DESIGN AND BENDING FATIGUE CHARACTERISTICS OF COMPOSITE MULTILAYER SURFACE ANTENNA STRUCTURE FOR SATELLITE COMMUNICATION

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Abstract

The present study aims to design a multilayer microstrip antenna with composite sandwich construction and study the fatigue behavior of the resulting multilayer SAS (Surface Antenna Structure), which has an asymmetric sandwich structure. In a SAS the structural surface itself acts as the antenna. Constituent materials were selected for their electrical properties, dielectric constant and tangent loss as well as their mechanical properties. Antenna elements inserted into structural layers were designed for satellite communication at a resonant frequency of 12.2GHz. Electrical measurements revealed that antenna performance was consistent with design requirements. Flexure behavior was investigated by static and fatigue cyclic 4-point bending test. The fatigue life curve of the SAS was obtained. Experimental results for bending fatigue were in good agreement with single load level fatigue life prediction equations. The SAS concept can be extended to provide a useful guide for manufacturers of structural body panels as well as antenna designers.

1 Introduction

In the future, communication will be expanded by the use of satellite communication and satellite internet availability in vehicles. To implement these services, in vehicles and elsewhere, antenna technology is central. Antennas located on the surface of a structure take up much space, and suffer from large path-loss and junction-loss. In the past ten years, research has turned to the embedding of antennas in load-bearing structural surfaces of aircraft in order to improve structural efficiency and antenna performances. "Structural surface becomes an antenna." Structures, materials and antenna designers have recently joined forces to develop a new high payoff technology, called *conformal load-bearing antenna structure* or CLAS. The embedding of radio frequency antennas in load-bearing structural surface is a new approach to the integration of antennas into structural body panels. It emerged from the need to improve structural efficiency and antenna performance. The concept demands integrated product development from disparate technologies such as structures, electronics, materials and manufacturing [1-3, 7].

The present study aims to design, fabricate and validate the structural and electrical performances of a microstrip antenna for satellite communication application as the next generation of structural surface technology, using composite sandwich construction. This is termed a Surface Antenna Structure (SAS). Design is focused electrically toward high gain and wide bandwidth, and mechanically toward high strength, stiffness and environmental tolerance. The basic structure is a composite sandwich that is very weight efficient; the core of the sandwich provides the necessary space for the antenna to function properly. Structural stability, including fatigue behavior and the fatigue life of SAS, will be estimated and predicted using the 4-point fatigue bending test.

2 Surface Antenna Structure and Materials

The fundamental design concept for the SAS panel is an organic composite multilayer sandwich panel into which mirostrip antenna elements are inserted. The design concept is based mechanically on the composite sandwich structure, and electrically on the microstrip antenna, as shown in Fig. 1.

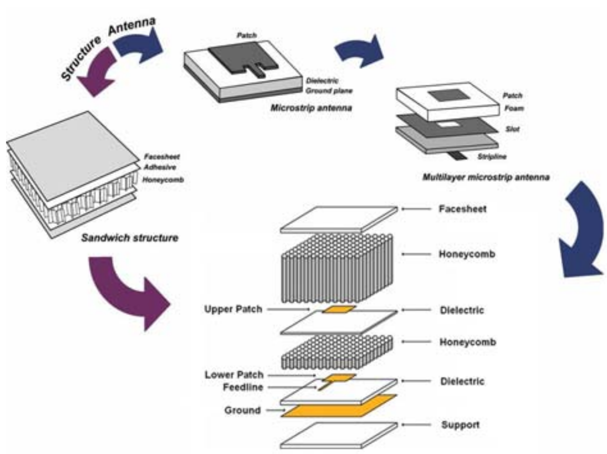


Fig. 1. Basic concept of surface antenna structure (SAS)

Microstrip antennas can be used in high-performance aircraft, spacecraft, satellites and missile applications, where size, weight, cost, ease of installation, and aerodynamic profile are all constrains. Such antennas are low-profile, conformable to planar and nonplanar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology, and compatible with MMIC designs. A disadvantage of the original microstrip antenna configuration is its narrow bandwidth. The conventional sandwich construction consists of two relatively dense and stiff facesheets that are bonded to either side of a low-density core. This helps to resist buckling of the facesheets under axial compressive loading, and can carry bending-induced axial loads and improve fatigue characteristics. As shown in Fig. 2, the basic panel layers are honeycomb core and antenna elements on dielectrics without facesheet and with facesheet for increasing gain and mechanical properties.

Mechanically, the facesheet and supporter carry a significant portion of the in-plane loads, contribute to overall panel buckling resistance, and provide low velocity impact and environmental resistance; electrically, the outer facesheet that is placed above the radiating patch causes signal loss as a result of its high electrical loss (loss tangent) when the signal passes through it. However, it can cause the antenna to radiate more efficiently without electrical loss when it is placed at the resonance position [7].

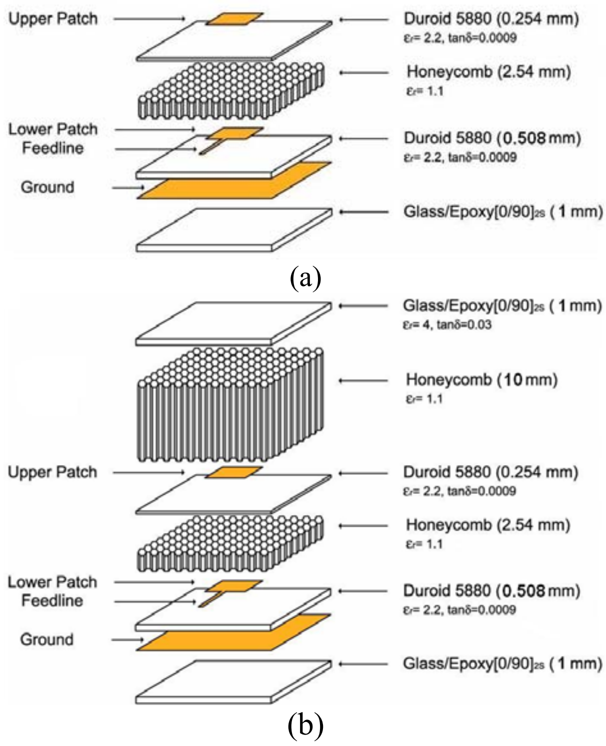


Fig. 2. Geometry of composite surface antenna structure (a) without facesheet, (b) with facesheet

The honeycomb cores mechanically transmit shear loads induced by bending loads in the panel; they support the outer facesheet against compression wrinkling, provide impact resistance and increase the overall panel buckling resistance. Electrically, they provide an air gap without signal loss and allow for adjustment of the outer facesheet position for maximum antenna performances. The thickness of honeycomb cores contributes to antenna efficiency as well as to overall rigidity.

The upper patch and lower patch are separated by an air gap provided by honeycomb of thickness 2.54mm. Duroid 5880 was used for layers of the antenna elements. It has good electrical properties − low dielectric constant and low electrical loss − but it does not contribute to structural performance. The electrical and mechanical properties of materials composed of SAS are set out in Table 1.

Table 1. Electrical and Mechanical Properties of Constituent Materials

Materials	Properties
Woven Glass /Thermosetting Plastic (RT duroid 5880 Rogers co.)	Elastic Modulus: 1.07 GPa Tensile Strength: 29 MPa Dielectric Constant: 2.2 Loss Tangent: 0.0009

Glass/Epoxy[0/90]$_{2s}$	Elastic Modules: 25.4 GPa Tensile Strength: 573.6 MPa
Nomex Honeycomb(Hexel co.) 10mm 10-1/8-5	Compressive Modulus: 5.31 MPa Compressive Strength : 255 MPa Shear Strength : 70.3MPa Dielectric Constant: 1.1
Nomex Honeycomb(Hexel co.) 2.54mm 10-1/8-6	Compressive Modulus: 7.76 MPa Compressive Strength : 414 MPa Shear Strength : 88.6 MPa Dielectric Constant: 1.1

Fig. 3 shows the antenna elements with their designed dimensions. The upper radiating patch is smaller than the lower patch, and the impedance at the central edge of lower patch is 100Ω, which is transformed to a 50Ω feedline. To overcome the problem that original microstrip antenna configuration is narrow bandwidth, two-stacked radiating patches are used for wide bandwidth, made by coupling of the dual resonance system. In design procedure, antenna performances are aimed for Ku-band satellite communication, in the frequency range from 11.7 to 12.75GHz with linear polarization. A computer-aided design tool (Ansoft Ensemble 6) is used to assist in choosing a large number of strongly interacting parameters by integrated full-wave electromagnetic simulation.

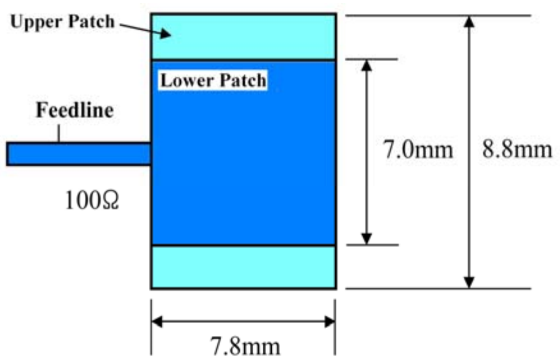


Fig. 3. Designed antenna element with stacked patches

In the design procedure, the optimized thicknesses of the outer facesheet and honeycomb are 1mm and 10mm respectively. Maximum gain is obtained via the resonance condition, and wide bandwidth is also achieved at 10mm by using stacked radiating patches. Fig. 4 shows the reflection coefficient and the gain of the SAS. It resonates at the central frequency of 12.4GHz, with frequency range from 11.3 to 12.8GHz with linear polarization. This is also satisfied in the desired frequency range with bandwidth of 1.5GHz at VSWR 2. The gain is higher by 2.3dBi, with the outer facesheet (11.55dBi) than for the antenna without the facesheet (9.25dBi).

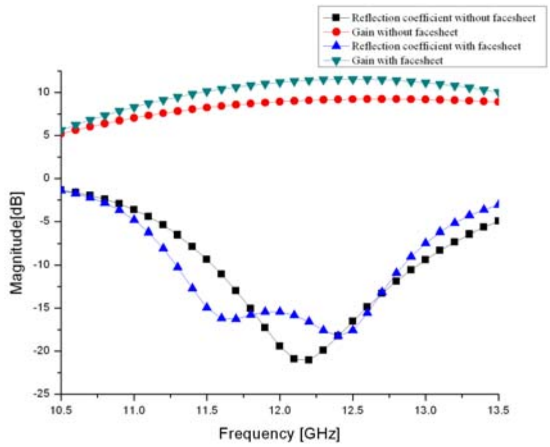


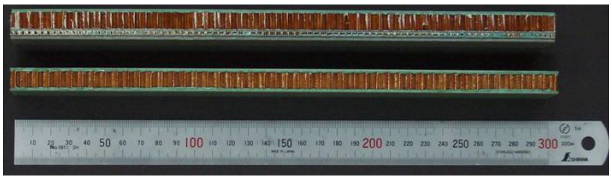
Fig. 4. Reflection coefficient and gain of SAS with facesheet and without facesheet

3 Structural Experiments

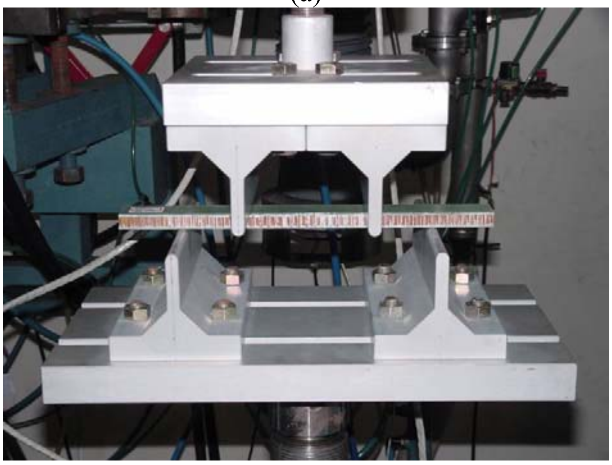
3.1 Experimental procedure

To find the mechanical properties of the SAS, the static 4-point bending test, in accordance with ASTM C 393-62 [4], and the 4-point bending fatigue test, were performed using a MTS 458 material testing system. The specimen was supported by a quarter point-loading jig, as shown in Fig. 5. The upper specimen of Fig. 5(a) is an asymmetric sandwich structure, and the lower specimen is symmetric sandwich structure. Static bending tests were performed under displacement-control at a cross-head speed 1mm/min until failure occurred. The fatigue tests were performed under load-control using a sinusoidal wave form applied at a frequency of 1Hz, which should cause negligible temperature increase during testing, and were carried out to the life-time limit of 10^6 cycles. This 10^6 cycle limit was chosen as representative of the industrial reference for fatigue tests performed on such shapes. The failure criterion in the fatigue test was chosen according to the maximum deflection obtained from static tests. Applied load levels were determined at 0.9-0.6 load levels for the static bending test. Three test specimens were used for each load level. All tests were conducted at room temperature under laboratory conditions.

Manufacture of SAS was a sequential process. First, the top sheet with the radiating patch was etched. Then the middle sheet for the slot on the ground plane and feedline was etched. The honeycomb cores and each layer must be aligned before making permanent bonding. The layers were bonded to the top and bottom of the honeycomb cores with epoxy film adhesive (AF126, 3M corp.). The assembly was then cured under pressure in an autoclave. The result was a 300×200×22.1 mm flat antenna panel. Fig. 3 shows the appearance of each layer and the final assembly.



(a)



(b)

Fig. 5. (a) Test speciments 300(mm) x 30(mm), (b) Configuration specimen and jig

3.2 Results and discussion

Fig. 6 shows the displacement-load curve from the static test. The displacement-load curve can be divided into four regions (denoted by A, B, C and D), since the SAS has a sandwich structure with facesheets, honeycombs, and two antenna elements with dielectrics. Damage development was as follows.

I. Region A: deflection propagates linearly through the entire specimen. Then, at the transition point between regions 'A' and 'B', failure of the facesheet begins.
II. Region B: after failure of the facesheets, the deflection again propagates linearly. Failure then occurs of honeycomb and antenna elements with dielectrics.
III. Region C: After the deflection propagates, shear failure of both honeycombs occurs
IV. Region D: The entire SAS fails completely with delamination.

Face failure and core wrinkling were observed in all specimens, as a result of the asymmetry between the top and bottom faces. At final failure, the bending load of the SAS was 2.09kN, and the bending displacement was 4.5mm. The flexural behavior of the SAS was followed mode B (Core shear) of the Ashby [5].

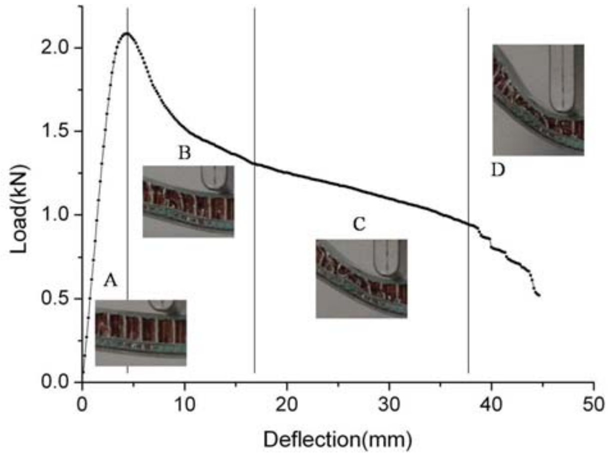


Fig. 6. Static flexural behavior of SAS

Fig. 7 shows the resulting displacements at the load level of 0.8. This result shows a continuing increase of both the resultant and permanent displacement with the number of cycles. This observation suggests that the sandwich structure of the SAS might undergo continual degradation from the early stage of loading until failure. The displacements increase faster at higher loads than at lower loads. The rate of increase of both resultant and permanent displacements, d(displacement)/dn, decreases with the number of cycles in the early stage of fatigue, and increased drastically during the final few cycles. Also, the hysteresis loop energy decreases after the first cycle up to a certain number of cycles, and increases rapidly during the final stages. After failure, the resultant displacements of the SAS were 4.1mm, which is less than the value of 4.5mm from the static bending test. This result confirms Hwang's failure criterion [6] in which the failure of composites under fatigue loading occurs when the fatigue resultant displacement reaches a specific multiple of the static ultimate displacement. Fig. 8 shows the log scale relation of load levels (ratio of applied load and bending load) and fatigue cycles. The test results show that the SAS can support external loads as a structural surface while providing excellent antenna performance.

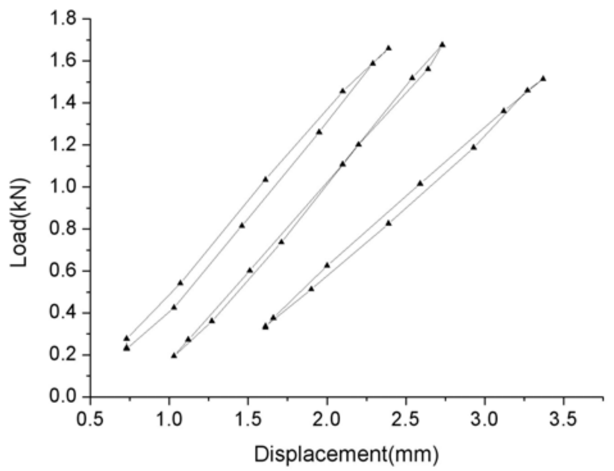


Fig. 7. Cyclic load-displacement behavior of SAS at load level 0.8

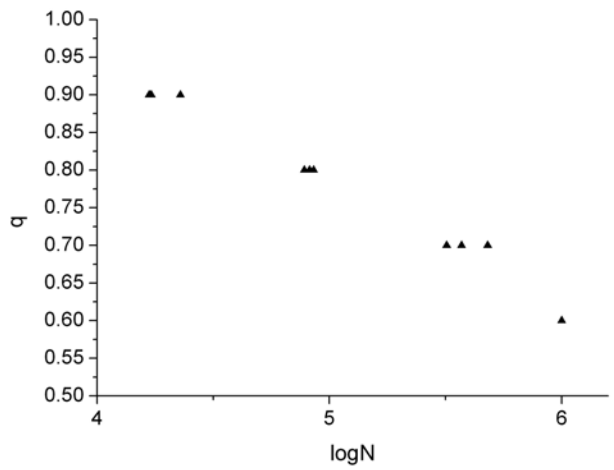


Fig. 8. Fatigue life data of SAS

Using the flexure test results, we compared various Single Load Level Fatigue Life Prediction Equations with the experimental data. The equations to be compared were Hwang's Equation, Basquin's Relation, and S-N Curve.

Hwang's Equation : $N = [M(j^B - q^B)]^{1/C}$ (1)

Basquin's Relation : $\sigma_a = \sigma_f^{'}(2N)^b$ (2)

S-N Curve : $q = k \log N + d$ (3)

where N is the fatigue life, σ_a is the applied load, q is the applied load level, and k, d, $\sigma_f^{'}$, and b are material constants.

Our experimental data were used with commercial software Origin 7.5 to estimate these parameters. Results are as follows.

Hwang's Equation :

$$N = [\frac{0.6308^{-7.516}}{-0.0001832}(0.9111^{-7.516} - q^{-7.516})]^{-1/1.1519} \quad (4)$$

Basquin's Relation :

$$\sigma_a = 482.4396(2N)^{-0.09287} \quad (5)$$

S-N Curve :

$$q = -0.15912 \log N + 1.57628 \quad (6)$$

Fig. 9 shows the experimental results compared with single load level fatigue life prediction equations, displaying particularly good agreement for Hwang's equation.

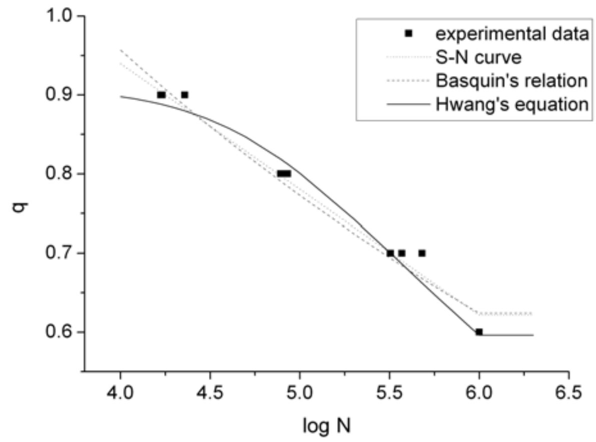


Fig. 9. Fatigue life prediction curves

4 Conclusions

The surface antenna structure (SAS) was designed using structurally effective materials without compromise with the electrical properties. SAS is a composite sandwich structure in which a microstrip antenna is placed between the honeycomb core and lower facesheet. SAS having both high electrical and mechanical performances have been designed for satellite communication needs. Their bending characteristics under static loading has been investigated, and flexural behavior of cyclic loading was studied using a 4-point bending fatigue test. The test results were compared with various single load level fatigue life prediction equations, and good agreement was found. The SAS concept makes it possible to design the antenna structure with structurally effective materials for a communication body panel in vehicles. It can be extended to provide a useful guide for manufacturers of structural body panels, as well as antenna designers, promising advances in communication technology.

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