MECHANICAL AND RF CHARACTERISATION OF SMA CONNECTIONS IN FUNCTIONAL COMPOSITE LAMINATES

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Keywords: Functional composites, Hybrid composites, Characterisation

ABSTRACT

Modern military platforms feature multiple antennas, which are typically externally mounted, making them damage prone and increasing drag and signature. They are also typically heavily reinforced to withstand operational and environmental loads, leading to parasitic weight and reduced payload. It is therefore desirable to replace these external antennas with conformal antennas integrated into structural components or into load-bearing structural surfaces which conform to existing components, through use of functional composite laminate structures.

This study focuses on radio frequency (RF) connection points within functional composite antenna structures, a connection necessary to carry the electrical signal to and from the antenna element. The RF connection also carries all mechanical loads between the cable and the composite structure. This study describes a novel methodology to simultaneously test the mechanical and electrical properties of RF connections in functional composite structures. This methodology is then demonstrated by quantifying the operational load limits of SMA connectors within functional composite laminate test specimens that are representative of functional antenna structures designed for aerospace applications, containing a copper ground plane and copper microstrip feed bonded to glass/epoxy.

The status of the RF connection is monitored continuously using a vector network analyser (VNA) while the test specimen is under load. Preliminary results demonstrate that the methodology successfully measures degradation and loss of RF function distinct from conventional mechanical failure of the laminate. The development of this testing methodology that simultaneously characterises the mechanical and electrical performance of the joint is vital to understanding the failure of RF connections in functional composite structures and improves the capability for rapid experimental assessment of candidate designs for these types of connections.

1 FUNCTIONAL COMPOSITE STRUCTURES

In addition to their role as a load-bearing structural component, functional composite structures have extra functions ranging from biocompatibility to electrical, magnetic or optical properties. Commonly, these functional properties are achieved through creating hybrid composites, or composites-of-composites. The hybridisation can be

- nanoscale (e.g. thermal and electromagnetic signature control by addition of carbon nanomaterials to a polymer)
- microscale (e.g. embedded fibre optics for sensing vibrations), or
- macroscale (e.g. inclusion of active electronic elements for communications).

For all scales of hybridisation, this approach to creating functional composites brings challenges. Adapting conventional manufacturing methodologies for hybrid composites increases the number of processing parameters, for example when bonding dissimilar materials or dispersing nanoparticles in a resin. Predicting the resultant material properties of a hybrid material system may not be straightforward, especially predicting the strength of material systems where hybridisation leads to unique damage modes.

Importantly for functional composite structures, the application of load may cause a decrease in functionality before any conventional material damage. In this case, the structure has "failed" in the sense of its extra functions, but not in the conventional structural sense. It is critical to understand how the functionality of the material changes with applied load and to determine appropriate operational limits for these functions when designing functional composite structures.

2 RF CONNECTIONS IN FUNCTIONAL COMPOSITE STRUCTURES

Antenna structures for communication, navigation, telemetry, etc. are vital to the operation of a wide range of products. There are limitations in the use of conventional antennas including weight penalties, durability and performance. These limitations can be addressed through the integration of antenna devices and feed networks with structural components, either by integrating them into structural components or into load-bearing structural surfaces which conform to existing components.

Aerospace has been the driving application area behind this technology, where existing antennas that protrude from an aircraft are replaced by integrating this functionality into the airframe structure [1]. This is particularly promising for smaller unmanned aerial vehicles (UAVs) for which antennas are essential for data and telemetry, and where light-weighting and radio performance are both greatly pursued.

Radio frequency (RF) connectors are electrical connectors designed to work at radio frequencies, roughly from 20 kHz into the gigahertz range. When designing functional composite structures incorporating active antenna elements (or other RF electronics), a connection must be included to carry the electrical signal to and from the antenna. Typically this connection is by a standard connector, such as Type N or SMA [2,3], attached to the composite to enable a cable to connect to the RF backend.

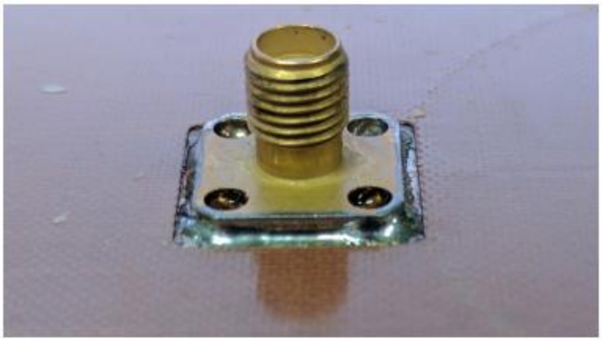


Figure 1: SMA connector soldered to exposed conductive plane of functional composite laminate.

The RF connector carries all mechanical loads between the cable and the composite structure, and these loads are in turn carried by the joining interface between connector and composite, which can take the form of a bolted joint, conductive adhesive or solder. Mechanical failure of this joint may occur due to weighting of the cable, vibration of the structure including the cable, or structural loads within the component. Functional composite antennas structures are typically load-bearing and design of these structures including RF connections must be informed by an understanding of the mechanical performance of these joints under operational and environmental loading.

With these considerations in mind, a concept has been developed for characterising the functionality of RF connections with applied load and determining appropriate operational limits for the design of functional composite structures. Test specimens are manufactured which are representative of the RF connection including geometry, materials used and manufacturing methodology. As described in the concept chart in Figure 2, this representative specimen has an electrical circuit embedded within a physical structure, and simultaneous tests are performed on each. A controlled load is applied to the mechanical structure through a universal testing machine, and the load and extension (and/or any other relevant mechanical data) is collected. At the same time, the electrical circuit embedded within the composite specimen is measured by a vector network analyser (VNA). For flexibility of testing configuration, the representative specimen can have two RF connection points – one used for mechanical testing, and one at the other end of the circuit. Then, the structure can be measured by the VNA using a 1-port configuration, with the VNA connected only to one of the RF connections, and the other connection terminated by a 50 Ω dummy load. Alternatively, a 2-port configuration can be used, with the VNA connected to both RF connections. Importantly, in both configurations, the connector that is under mechanical load is physically connected to both the loading machine and the electrical connection.

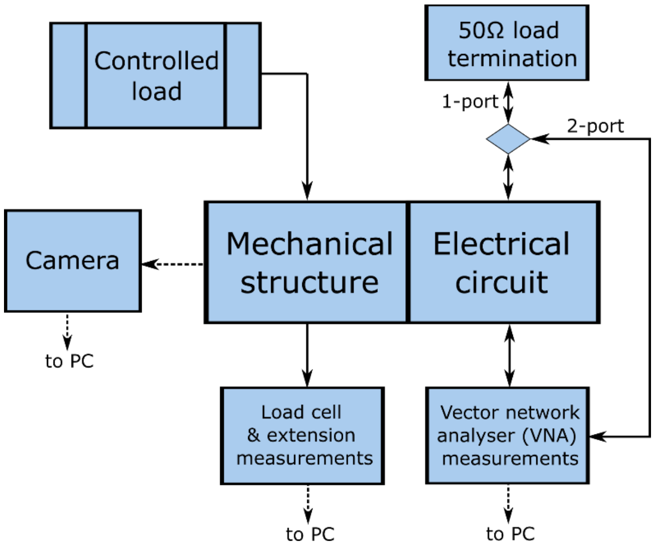


Figure 2: Concept for simultaneous characterisation of mechanical and RF performance of a representative functional composite laminate specimen.

3 MANUFACTURING REPRESENTATIVE SMA CONNECTION SPECIMENS

In this study, functional composite laminate test specimens that are representative of functional antenna structures designed for aerospace applications were manufactured according to Figure 3. A copper foil microstrip line is bonded to a 90 mm x 90 mm glass/epoxy laminate, with a copper foil ground plane on the reverse side.

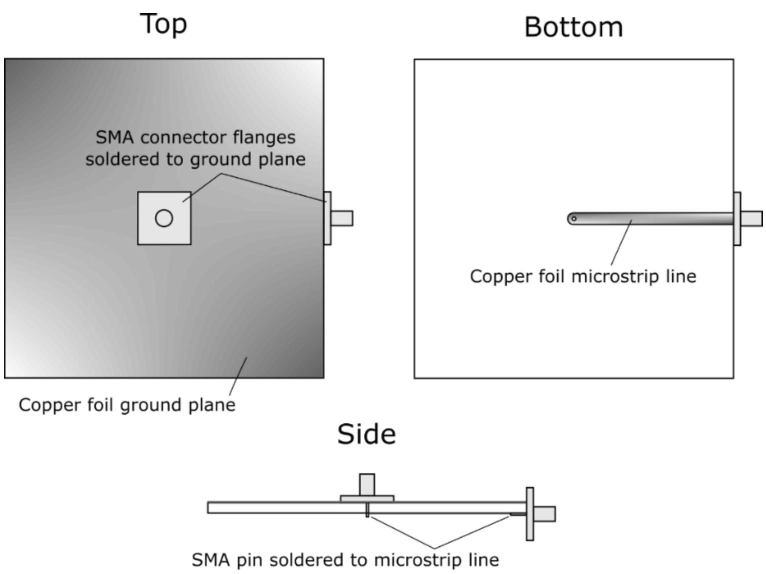
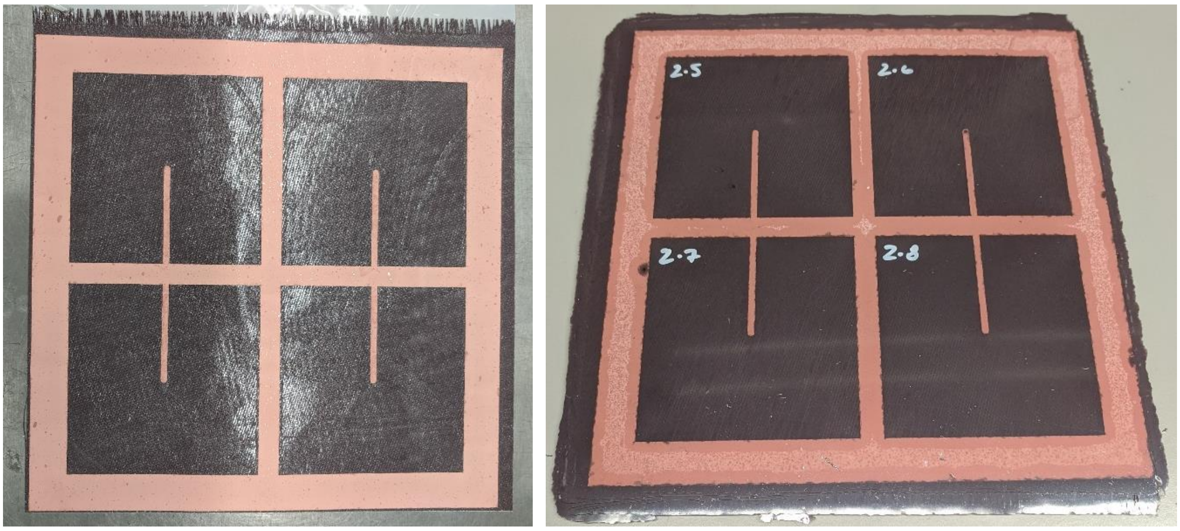


Figure 3: Functional composite laminate test specimen, representative of RF connections used in prototype functional antenna structures.

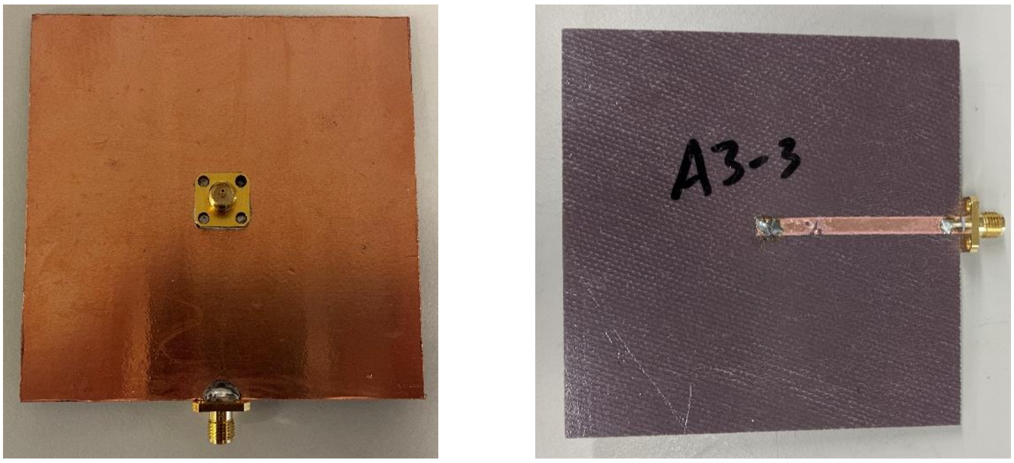
The width of the microstrip line (3.17 mm) is calculated for 50 Ω impedance by taking into consideration the dielectric impedance of the substrate and the through-thickness distance to the ground plane (1.6 mm). SMA connectors are located on either end of the microstrip line, with the pins soldered to the microstrip line and the flanges soldered to the ground plane. The manufacturing of these laminates is aided by laser cutting of the copper foil for the microstrip line profile, which allows for accurate positioning of one end of the microstrip line at the centre of the laminates.

Figure 4(a) shows the laser cut copper foil profile for four specimens transferred onto a ply of glass/epoxy prepreg (Deltatech VV300S/FR150N). After curing, the 90 mm x 90 mm square profiles of copper are used as a guide to cut into four specimens per panel. After this, a 4.3 mm keep-out and 1.3 mm pin hole are machined from the top side of the specimen to allow for insertion of the SMA connector. Figure 5(a) shows the top view of a specimen after this machining operation and soldering of the SMA connectors, while Figure 5(b) shows the reverse side of a specimen, showing the microstrip line soldered at both ends to SMA connectors.



(a) (b)

Figure 4: (a) Laser cut copper foil profile transferred onto prepreg ply, (b) final cured laminate, showing four of the 90 mm x 90 mm specimen profiles from microstrip line side.



(a) (b)

Figure 5: (a) Top view of specimen after soldering of SMA connectors (b) Bottom of specimen, showing microstrip line.

4 SIMULTAENOUS MECHANICAL AND RF TESTING METHODOLOGY

The experimental setup used for testing is shown in Figure 6. The test specimens described in Section 3 are connected to a universal testing machine via an aluminium clamping fixture that produces symmetric clamped boundary conditions while allowing access to the side-mounted SMA connector. The underside of the specimen is supported by a piece of the fixture made of ultra-high-molecular-weight polyethylene (UHMWPE) so that RF transmission along the microstrip line is not affected by proximity to aluminium.

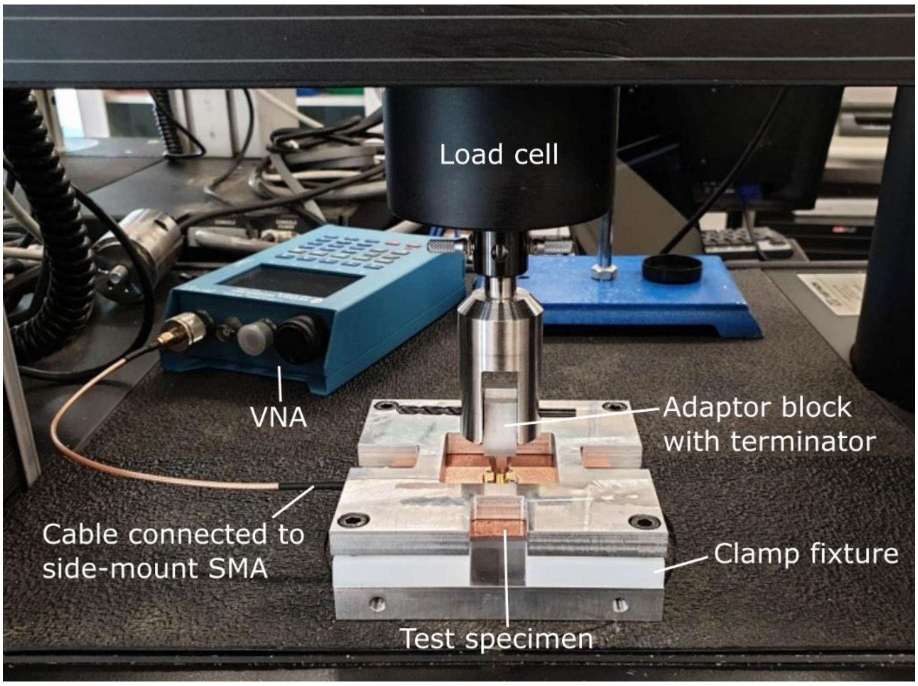


Figure 6: Experimental setup for pull-off testing of SMA connectors with simultaneous RF testing.

The mechanical loading frame is connected through a load cell to an adaptor block, which screws into the SMA connector on the top side of the specimen to transfer mechanical load. The adaptor screws in via an integrated 50 Ω dummy load terminator, as this setup is the 1-port configuration described in Figure 2. A cable connects the side-mounted SMA connector to a VNA which is controlled remotely by PC software. A camera (out of frame) is brought in during tests to capture close-up vision of the joint under load.

The experimental setup demonstrated here is configured for loading the specimen in a “pull-off” mode, where the laminate is held fixed and a vertical load (or cylic load in this direction) is applied to the SMA connector on the top side of the specimen. In addition to this, the methodology has been developed for inclined pull-off (i.e. the configuration shown in Figure 6 but with an inclined clamp fixture, leading to addition of some bending to the joint) and for torsional loading of the connector (i.e. loading and unloading due to attachment and torquing of a cable). Some preliminary results for the pull-off configuration are shown here to aid in explanation of the methodology and analysis.

Results for the pull-off configuration show three distinct phases of the test:

- Phase 1: No damage present, load increases monotonically.
- Phase 2: Delamination occurs, load drops rapidly.
- Phase 3: Connector pin pulls out, followed by copper tearing.

Typical load-extension data from a sample test are shown in Figure 7, with the onset of delamination and pin pull-out labelled with orange and grey lines, respectively. Figure 8 shows photos taken around the SMA connector at the moment of delamination and immediately after, showing increasing doming of the copper as it pulls away from the laminate. Coinciding with the sharp drop in load is the rapid growth of this dome when the area under the connector delaminates.

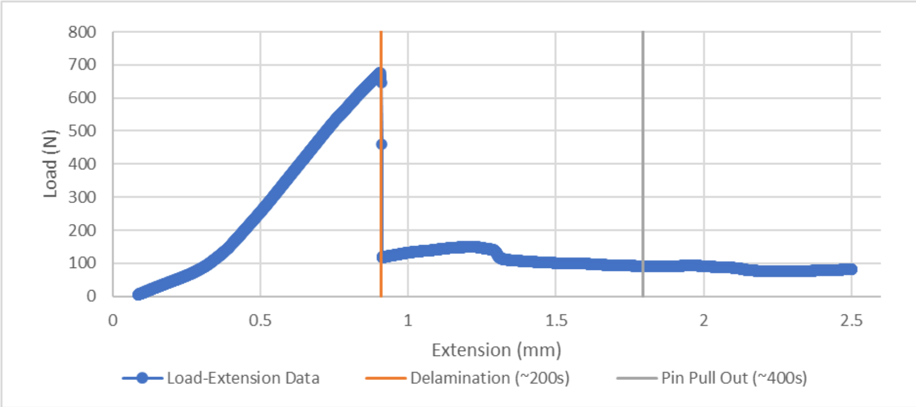
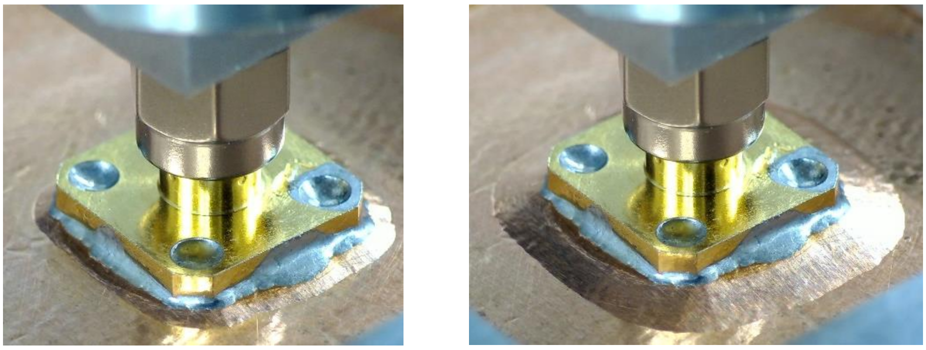


Figure 7: Load-extension data from sample test with delamination and pin pull-out failure modes.



(a) (b)

Figure 8: Copper foil doming around SMA connector (a) at the moment of delamination, and (b) immediately after delamination.

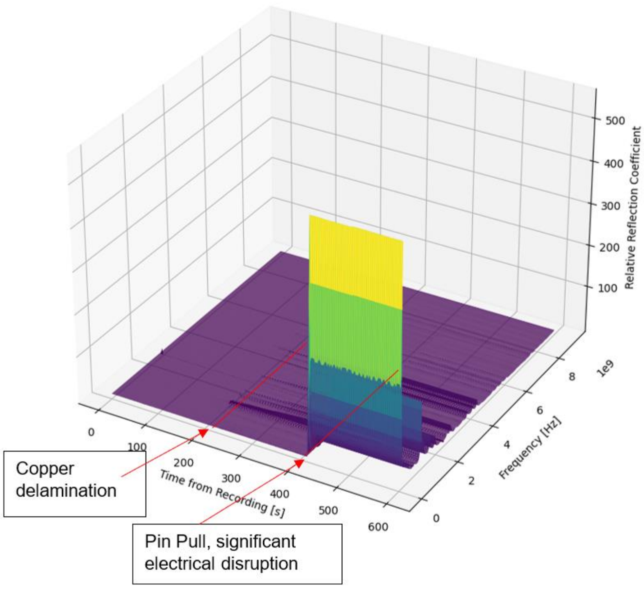
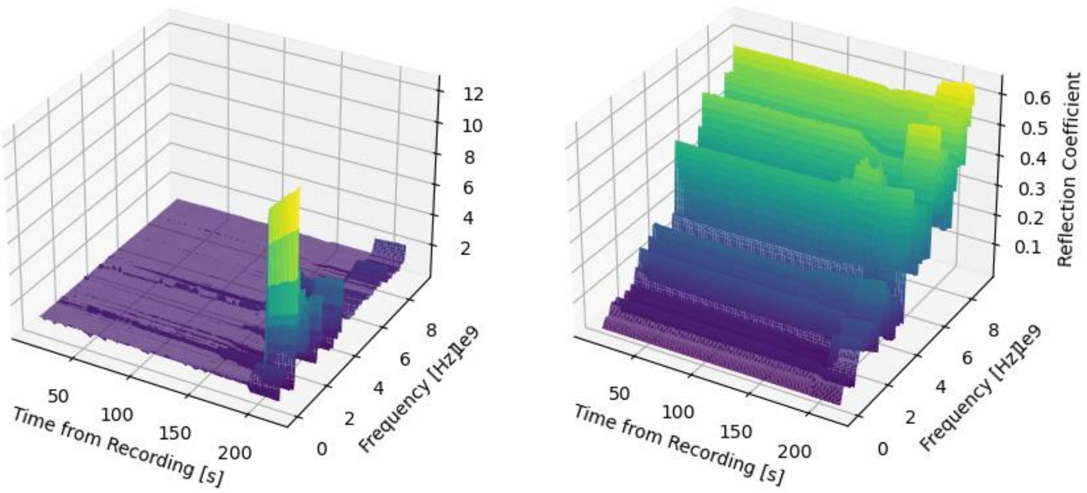


Figure 9: Relative reflection coefficient over the inspected frequency range during sample test.

A LabVIEW program interfaces with the VNA and allows for the automated collection of data during testing, with one sample of reflection coefficient from DC to 9 GHz captured approximately every 2.74 seconds. In the configuration used during this sample test, the reflection coefficient of the sample during the beginning of the test (average of first 5 samples) was used to establish a baseline, and for the duration of the test a relative reflection coefficient was calculated by subtracting from this baseline. Figure 9 shows the relative reflection coefficient data over the inspected frequency range for the duration of this test. The moment of copper delamination occurs approximately 200 seconds into the test, and pin pull out occurs approximately 400 seconds into the test.

Reflection coefficient data for period immediately prior to delamination of the copper ground plane from the laminate are shown in Figure 10, with a change of vertical ranges between Figure 10(a) and Figure 10(b) to show more detail of the evolution of the reflection coefficient in the lead up to delamination. The large spike at approximately 200 seconds corresponds to the drop in load due to delamination. At approximately 150 seconds into the test, features begin to emerge in the RF spectrum prior to delamination of the copper, during a period in which the load increase is still linear. Is it particularly noteworthy that the relative reflection coefficient increased from the baseline during Phase 1 of the test, demonstrating degradation of RF function distinct from conventional mechanical failure of the laminate.



(a) (b)

Figure 10: Reflection coefficient data immediately prior to delamination. Note the difference in vertical scale between (a) and (b).

5 CONCLUSIONS

The developed methodology combines mechanical testing and RF testing with relatively simple data analysis techniques to provide at-a-glance relationships between mechanical and RF performance of functional composite laminates. Preliminary testing work demonstrated here shows that for the pull-off mode, SMA connector joints in functional composites exhibit change in RF performance, as measured by baseline subtraction of reflection coefficient, prior to and distinct to conventional mechanical failure of the joint. Current and future work will explore loading and unloading of the joint in bending and torsional modes, as well as investigate the effects of manufacturing parameters (e.g. soldering methodology) on the performance of these joints.

The development of this testing methodology that simultaneously characterises the mechanical and electrical performance of critical interfaces in functional composite laminates will allow for rapid experimental assessment of candidate designs for RF connections, with the ultimate goal of designing RF connections that facilitate the development of functional composite structures that withstand the operational load requirements of aerospace while retaining their functionality.

ACKNOWLEDGEMENTS

This paper includes research that was supported by DMTC Limited (Australia). The authors have prepared this paper in accordance with the intellectual property rights granted by a DMTC Project Agreement.

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