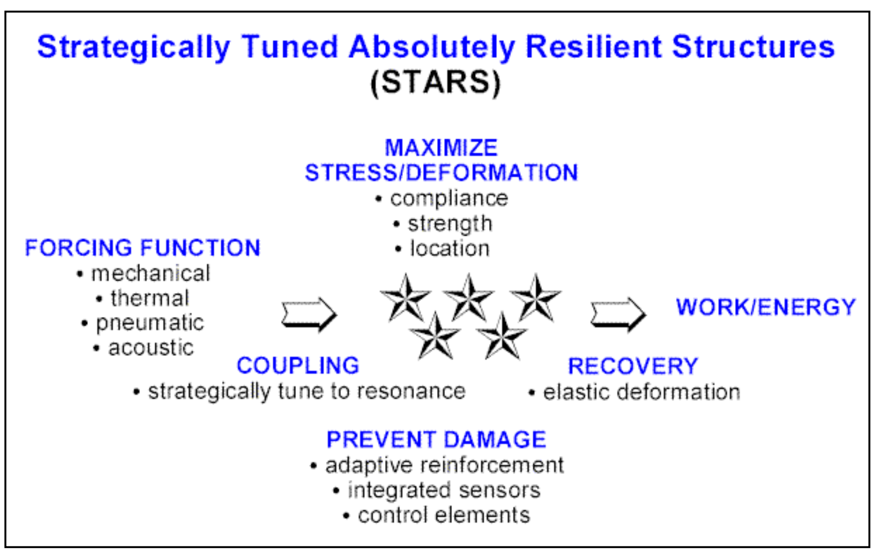

Figure 2. How "STARS" work.

Using adaptive reinforcement can prevent damage. Control elements may be employed to adjust the dynamic response of the STAR structure in real time. The overall design goal is to make STARS absolutely resilient so that potential energy, stored as elastic deformation, can be completely recovered and efficiently converted into work or energy.

FIRST GENERATION STARS

Pioneer research involving STARS focused on producing a new generation of thin, lightweight, and structurally efficient panels capable of resisting the dangerous stresses procuced by reverse loading [7]. The study showed that a very efficient composite structure could be fabricated by placing a flexible polymer-enhanced cementitious matrix having a relatively low elastic modulus over two layers of a rigid steel wire mesh having a relatively high elastic modulus. The design relied on the large difference in stiffness between the constituents in the composite section to drive the internal stress from the cementitious matrix to the steel reinforcement and materials were placed symmetrically to form an 'adaptive" section that reacted similarly when bending couples were reversed.

A modified transform section theory was developed to determine the deflections and stresses in such highly compliant cementitious structures [2] and the method was applied to study graphite-reinforced composites. Multi-layered composite beams were analyzed by incorporating material properties established from tensile tests and finite element modeling was used to verity results.

The work fueled another investigation that quantified the dynamic characteristics of GRCC laminated plates [3] and an analytical dynamic finite element model was developed to evaluate the natural frequencies and mode shapes for structures subjected to different boundary conditions. This model was subsequently applied to study the dynamic performance of "Survivor," the winning entry fielded by the University of Alabama in Huntsville's concrete canoe team (Team UAH) in the 2001 ASCEIMBT National Concrete Canoe Competition [4].

Numerical results compared favorably with experimental impact hammer test data. As a result, it was concluded that the classical laminated plate theory developed for composite materials could be applied to quantify the dynamic behavior of highly compliant composite structures made from GRCC materials.

CONQUEST

Team UAH relied on these findings to design concrete canoes that had the correct balance of flexibility and strength to further increase their edge over their competition. This year, the students qualified for the 2004 ASCE/MBT National Concrete Canoe Competition [10] with a boat called "Conquest."

They designed a graphite reinforced cementitious composite section capable of sustaining reverse loading and strategically tuned their hull by lowering its natural frequency so that the forcing function created by their paddlers drove the boat toward resonance. When the flexible hull deformed in response to the torsional and bending moments applied, very large stresses and strains developed.

Efforts were made to keep all of the materials elastic so that the structure was absolutely resilient, enabling the strain energy stored in the deformed shape to be recovered. As paddles were pulled from the water, this energy was converted into forward momentum, thereby, forcing the boat to surge forward between strokes and swim [8].

Team UAH used input the material mechanical properties of their cementitious composites into a dynamic finite element model based on classical laminated plate theory and studied how changes in fiber location and orientation affected the modal parameters of their canoe. The finite element model consisted of equally spaced quadrilateral membrane-bending plate elements with uniform thickness. Damping was neglected in the analysis and refinements in element sizes were made until the natural frequencies converged. Only the lower natural frequencies and their associated mode shapes in a free-free boundary condition were calculated because they adequately describe the dynamic behavior of the hull.

The students found it beneficial to position two layers of reinforcement as close as possible to the upper and lower surfaces of the section to increase the moment of inertia. Fibers were aligned longitudinally and transversely with respect to the longitudinal centerline of the canoe so that they were positioned in the principal stress directions. They also placed a third layer of reinforcement at the center of the section, with fibers oriented at plus and minus 45^o to the structural axes.

The composite was modeled based on the modified transform section theory and conceptualized as consisting of three homogeneous plate elements embedded in a cementitious matrix. As illustrated in Fig. 3, fiber orientation affected the materials properties of the plate elements.

Rotating the central layer of mesh increased the torsional stiffness and decreased the flexural stiffness of the hull. As compared to the case in which all layers are similarly oriented, this lowered the first and second fundamental frequencies and resulted in a better balance between the amplitudes of the corresponding modes.

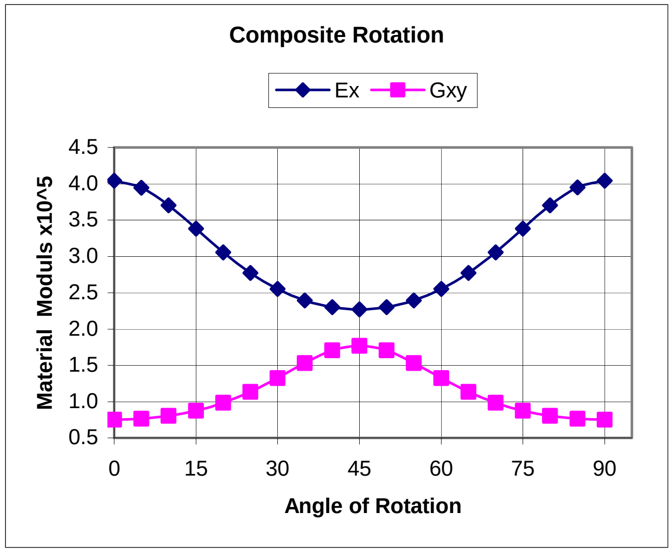

Figure 3. Changes occur in material properties when the fibers in the central layer of mesh are rotated.

Computer simulations showed that the boat's movement mimicked the locomotive motion of aquatic mammals and, as illustrated in Fig. 4, the composite lay-up resembled the semi-helically wound configuration found in a shark's skin.

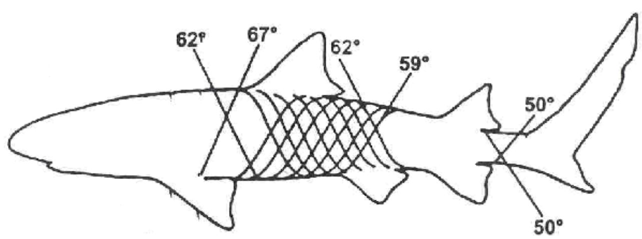

Figure 4. The composite lay-up resembles that of aquatic creatures.

Figures 5 and 6 illustrate how the boat moves. The first mode is anti-symmetrical torsion (7.1 Hz) and the second mode is flutter bending (10.3 Hz). When these modes combine, the boat acts like a fish swimming along with its paddlers to increase their input efficiency [9].

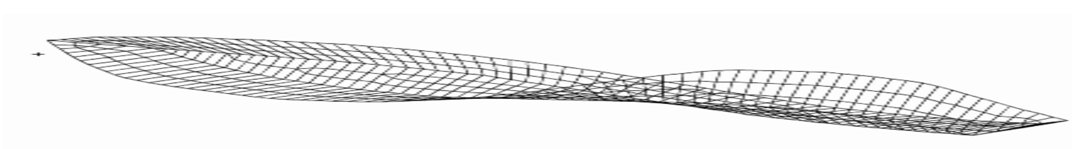

Figure 5. The first mode is anti-symmetrical torsion and it occurs at a frequency of 7.1 Hz.

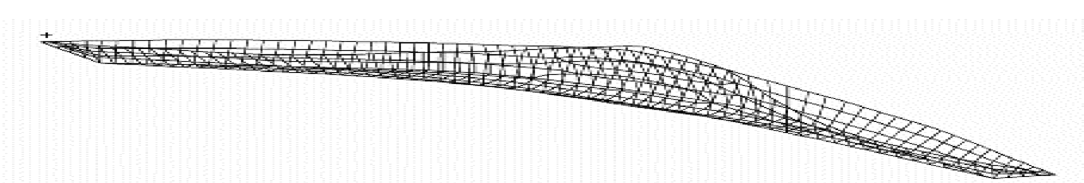

Figure 6. The second mode is flutter bending and it occurs at a frequency of 10.3 Hz.

Impact hammer tests are currently being conducted to verify the numerical results of the modal analysis. RRAPDS technology is being modified to quantify the boat's movement.

As illustrated in Fig. 7, the key component is the three-axis accelerometer shown on the right. The accelerometer is mounted along with an RF processor and an on board battery as illustrated on the left. The combination will be mounted at different locations on the hull and measurements will be taken remotely in real time as the team paddles their canoe.

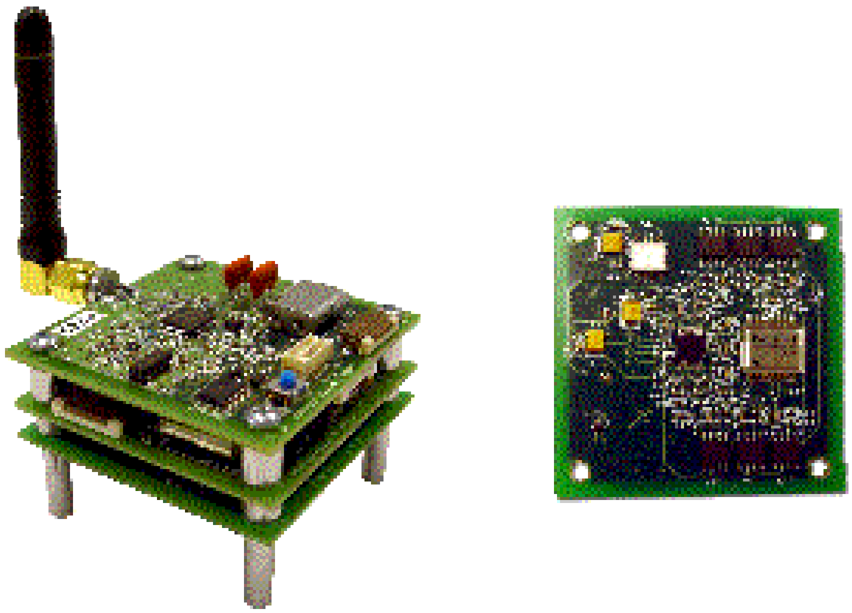

Figure 7. The key component of RRAPDS is a three-axis accelerometer.

If all goes well, Team UAH hopes to demonstrate the system in June when they compete as the Southeast Regional Champion in Washington, DC at the 2004 ASCEIMBT National Concrete Canoe Competition.

The students hope that the competition will help engineers and scientists realize the team's vision that cementitious composites may someday replace advanced aerospace composites [11-13. But they shouldn't be too concerned because cementitious materials and composites are already being targeted for many unique applications ranging from retrofitting commercial airline parts to supporting telescopes in space [14].

CONCLUSION

This paper has described one way researchers are dealing with the challenges associated with the development of STARS. Expectations are high that RRAPDS will accurately detect phenomena linked to structural performance and component failures to enable the advanced determination and prediction of critical failures. This prognostic information can initiate supply and maintenance actions resulting in greatly streamlined logistics operations.

Additionally, RRAPDS will allow for real-time access of source data and provide critical information needed to monitor and control the structural response. Sensor data analyzed by data mining algorithms and predictive trending has the potential to extend life and save millions in maintenance costs. Over time, the data collected can be used to refine structural designs and improve reliability, resulting in improved overall life cycle.

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