AN INVESTIGATION INTO THE POTENTIAL OF MICROWAVE NDE FOR MARITME APPLICATION

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Abstract: The ability of microwaves to penetrate dielectric materials has been shown to produce unique inspection capabilities and potentially large cost benefits when applied to some inspection tasks usually performed using more traditional NDE methods. Fibre reinforced polymeric (FRP) materials and in particular FRP sandwich composites are finding increased use in the field of maritime structures and this investigation has demonstrated the ability of microwave NDE to detect near-side, core and far-side defects including skin / core debonding, core cracking and impact damage. It is also the case that maritime vessels employ large volumes of lagging materials to restrict heat emission from pipework and also to prevent condensation, e.g. on the inner side of a hull. Defects may grow unseen beneath this lagging and it is traditionally only by removal of all insulation that an NDE inspection may be performed. However, by employing the ability of microwaves to pass through non-conducting media it has been shown that not only defects within FRP structures, but also, corrosion /wall thinning and surface breaking defects in metallic components can be detected without the necessity of removing lagging. It is therefore envisaged that such an inspection method would lead to large cost benefits to the owners and operators of such vessels.

Introduction: Monolithic and sandwich construction glass-fibre reinforced polymer (GFRP) materials are finding increased use within the maritime field, including many of the ships and boats that operate in littoral waters. The structures and methods of construction of these vessels varies considerably, stretching the capabilities of conventional Non-Destructive Evaluation (NDE) methods, e.g. whilst ultrasonics may be applicable to the inspection of thin single-skin structures it is perhaps not applicable to inspection of composite sandwich structures. Added to this is the never-ending drive to reduce cost of ownership (i.e. Life Cycle Costs) and equipment 'down-time'. Therefore to improve inspection methods and reduce costs there is a constant need to review existing and novel techniques. The fact that microwave energy passes through dielectric (non-conducting) materials means that it has the potential for use as an inspection method for not only single skin but also sandwich composite materials.

Within the UK, expenditure on NDE inspection of naval ships and submarine components and structures at build, during refit and in-service is considerable and therefore methods of reducing the overall costs are constantly under review. Microwave NDE has been shown to have the potential to solve some of the inspection problems associated with GFRP composite materials whilst also offering potential cost savings in areas in which only conventional techniques have been employed, e.g. pipe inspection and detection of corrosion.

Within almost all naval ships lagging is extensively employed to alleviate the problems associated with the temperature differential. This differential can be either hot - ambient, as in the case of lagged high temperature pipework, or cold - ambient as in the case of hull insulation. The removal and replacement of this lagging to enable an NDE inspection of components is not only expensive but may also be an unnecessary health hazard. To be able to perform an inspection without the need to remove the lagging would have obvious benefits. Microwave NDE has been shown to have this potential.

This paper explores maritime applications to which microwave NDE offers the promise of an improved inspection procedure.

Microwave NDE: Microwave signals easily penetrate inside non-conducting materials and may therefore be employed for defect detection within these materials. Microwave NDE can be conducted with the probe in contact or non-contact whilst operating from one side only or from both sides (reflection or through-transmission). There are several approaches to making microwave measurements but the two most prominent are the near and far-field (i.e. radar) techniques. In the near-field the size of the source is significant but in the far-field the source is small compared with its distance away. Near-field microwave imaging is based on transmitting a wave into a dielectric structure, located in the near-field of a sensor, and mapping the magnitude or phase of the reflected wave to create two- or three-dimensional images of the structure under investigation.

This investigation employed near-field techniques as these have been shown to be most suited to this application for the following reasons;

- The spatial resolution when operating in this region is primarily influenced by the dimensions of the probe rather than the operating wavelength (typically 7.5 to 30 mm) and therefore much better spatial resolution may be obtained compared to that achieved with plane or spherical waves (far-field).
- Contact as well as non-contact measurements are possible.
- Unwanted reflections from changes in geometry associated with far-field methods are minimised.
- Suitable open-ended waveguide probes are generally easily available.
- Signal detection may be achieved using a simple, inexpensive diode detector at a strategic location within the waveguide source.
- Inspection systems are less bulky and cumbersome and could be battery operated.
- The microwave power associated with these systems is low (in the milliwatt range) and therefore poses no Health and Safety concerns.

For NDE purposes the two main operating parameters to be considered are operating frequency and stand-off distance, (the distance between the inspection surface and the waveguide aperture).

Table 1 shows details of microwave (Bands G - K) and millimetre wave (Bands Ka, Q and U) frequency bands. Those highlighted are the bands generally, though not exclusively, employed for non-destructive testing. Dimensions are given in inches as the length of the long side of the rectangular waveguide aperture corresponds to the Waveguide Standard Designation.

The optimum stand-off distance will be largely dependent on the waveguide being employed and the structure under test. It is therefore suggested that this parameter is adjusted and optimised on the work-piece or a calibration piece of an identical nature.

Table 1. Waveguide Frequency Bands

Frequency Band Designation	**Waveguide Standard Designation**	**Frequency Limits (GHz)**	**Waveguide Inside Dimensions (inches)**
G band	WR-187	3.95 to 5.85	1.870 x 0.940
F band	WR-159	4.90 to 7.05	1.590 x 0.800
J band	WR-137	5.85 to 8.20	1.370 x 0.690
H band	WR-112	7.05 to 10.00	1.120 x 0.560
X band	**WR-90**	**8.2 to 12.4**	**0.900 x 0.450**
Ku band	**WR-62**	**12.4 to 18.0**	**0.622 x 0.311**
K band	**WR-51**	**15.0 to 22.0**	**0.510 x 0.255**
K band	**WR-42**	**18.0 to 26.5**	**0.420 x 0.170**
Ka band	**WR-28**	**26.5 to 40.0**	**0.280 x 0.140**
Q band	WR-22	33 to 50	0.224 x 0.112
U band	WR-19	40 to 60	0.188 x 0.094

Unbonded/Disbonded Skin To Core Joints: In the continuing quest for strong, lightweight and tough materials for maritime use sandwich composites are being extensively employed. In the U.K. all lifeboats produced for the Royal National Lifeboat Institution (RNLI) are now built of sandwich composite, as indeed are many motor yachts and pleasure craft. These applications generally employ polymer foam cored composites. However, for naval use, end-grain balsa-wood is often used as the core material. Whilst uncommon, it is possible during construction to produce regions in which either the outer or inner skin is not bonded to the core. Also, normal wear and tear during service may cause weak bonding to fail thus generating disbonded regions. Microwave NDE is well suited to the detection of this type of defect.

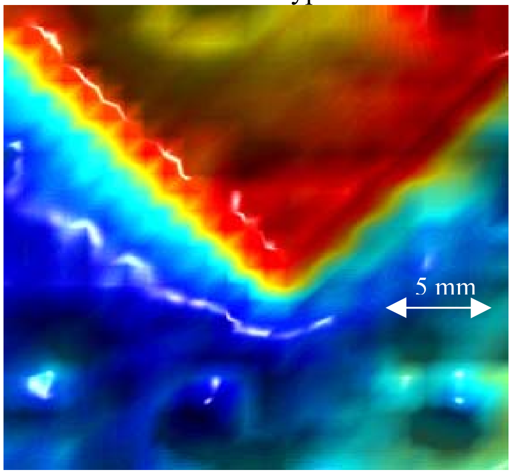


Figure 1. Image of a Triangular Unbonded Outer Skin / Core Joint Produced at 35 GHz

Figure 1 shows an image of a triangular unbonded region in the outer E-glass skin of a PVC foam-cored sandwich sample, the skin was less than 5 mm thick. This inspection was performed at 35 GHz (Ka band). The circular indications at the bottom of the image are due to bleed holes drilled in the core to allow excess adhesive to flow away from the bondline.

When the inspection is performed from the inner skin side the data shown in Figure 2 is produced. It can be seen that, although the image is not as clear as that of Figure 1, the defect is clearly visible and demonstrates that, for vessels constructed of sandwich composite, single-sided inspection is an option.

Skin and core material dielectric properties, as well as their thicknesses, will govern the optimum operating frequency and the ultimate defect detection capability. At present this is not considered to be a particular problem because critical defect sizes in this form of construction are generally large.

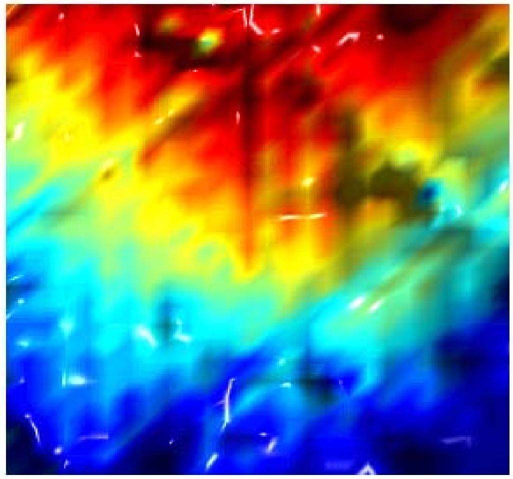


Figure 2. Image of a Triangular Unbonded Outer Skin / Core Joint Inspected from the Inner Skin Side

Impact Damage: A large proportion of in-service damage is of an impact nature; either the vessel comes into contact with some other floating object or the vessel contacts a fixed object such as a rock or jetty. In either case visual evidence of that impact is usually available. However, it is the case with most instances of impact damage that visual observation cannot reveal the true extent of the damage and an NDE method capable of providing that information [2] is required to enable a repair strategy to be defined.

The example shown in Figure 3 below is a 10 mm thick monolithic sample which has been subjected to impact testing. The area of damage observed visually from the impacted surface (Front face) is small compared to that observed on the reverse. Microwave inspection from the front face generates an image that accurately reproduces the size and shape of the overall damage.

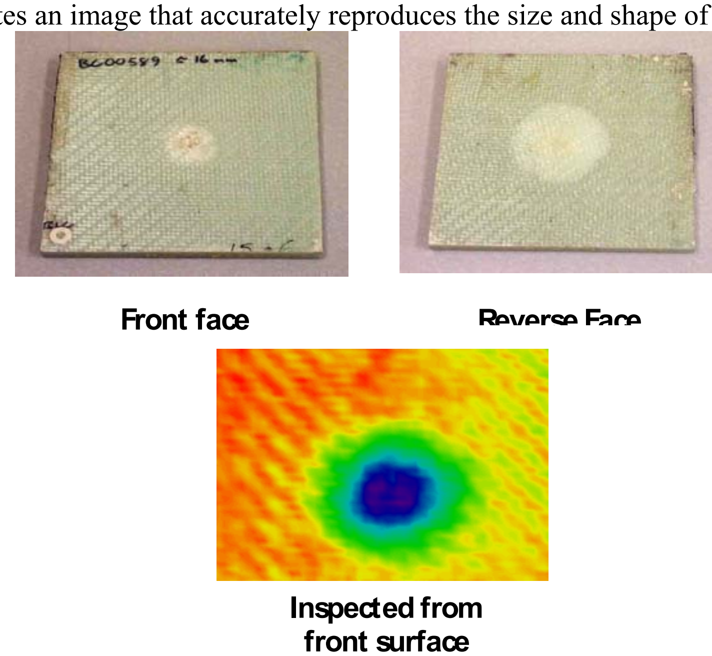


Figure 3. Microwave (35 GHz) Inspection of Impact Damage

In the case of impact damage to PVC foam cored sandwich composite structures, unless the magnitude of the impact is excessive, it is usual that damage will occur to the outer skin and the impact energy will be dispersed within the core. As a result, core crushing or core cracking may occur. Microwave NDE of both types of damage is considered later in this paper.

Sandwich Composite Core Cracking: Obviously the strength of a sandwich composite is dependent on the integrity of the core material. Excessive overload may cause a shear stress between the two skins and result in core cracking. It is possible for this situation to exist whilst there is no outwardly visible indication of the damage.

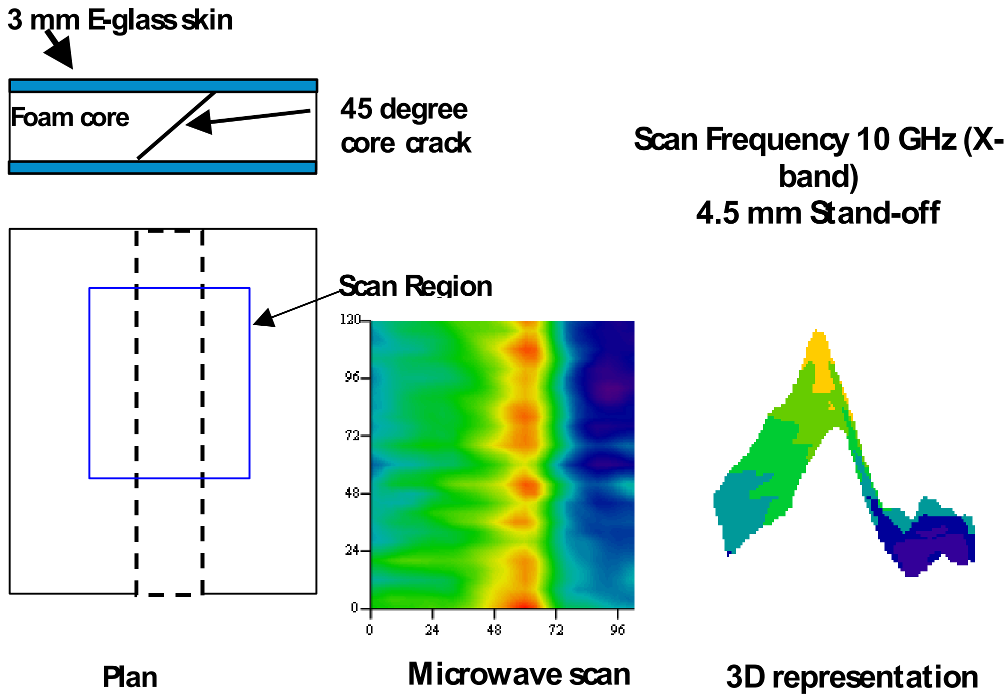


Figure 4. Microwave NDE Image of Core Cracking

The data presented in Figure 4 not only gives a good indication of the presence of the core crack defect but also shows the orientation of the crack. The rapid change of signal amplitude from right to left, i.e. from deep blue through green to yellow and red, indicates the close proximity of the defect to the test surface whilst the slow transition from red and yellow through green to blue indicates that the defect is moving away from the probe.

Sandwich Composite Core Crushing: Core crushing in PVC core composites can be caused either by impact loading or by long-term excessive localised loading and can result in reduced structural performance. This form of defect is very difficult to detect as often there is little if any visual evidence and it is undetectable using ultrasonics.

Figure 5 shows a microwave NDE image of a region of core crushing in a 3.5 mm, E-glass skinned, PVC foam cored sandwich sample produced by a spherical impact.

This inspection was performed at 15 GHz, a frequency low enough to enable interrogation of the core of the sample.

In the region around the defect the regular pattern of core bleed holes can be seen and it is evident that, although the impactor was circular, these resin filled holes have affected the shape of the defect due to their increased stiffness.

A better impression of the actual size of the defect is obtained by reversing the colour palette of the image as shown in Figure 6.

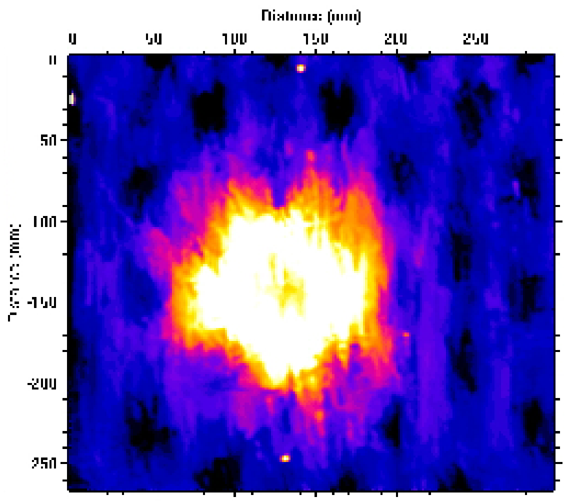


Figure 5. Microwave NDE Image of Core Crushing in a 3.5 mm, e-glass PVC Foam Cored Sample

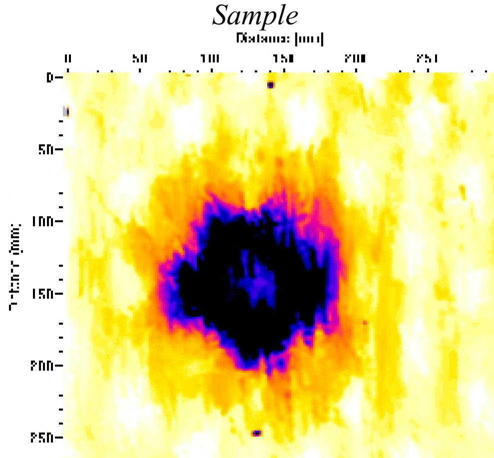


Figure 6. Reverse Palette Image of Core Crushing Defect of Figure 5

Corrosion Under Lagging: Within naval ships and submarines, the majority of situations where large temperature differences exist between a system and the ambient atmosphere employ insulation or lagging to alleviate the effects of this difference. Prime examples are lagged steam and cold water pipe systems, and the inner surface of the hull will be lagged to prevent condensation. Periodically this lagging has to be removed to enable inspection of the steel plate and afterwards it has to be replaced. This can be time consuming and ultimately very costly. It can therefore be seen that any inspection that can be performed without the need to remove the lagging will have major benefits both in terms of the time required and the cost of the inspection.

A test plate was made with machined recesses to represent varying degrees of plate thinning as shown in Figure 7. The example shown has five recesses from 3.0 to 5.0 mm in 0.5 mm steps. The sample was then covered with 50 mm of glass-fibre insulation prior to inspection. The 2-D data image indicates differing output levels for each recess and this can be seen even more clearly in the 3-D image. From this it can be seen that using this amplitude data it will be possible to calibrate the system in order to make quantitative measurements.

Crack-Like Defects Under Lagging

The detection of surface breaking defects is not a particularly arduous task. Many NDE techniques are available and individually each may be better suited to particular inspection tasks than others. However, at present one common factor is that, for lagged structures and components, lagging has to be removed before an inspection can be performed. As described previously, microwave NDE can be used to inspect the surface of metallic components under lagging and this has been shown to be the case for surface breaking defects.

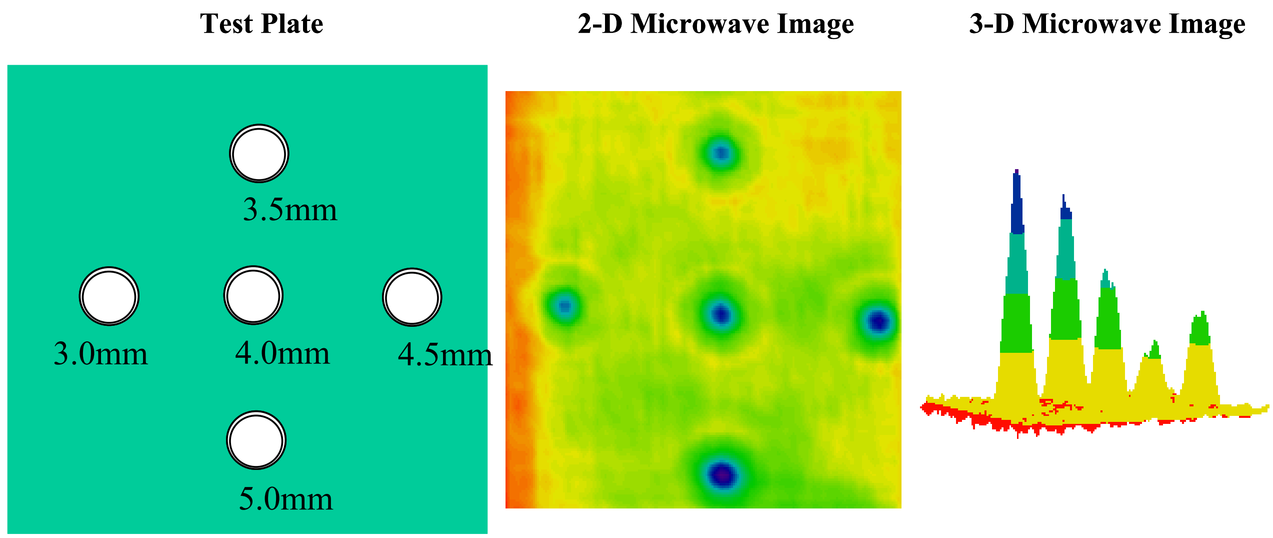
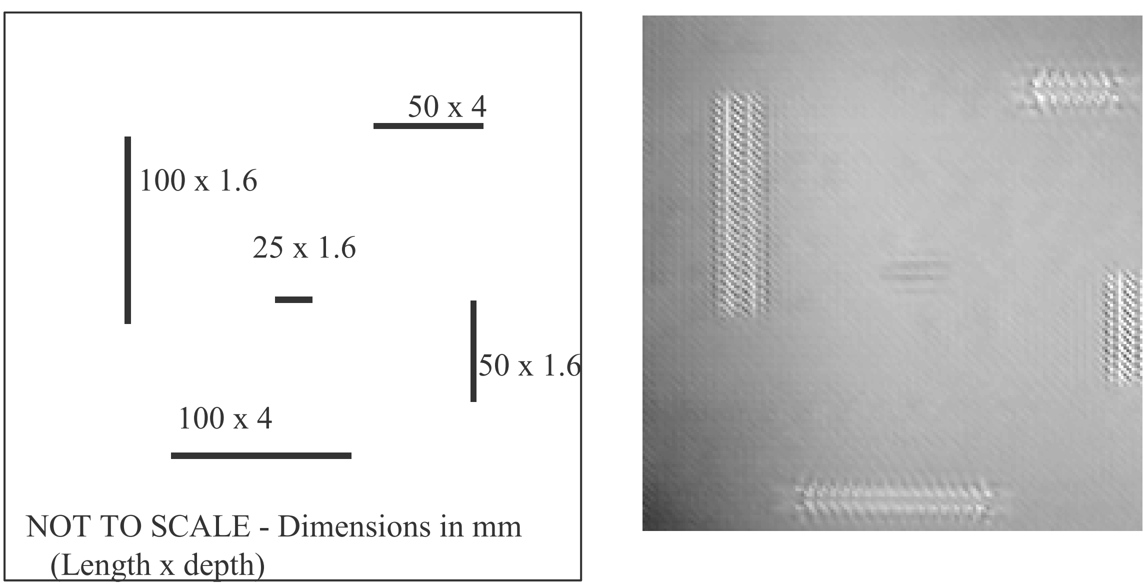


Figure 7. Example of the use of Microwave NDE for the Detection and Measurement of Wall Thinning.

Figure 9a shows a 300 mm square test plate with five spark eroded artificial crack-like defects, each defect is 0.2 mm wide. Figure 9b shows the Ka-band microwave image of the bare plate.



(a) (b)

Figure 8. Crack-like Defect Test Plate (a) Dimensions, (b) Microwave Image, Ka-Band

Figure 10 shows the microwave NDE images of just one of the notches when covered with a variety of insulating materials. It can be seen that the notch is still just visible under 50 mm of glass-fibre insulation.

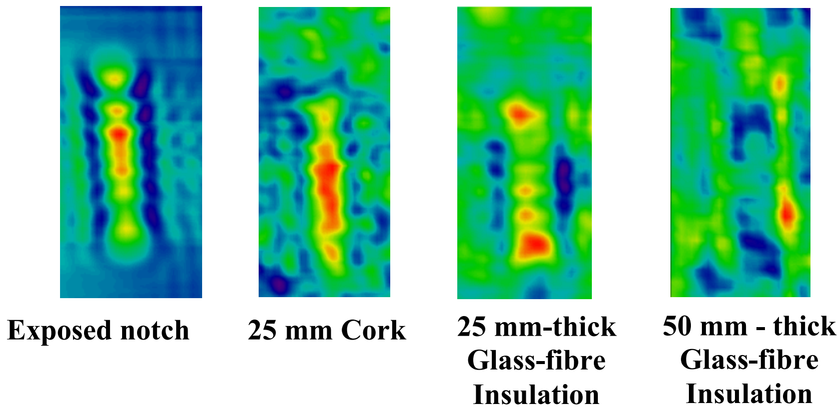


Figure 9. Microwave NDE Images of Surface Breaking Notch Under Insulation

Conclusions: The data presented here shows that there is a place for microwave NDE in the inspection of the types of dielectric composite materials and structures employed in maritime applications.

Monolithic composite structures are readily inspected by this method. It has been shown that core defects in sandwich composite structures can successfully be detected. The fact that microwaves are susceptible to the surface finish of conductors enables microwave NDE to be used to inspect a metallic surface for cracks and corrosion without the need to remove lagging. It is now intended that prototype production systems are produced to enable a greater depth of in service inspection experience to be gained. Future investigations will include an assessment of pulsed techniques to enable time domain, i.e. defect depth, information to be obtained.

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2. Hughes, D., Behrens, C., Zoughi, R., Green, G., and Campbell, P., *Microwave and Millimeter Wave Inspection of Impact Damage in GFRP Composite and Pitted Corrosion in Steel,* ASNT Spring Conf. 2002, Portland, Oregon