Evolution of Strategically Tuned Absolutely Resilient Structures (STARS)

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ABSTRACT

This paper describes how Strategically Tuned Absolutely Resilient Structures (STARS) are being designed for energy transfer and morphing applications based on the strength, stiffness, and the position of the component materials in the composite section. The discussion ranges from on-line health monitoring and smart diagnostics/prognostics strategies developed to improve the readiness and performance of STARS to integrated sensors and structural information systems designed to keep the stress in the reinforcement below yield and prevent cracks from propagating through the surrounding matrix.

INTRODUCTION

Strategically Tuned Absolutely Resilient Structures (STARS) represent a new generation of composites fabricated by placing a low modulus, lightweight matrix over multiple layers of a relatively stiff reinforcement [1]. These remarkable concoctions are designed to morph based on the strength, stiffness, and the position of the component materials in the composite section and their ability to store and release energy depends upon a complex interaction between the shape, modal response, and the forcing function applied to drive the structure [2].

Pioneer research involving STARS focused on producing a new generation of thin, lightweight, and structurally efficient panels capable of resisting stresses produced by reverse loading [3]. 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 [4] and the method was applied to study graphite-reinforced composites. Multi-layered composite beams were analyzed by incorporating material properties established from standard tests and finite element modeling was used to verity results.

The work fueled another investigation that quantified the dynamic characteristics of laminated plates [5]. 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 a larger structure [6]. 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 cementitious materials.

COMPOSITE DESIGN AND STRESS TRANSFER

STAR structures are fabricated from composite materials with constituents that are purposefully stressed and deformed to the largest extent possible so that the maximum amount of strain energy can be stored and released. Their design relies on large differences in stiffness between the constituents in the composite section to drive the internal stress from a flexible matrix to relatively stiff reinforcement.

In most cases, reinforcements are strategically placed, symmetrically through the thickness, to form an “adaptive" section that reacts similarly when mechanical loadings are reversed. This stress transfer can be visualized using the method of photoelasticity by observing the isochromatic fringe patterns shown in Figure 1 [3].

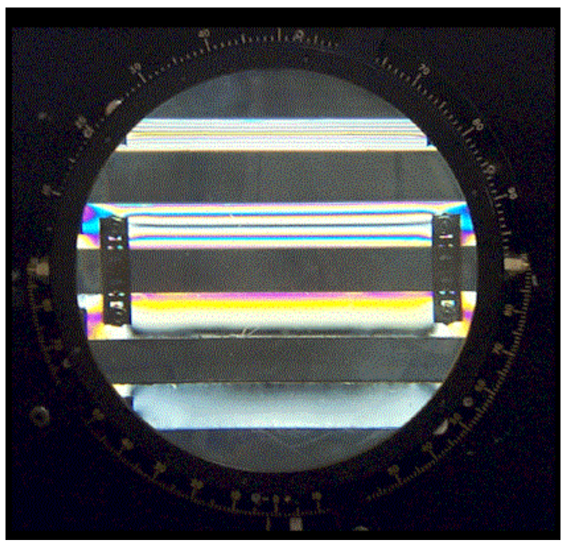

Figure 1. The bottom beam represents an “adaptive” section used to fabricate STARS.

The beams shown in Fig. 1 are all made from a plastic called PSM-1. They have a constant thickness of 9.5 mm (0.375 in.) and each beam is subjected to a moment of 0.82 N-m (13.33 in.-lb). A portion of the loading fixture can be seen at the edges of the field of view.

The distribution and number of fringes are directly proportional to the stress. The heavy black fringe in each beam represents the neutral axis that passes through the centroid of the section. The stress varies linearly with depth: compression on one side, tension on the other.

The beam situated second from the top is a 2.54 cm (1 in.) deep standard and represents an unreinforced, homogeneous beam with a matrix having an elastic modulus of 2.5 GPa (360 ksi). The maximum stress is 1.50 MPa (218 psi). The top beam is only 1.91 cm (0.75 in.) deep and illustrates that the maximum stress [2.76 MPa (400 psi)] becomes much higher when the depth is smaller.

A 0.64 mm (0.025 in.) deep, 9.5 mm (0.375 in.) wide, steel strip is bonded to the lower surface of the beam situated third from the top. The maximum stress in the plastic is 751 kPa (109 psi), half that found in the standard. Finally, the bottom beam has steel strips bonded on both the top and bottom faces. The isochromatic fringe pattern in the plastic is barely visible and corresponds to a maximum stress of only 103 kPa (15 psi). This value is over fourteen times less than that in the standard, clearly indicating that the stress has been driven from the plastic (matrix) to the steel (reinforcement).

In this case, the stiffness ratio between the steel and matrix is approximately 83, typical of that found in today's common advanced composite materials made of continuous fibers, either graphite or Kevlar®, suspended in a polymeric matrix, typically an epoxy of some type. The technology underlying these materials has been developed over the past sixty years and the materials have been widely used in numerous manned and unmanned aircraft structural applications primarily due to their high strength-to-weight and/or stiffness-to-weight ratio.

While advances in such composite materials have been steady, there have been relatively few revolutionary changes of late. But the investigation and development of STARS, designed with much higher stiffness ratios by fabricating matrices based on unique hybrid blends of inorganic and organic components, has the potential to revolutionize both structural design and tactical military strategies.

ENERGY TRANSFER AND STRUCTURAL MORPHING

Figure 2 illustrates how STARS can be designed to transfer energy. In this case, the structure is driven to controlled resonance by using a forcing function having a frequency close to the structure's natural frequency. Sensors are used to monitor the structural performance. The objective is to maintain structural integrity by keeping all materials within the elastic range.

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 strain energy, stored as elastic deformation, can be completely recovered and efficiently converted into useful work or energy. They are unique in that they can sustain large deformations without compromising structural integrity making it possible to utilize relatively crude and insensitive experimental techniques for structural health monitoring. This also makes STARS ideal candidates for structural morphing [7].

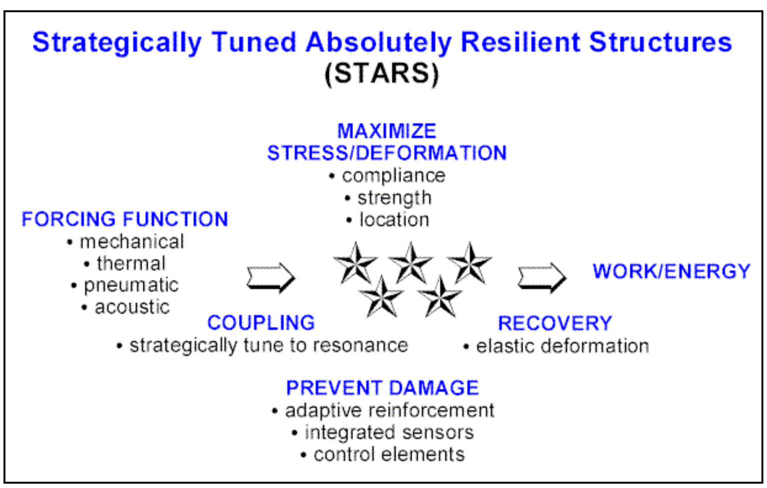

Figure 2. "STARS" can be used for energy transfer.

STRUCTURAL HEALTH MONITORING USING RRAPDS

Some STARS are being targeted for use in weapons systems (missiles, munitions, land vehicles, helicopters, unmanned air vehicles, etc.) because the materials used to build them are inert and relatively insensitive to corrosion, nuclear bombardment, and electromagnetic radiation. Incorporating sensors into these systems is an extraordinary technology that provides ample warning that structural integrity is being compromised. The approach also allows the structure's dynamic performance to be quantified. To this end, efforts are currently underway to monitor the structural health of STARS by making modifications to the Army's **R**emote **R**eadiness **A**sset **P**rognostic and **D**iagnostic **S**ystem (**RRAPDS**) [8].

RRAPDS is being developed to provide an integrated system transparent to the war fighter that delivers advanced diagnostics/prognostics and monitors health/condition while an asset (i.e., missile) is tactically deployed, in storage, and/or being transported [9-12].

As illustrated in Figure 3, 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 ten or more years of continuous system life, a capability to transmit real-time data, and the necessary tools to provide seamless user interfaces.

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, survivability, 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 maximize weapon structure service life, significantly reduce maintenance burden and costs, and enable a highly accurate and timely awareness of weapon health status. Over time, data collected can be used to refine structural designs and improve reliability, resulting in an improved overall life cycle.

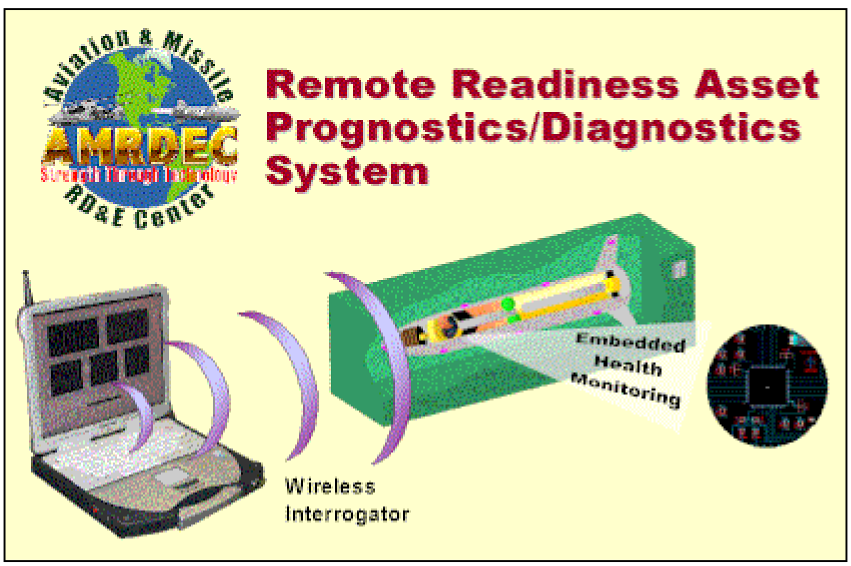

Figure 3. RRAPDS features wireless communication links and embedded sensors.

STRUCTURAL INFORMATION SYSTEM

Sensors are currently being integrated/encapsulated into STARS and a sophisticated information system is being developed to monitor them. The advantages of this approach are that the information system can be used immediately after placement of the matrix to monitor the cure cycle; to identify anomalies or to quantify bond strength once the constituents have cured; to verify performance during calibration procedures performed prior to service; to measure changes in the environment surrounding the structure; and, to accurately monitor the structural system in real-time under load conditions throughout its lifetime.

For the thin plates developed in earlier studies [3-5], Bragg sensors are being embedded along with the reinforcing fibers. In many cases, it has been found beneficial to install sensors on the outer surfaces. Although Bragg sensors can be used for this purpose, strain gages have proven advantageous.

In the case of thick plates and beam elements, the structure is being reinforced using hollow graphite tendons equipped with sensors bonded at critical locations on their inner walls. The leads to the sensors are fed through the cavities in the reinforcement so that strain can be easily measured free from sensor-lead effects.

In contrast to other systems designed to pinpoint structural defects in more conventional reinforced structures [13], the proposed monitoring system is intended to keep the stress in the reinforcement below yield, and prevent cracks from occurring in the surrounding matrix. The strategy is significantly different from that taken while designing traditional systems, since the goal is to minimize structural damage by maintaining resilience.

INTEGRATED SENSING

The cross section shown in Figure 4 illustrates some of the possibilities that are currently being explored. In this example, graphite tape {see No. 1 on the figure} is wrapped around a mandrel {No. 2} having the geometry required to accommodate embedded sensors. The mandrel could either be removed or employed to add strength. It could also be designed to act as an optical wave-guide for light transmission.

Optical fiber(s) {No. 3} could be embedded in the material to provide integrated sensing or access to discrete sensors. The core could be hollow so that lead wires/optical fibers fed through it {No. 4} would be environmentally protected as they convey information to and from the sensors.

The hollow core could be used to gain optical access to critical areas on which pressure sensitive paint {No. 5} was applied. An outer sheath {No. 6} could be designed to act as an environmental sensor, or, as a tool for monitoring the bond strength and the behavior of the matrix.

The work combines a novel design concept with proven sensor technologies and is expected to result in cost effective, easily serviceable, safe, reliable, survivable, and efficient structural systems.

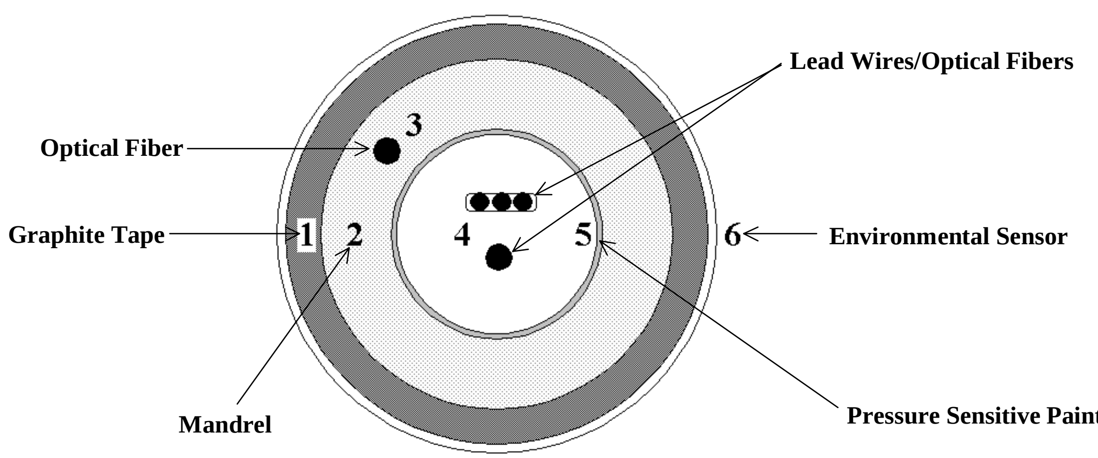

Figure 4. Cross-section of the reinforcement.

CONCLUSIONS

STARS are expected to have a positive long-term impact on U.S. productivity and their further development will provide revolutionary new tools for planning, designing, and maintaining civil infrastructure systems and military installations and facilitates.

The on-line health monitoring and smart diagnostics/prognostics strategies discussed above are designed to improve the readiness and performance of STARS and will lead to significant savings in the total life cycle costs by improving a structure's reliability, maintainability, and survivability.

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