Materials Research Proceedings **27** (2023) 331-339 https://doi.org/10.21741/9781644902455-43

Fatigue response of conformal load bearing antenna structures

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Keywords: CLAS, Fatigue Effect, Resonance Frequency

Abstract. Non-woven, metal-coated, carbon veil has the potential to replace copper in radiofrequency transmission lines and micro-strip antenna elements. It is of importance to characterise the mechanical properties of these veils to implement them into antenna design. These veil materials are incorporated into a dielectric substrate made from glass-fibre reinforced plastic (GFRP). This antenna system can be integrated into a load bearing composite structure enhancing its multi-functionality and will therefore be exposed to the operational loads of the primary structure. An example of such primary structure is the wing of an unmanned aerial vehicle (UAV). This paper will report on a set of investigation detailing the effects of fatigue loading on the durability and the performance of this load bearing conformal antenna system. The fatigued antenna will be subjected to a series of cantilever loading to show the performance of the conformal antenna when the fatigue-exposed antenna is subjected to quasi-static loading that is expected during normal operation of the structure.

Introduction

Communication and sensing systems in aircraft are generally implemented as individual sub-systems with pre-determined locations on the aerospace platform. Therefore, customization and innovation of antenna systems based on the electromagnetic and structural requirements is less possible [1]. Through the design of Conformal load-bearing antenna structures (CLAS), communication and sensing capabilities can be integrated into the skin of airframes. The direct inclusion of radiofrequency (RF) devices into composite skins through manufacturing enables positioning along the exterior of the airframe, thereby freeing up internal space and enhancing its structural efficiency. [2-4]. Moreover, a smooth exterior surface of the aircraft, without antenna structures protruding into the airflow, significantly reduces aerodynamic drag during the flight [5-7]. While conventional antenna structures which are exposed to the environment are subject to damage, embedded CLAS have significantly more resilience to such damage [3].

Non-woven fibre mats (or surface veils) have the potential to replace copper in a variety of roles, in particular, microstrip antennas (pictured in Fig. 1) [8, 9]. Surface veils consist of randomly orientated, short-chopped, carbon fibres and can be metal coated (nickel, copper, etc, see Fig. 2), to achieve the desired electromagnetic properties [1]. However, due to the low stiffness of these veil materials, novel test techniques are required to determine their mechanical properties and thus structural effect. Limited understanding of the properties of surface veils results in difficulties in analysing and modelling them [10]. The CLAS considered in this paper will comprise of a copper-coated nickel veil that is embedded into a glass-fibre reinforced plastic (GFRP) dielectric substrate. The veil is used as a conductor to replace the solid metal foil since the performance of veil and composite substrate demonstrate little degradation under the mechanical load [1].

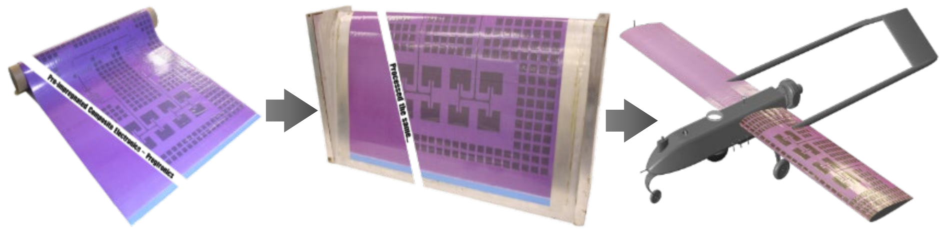

Figure 1. CLAS concept. Prepreg composite material with embedded electromagnetic traces can be cured in aerospace composite structures.

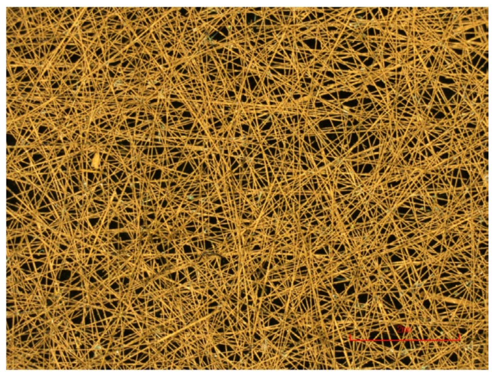

Figure 2. Close-up view of copper-coated carbon veil.

Under in-service conditions, CLAS will experience various loading types such as wind, vibration and impact which induce structural deformation. It is necessary to understand the mechanical and electromagnetic behaviour under the effects of the loading experienced by the aerospace structure, to ensure the performance of the RF system is sufficient/improved during the flight [11-14].

You and Hwang proposed integrating a microstrip antenna into a composite sandwich structure, finding that glass/epoxy can be utilised as a face sheet material without adversely affecting the antenna efficiency by capitalising on an open condition [11]. Also noting that experimental results met set requirements for an improved gain and wide bandwidth. Further work involving the integration of an antenna array into a cylindrical structure found the transverse radiation pattern to be strongly dependant on the curvature of the cylinder. Impact loading results demonstrated that contact force decreased as the curvature increased further highlighting the importance of the radius of curvature as a structural parameter [12]. The parametric investigation proposed by Yoon et al [13] demonstrated that the transverse shear moduli of the honeycomb core significantly affect the buckling load of the smart skin when shear deformation was considerable. Healey et al [6] reported on a series of computational study that detailed the effects of structural loading on the resonant frequency and the Q-factor of load bearing conformal antenna. They showed that structural loading can cause the antenna to stray out-of-band for Wi-Fi as defined in IEEE802.11.

In addition to the deformation induced by loading, the influence of fatigue loading and fatigue-induced damage to the model is also of great importance. During the flight, the CLAS will be exposed to a combination of fatigue and quasi-static loading conditions due to various loading. Therefore, it is necessary to investigate the effect on the mechanical and electromagnetic characteristics of a CLAS under fatigue and how the fatigue-exposed CLAS will performe under quasi-static loading.

In this study, the copper-coated carbon veil will be machined into a microstrip patch and embedded into the GFRP. The loading bearing antenna structure will be exposed to a series of constant amplitude fatigue loading. The RF response and the quality factor of the CLAS will be used to assess the performance of the antenna as a function of fatigue exposure. Since CLAS is

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expected to operate under in-flight conditions, the fatigued specimen will be removed from the fatigue test rig at specified intervals and subjected to static cantilever loading. The RF response and the quality factor of the antenna of the as-fatigued condition subjected to this loading will be measured to determine its functionality when used under simulated flight condition. The aims of this paper are to report on the effects of constant amplitude fatigue and quasi-static loading on this copper-veil/GFRP loading bearing composite antenna. The resonant behaviour of the CLAS and its potential to stray out-of-band will be reported in terms of the S11 parameter of the antenna and its quality-factor (Q-factor).

Methodology

Test specimens

The CLAS test coupon is constructed with di-electric made from 6 layers of GMS EP-280 S-Glass, of which dimensions of 300 mm x 60 mm x 2.2 mm, with patch antenna sitting on the top. The patch antenna is made from copper coated carbon of thickness 0.125 mm. The geometry of the antenna (see Fig. 3) is: $a = 40$ mm long, b =28.7 mm wide, with a feedline 29 mm long and 3.5mm wide. Inlet gaps Z_y =8 mm long and $Z_x = 2$ mm wide were utilized to impedance match with the patch being designed to resonant at approximately 2.4 GHz with bandwidth of 22 MHz to facilitate the wireless communication protocol as defined in [15].

Two sets of specimens were prepared. In one set, a Teflon tape of dimension (40mm x 5mm) is included at the antenna and substrate interface along the “a” direction as a defect initiator. The other set of specimens is prepared without any seeded damage.

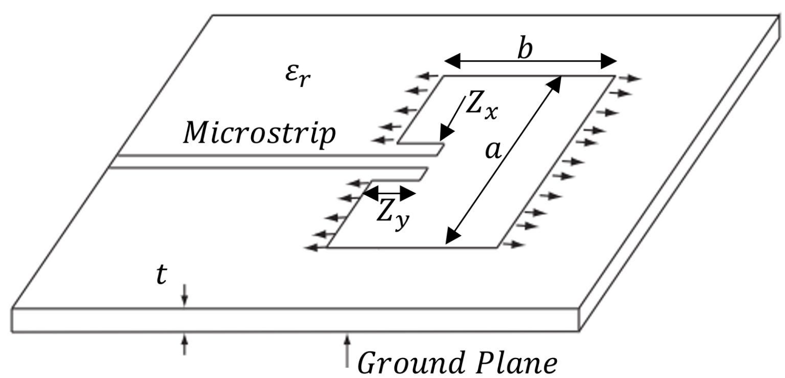

Figure 3. Schematic of a patch antenna.

Experiment setup

The RF measurement of specimens were performed with coupon resting on a wooden laboratory bench by employing NanoVNA V2 Plus 4. This RF result prior to fatigue tests was marked as ‘Pristine’. The test coupon is installed on an electro-mechanical shaker as shown in Fig. 4a. The specimen is transversely excited at the 2nd natural frequency (i.e., 90 Hz), and can accumulate one million constant amplitude fully reversed fatigue cycles in a matter of hours. The test specimen is held such that the edge of the antenna is located at the anti-node of the test specimen. The amplitude of response was controlled to subject the edge of the antenna to bending tensile strain of 4,000 $\mu\varepsilon$. The fatigue tests were interrupted periodically to measure the resonance response of the fatigued specimens at rest and when subjected to a cantilever static load. The specimens were placed into a cantilever test apparatus to perform the static tests (see Fig. 4b). During the static tests, the specimen was rotated to subject the antenna firstly to bending tension and to bending compression. This is to investigate the performance of the fatigue-exposed CLAS under the simulated quasi-static deformation of the wing during flight.

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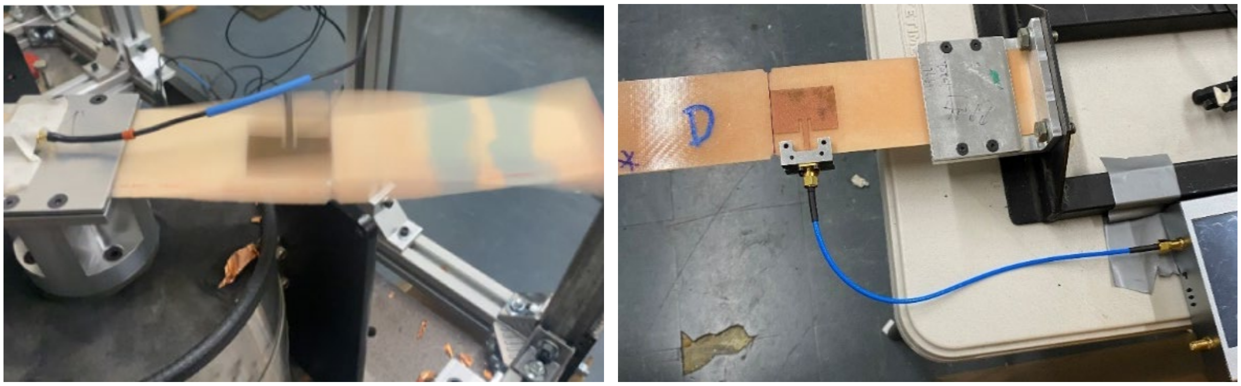


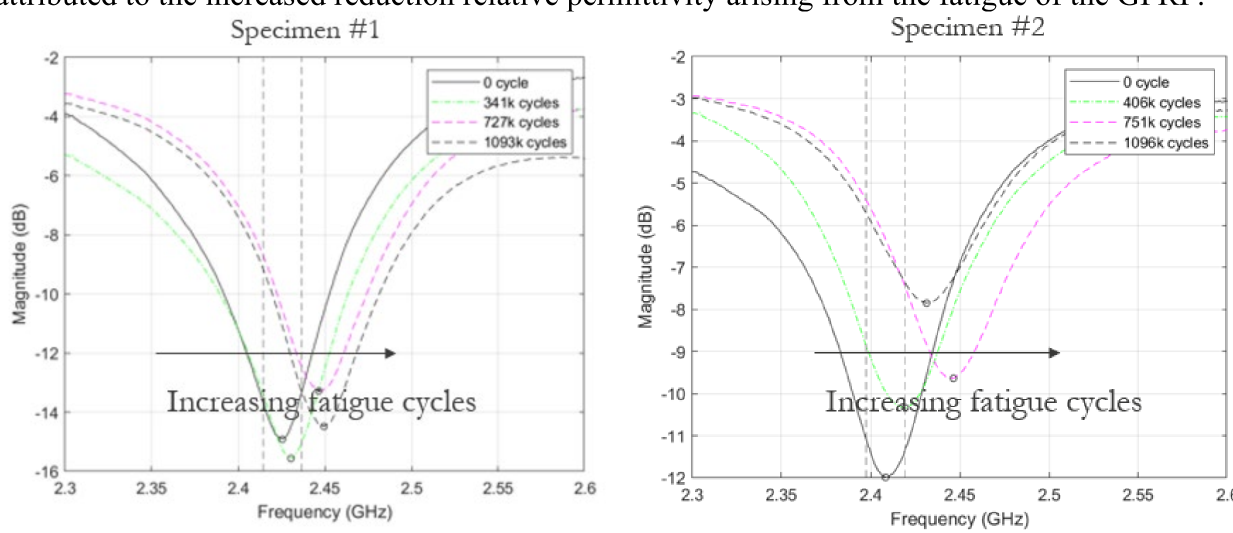
(a) (b)

Figure 4: Specimens under (a) Static cantilever test and (b) Fatigue test.

Result

Specimens with no seeded defect

Fig. 5 show the RF response of the CLAS when exposed to the constant amplitude fatigue loading. These results were recorded with the specimen resting on a wooden laboratory bench. The results show that the antenna will stray out-of-band with increasing fatigue cycles. It is interesting to note that the antenna remained within band for about 350,000 constant amplitude cycles at 4,000 με. This shows that the CLAS can withstand this severe loading that is consistent with the maximum strain levels expected of an aircraft structure. Using the resonant frequency equation for a patch antenna as a reference (Eqn. 1 [6]), it is likely that the increase in the resonant frequency can be attributed to the increased reduction relative permittivity arising from the fatigue of the GFRP.



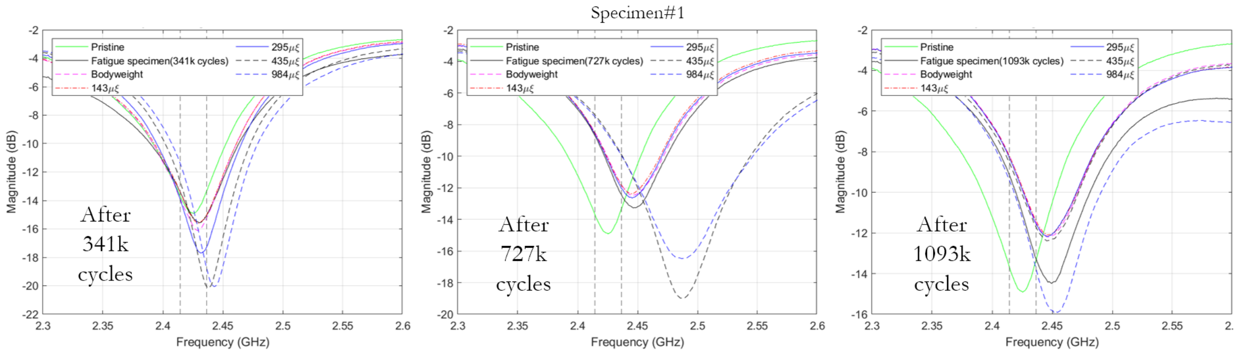
(a) (b)

Figure 5: Effects of fatigue (with specimen tested whilst resting on bench)

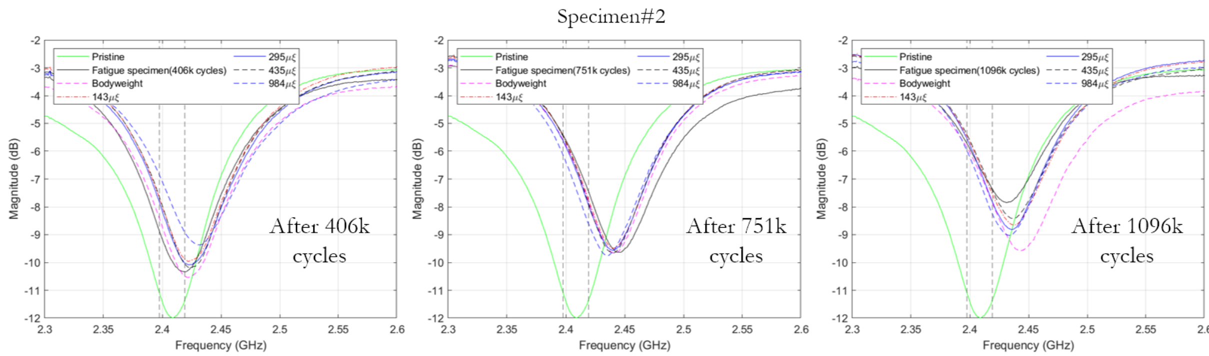
$$f_r = \frac{c}{2\sqrt{\varepsilon_{re}}(b+2\Delta L_{OC})} \quad (1)$$

Where c, is the speed of light in vacuum and ε_{re} is the effective permittivity of the substrate.

Fig. 6 shows the RF response of the CLAS when subjected to static cantilever loading with the patch antenna subjected to bending tension. Whilst the antenna remained within band after 350,000 fatigue cycles, the effect of the static loading is featured prominently after higher fatigue cycles. The results suggest that the antenna is usable after 350,000 fatigue cycles when the antenna is exposed to a peak strain of 4,000 με.



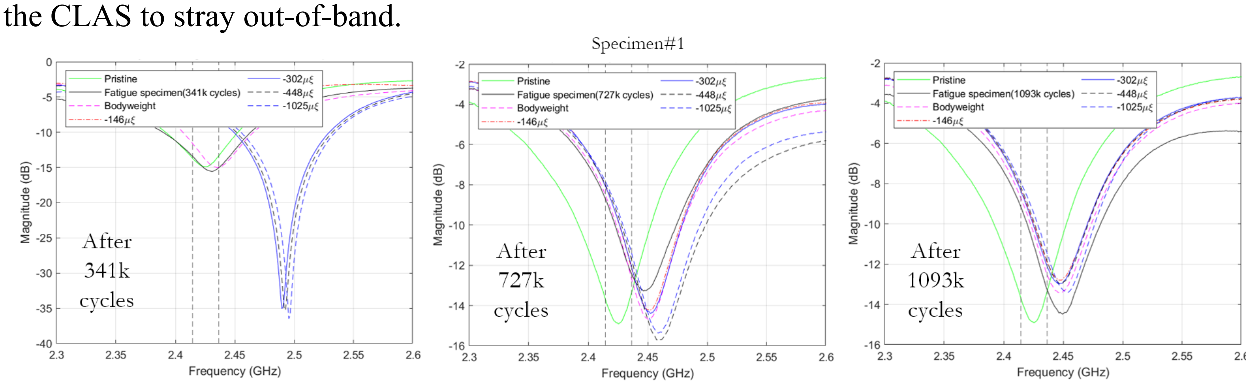
(a)



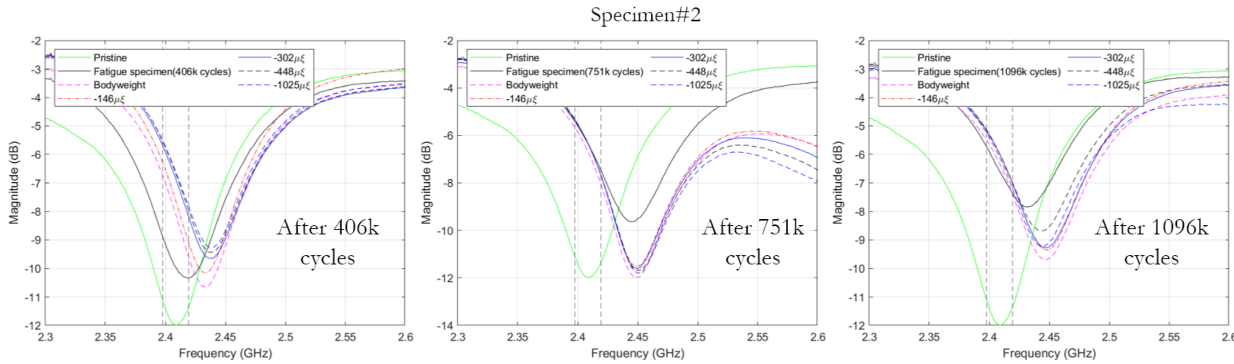
(b)

Figure 6. Effects of fatigue for specimen: (a) #1 and (b) #2. (With specimen tested loaded in a cantilever test rig; antenna in tension).

The RF response when the patch antenna is subjected to bending compression in shown in Fig. 7. The These results show that the effects of bending will accentuate the degraded region at the edge of the patch antenna. Although the CLAS remained within band after 350,000 fatigue cycles, exposure to a static compressive load will accentuate the fatigue damage accumulated and cause the CLAS to stray out-of-band.



(a)

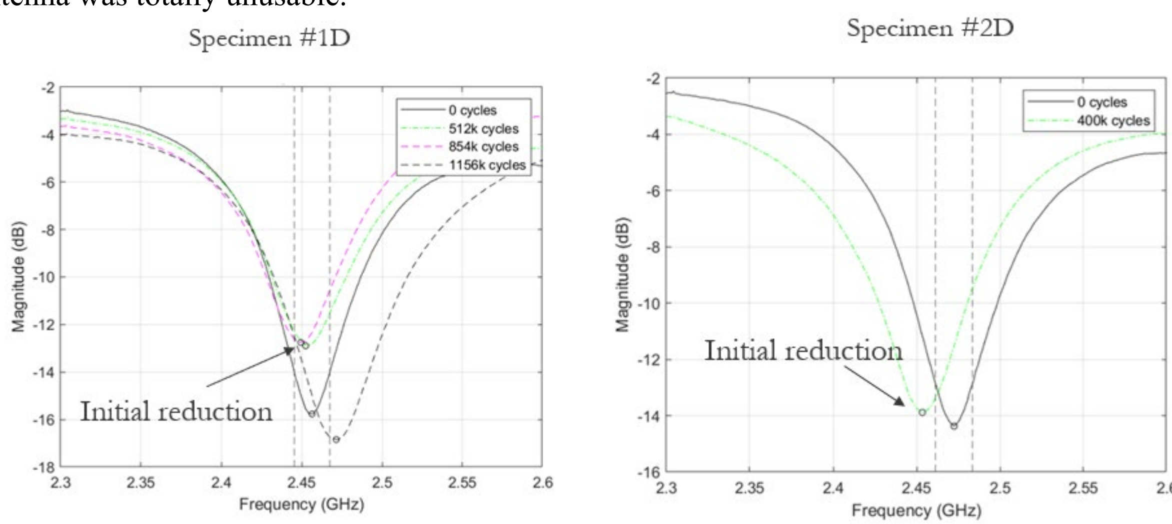


(b)

Figure 7. Effects of fatigue for specimen: (a) #1 and (b) #2. (With specimen tested loaded in a cantilever test rig; antenna in compression).

Specimens with seeded defect

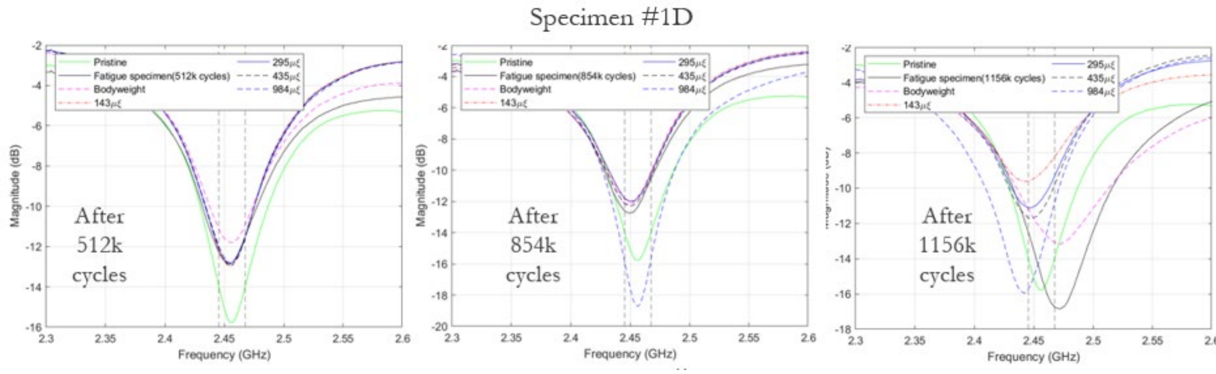
Fig. 8 shows the RF response of the CLAS with the seeded defect when exposed to the constant amplitude fatigue loading. These results were recorded with the specimen resting on a wooden laboratory bench. Specimen #1D showed an initial reduction in the resonant frequency. This is consistent with the effects of damage inflicted on the veil material and is accentuated by the presence of the disbond. Further exposure to fatigue led to an increase in the resonant frequency that eventually strayed out-of-band. In Specimen #2D, an initial reduction in the resonant frequency was recorded and the experiment was terminated after 400,000 cycles because the antenna was totally unusable.



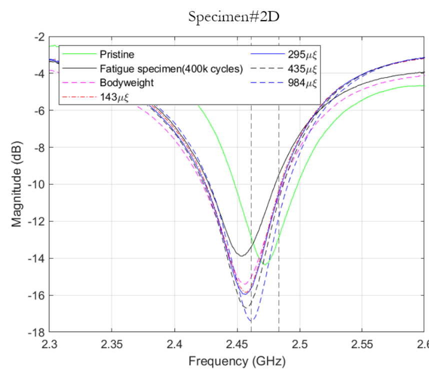
(a) (b)

Figure 8: Effects of fatigue (with specimen tested whilst resting on bench).

Fig. 9a shows the RF response of the fatigue exposed CLAS (Specimen #1D) when subjected to static cantilever loading with the patch antenna subjected to bending tension. It is interesting to note that the CLAS remained within band during these tests. Indeed, the relative increase in the resonant frequency with increasing cantilever loading can be attributed to the combined effects arising from the increased in permittivity and Poisson ratio effects that cause a reduction in “b”. The antenna in Specimen #1D was noted to be unusable when exposed to more than 1 million fatigue cycles. The results for Specimen #2D behaved similarly to that for Specimen #1D. As discussed previously, the fatigue tests for Specimen #2D was terminated after 400,000 cycles because of the unstable RF response.



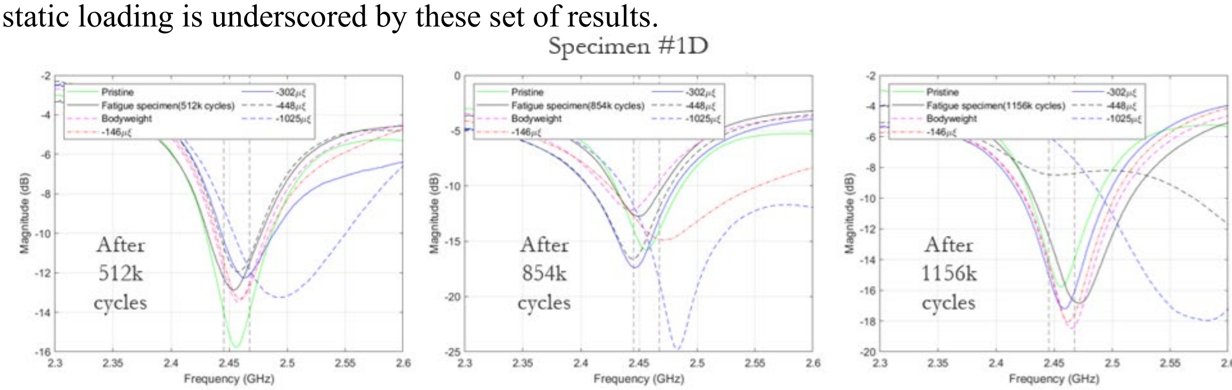
(a)



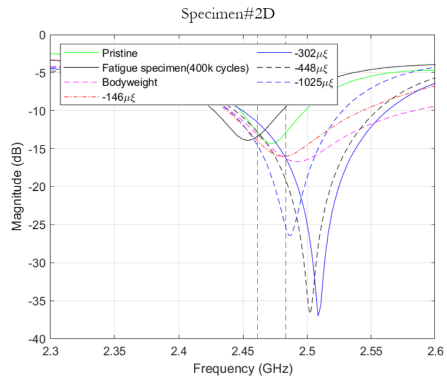
(b)

Figure 9. Effects of fatigue for specimen with seeded defect: (a) #1D and (b) #2D. (With specimen tested loaded in a cantilever test rig; antenna in tension).

The RF response when the patch antenna is subjected to bending compression shown in Fig. 10. The bending compression applied to the patch antenna (both Specimen #1D and #2D) virtually made the CLAS unusable. This highlights the effects of fatigue on CLAS and its response to quasi-static loading is underscored by these set of results.



(a)



(b)

Figure 10. Effects of fatigue for specimen with seeded defect: (a) #1D and (b) #2D. (With specimen tested loaded in a cantilever test rig; antenna in compression).

Conclusions

The effects of constant amplitude fatigue loading on the performance of CLAS is presented. The work presents a series of accelerated fatigue tests of the CLAS using an electro-mechanical vibration test rig. Although there is no specimen failure recorded, the effects of fatigue loading on the CLAS are evident. The major findings from the work presented is the importance of good quality control for the fabrication of CLAS, and that it is tolerant to exposure to 350,000 cycles of fully reversed constant amplitude up to a peak strain of 4,000 με. Moreover, the specimen with seeded defect #1D demonstrated similar resilience to the fatigue effect as the specimen without the defect. However, the resonance frequency of specimen #2D was unstable only after 400,000 cycles. The huge difference in the performance between specimen #1D and #2D indicated that the thin layer of Teflon as the defect initiator introduced an inconsistent performance of CLAS. Regarding the results of the cantilever test, for specimens without defects, the shift in the resonance frequency was significantly increased along with fatigue cycles. The occurrence of the unstable S11 behavior of defect specimen was also identified during the cantilever test, especially when under compression loading. The unpredictable performance of the specimens with seeded defects further evidenced the importance of quality control for prolonging the service life of the CLAS.

Funding

This research was funded by the US Office of Naval Research and Office of Research Global, grant number N6209-21-1-2003. The financial supported provided by the US Office of Naval Research and Office of Research Global is gratefully acknowledged.

Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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