

THE INFLUENCE OF SANDWICH STRUCTURE CORE MATERIAL ON THERMOGRAPHIC NDT TECHNIQUES

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ABSTRACT

Debonding of the face sheet to the core is one of the most common and critical defects in composite sandwich structures. Three non-destructive evaluation (NDE) techniques are compared for their ability to assess defects at the interface between the face sheet and core material. The NDE techniques are: C-scan ultrasonic testing (UT), pulse thermography (PT) and pulse phase thermography (PPT). The effect of defect type, face sheet thickness, defect location and core density are all considered. The sandwich panels were glass fibre reinforced polymer (GFRP) face sheets with PVC foam cores. The panels were manufactured using two approaches; firstly by resin infusion in a single shot process and secondly by using adhesive film to secondary bond the prefabricated face sheet material to the core. Face sheet thickness and core density were varied through the panels. Interfacial defects were simulated by the addition of PTFE inserts, contamination using silicon grease and by creating an area without adhesive. It was shown that only PPT could identify the size and shape of the defect as the thickness of the laminate was increased without any alteration to the setup. In the secondary bonded panels, it was shown that core density played an important role in detection of the defect. The positioning of the defect with respect to the adhesive layer was also found to effect detection with defects between the adhesive and the core being significantly more difficult to detect than those between the face sheet and adhesive.

1 INTRODUCTION

The use of sandwich structures is increasingly popular owing to the high specific strength and stiffness properties which are achieved through their use. Composite sandwich structures combine face sheets of high strength and stiffness, with a lightweight core. The overall component stiffness is achieved through the ability of the core to transfer shear loads between the face sheets. Defects in the face sheets or core reduce the strength and stiffness of the sandwich structure. Moreover defects between the core and face sheets can initiate debonding of the face sheets which is critical as the all stiffness is lost if the face sheets detach [1]. Defects can broadly be categorised as occurring either during manufacturing or through some in-service event. Manufacturing defects are typically caused by contamination, or through poor application of resin whereas in-service, delamination is known to be a common and critical defect [2]. Non-destructive examination (NDE) is necessary to identify defects so that remedial action may be taken. Ultrasound (UT) is the most common form of NDE and can provide more quantifiable and consistent results when compared to traditional visual inspections and tap testing. However UT investigations are time consuming, and the high frequencies used are quickly attenuated in air, necessitating the use of coupling fluid between the transducer and specimen surface. Components must therefore typically be removed to a test facility for inspection in a water filled ultrasound bath. UT relies on emitted pulses being received back to the transducer, which is difficult to achieve with non-planar specimens or those with complex geometry. The development of phased array ultrasonic techniques has overcome some of the limitations of C-Scan UT, by reducing inspection time and through post processing to enable beam focusing for complex geometry [3]. While the cost of

phased array equipment has reduced, it remains expensive in comparison to other NDE technologies [4]. The use of thermographic techniques such as pulsed thermography (PT) also overcomes some of disadvantages of UT and is an attractive proposition for the inspection of composites components. PT is easily deployed in the field, non-contact, requires minimal preparation, and large portions of a component can be inspected rapidly providing rich full field data [5,6]. PT is particularly useful where component geometry makes the use of UT challenging [7]. However PT is dependent on the thermal properties of the materials under investigation and is highly sensitive to material thickness [8]. Probe depth can however be improved using Pulsed Phase Thermograph (PPT). Converting the temporal thermal data to the frequency domain gives the phase and amplitude of the response which can be used to improve probe depth and reduce surface effects [9].

While many studies have considered thin laminates, Ibrahim reported in a recent review that research and literature relating to the NDE of thick laminates and sandwich structures is sparse and that more work was required [10]. Qin and Bao investigated the use of thermography for the NDE of sandwich structures, particularly considering panels with aluminium face sheets and a glass fibre reinforced polymer (GFRP) honeycomb core and vice versa [11]. The study used hot air to heat one side of a panel and an IR detector on the other side to monitor and record surface temperature changes. The study found that thermography could identify simulated de-bond defects in such panels for a variety of regular shapes including triangular, rectangular and circular. Where an aluminium core was used in conjunction with GFRP face sheets, the high thermal conductivity of the core affected the result, where honeycomb structure was visible in thermographic data. However it is not clear in [11], specifically what materials were used, how these defects were manufactured/simulated, and proportions of the sandwich panel and laminate are not provided. Garnier et al [7] conducted a comparative study of three NDE techniques on plate and sandwiched composites. The specimens studied were aircraft components which contained real in-service impact damage. The work compared ultrasound, thermography and shearography (speckle shearing interferometry). The authors experienced difficulty in using UT, mostly due to component geometry which made it difficult to receive reflections at the transducer. Where UT was used, it was shown to characterise the defect well in comparison to visual inspections. The study also showed that thermographic techniques were useful in identifying defects, and in most cases relatively accurately characterised them. Bates et al [12] also conducted a comparative study of damage and delamination defects (simulated with PTFE inserts) in carbon fibre reinforced polymer (CFRP) plates. Lock-in and transient thermographic (using halogen lamp) techniques were used in place of the techniques presented. It was found that transient thermography was better suited to the detection of PTFE inserts which simulate delamination than lock-in thermography. The work also found that while thermographic techniques could identify near surface defects, UT was still better at capturing defects in thicker plates. While most studies have not considered sandwich structures, Vikstrom investigated the use of thermography for the detection of simulated de-bonds [13]. PTFE inserts were used to simulate the de-bonds, and a variety of PVC core materials were tested. The study found that thermography was a useful tool for the detection of de-bonding and delamination in composite sandwich structures. The paper also suggested that core density has an effect on the contrast obtainable between defective and non-defective areas, with lower density core materials improving contrast.

The aim of the present paper is to assess the capability of PT and PPT to accurately identify and characterise laboratory-simulated defects in composite sandwich panels and compare this with UT. The size, type and location of the simulated defects was varied to determine sensitivity of the techniques to these parameters. The effect of core density was also investigated, three PVC closed cell foam cores were tested, each with a different density and thermal conductivity.

2 MATERIALS AND MANUFACTURING

Two types of panel were manufactured, one simulating interfacial de-bonds and the other simulating contamination defects. The panels containing interfacial defects were manufactured in a single shot resin infusion process. The interfacial defects were simulated using Polytetrafluoroethylene (PTFE/Teflon) inserts. Three different sized PTFE squares were used, 5, 10 and 20 mm, which were placed between each ply of the laminate and between the face sheet and the core prior to infusion. The face sheet laminates consisted of four plies of stitched biaxial E-Glass fibres with a total laminate thickness of approximately 2.4 mm. The configuration of the manufactured sandwich panel is shown in Figure 1 below. Three 30mm thick closed cell PVC core materials were chosen, each with a different density, and thermal conductivity as shown in Table 1 below. The panels were approximately 300 x 400 mm, with the PTFE inserts placed a minimum of 75mm from the edge of the laminate to avoid edge effects.

Manufacturer	Product	Material	Density (kg/m ³)	Thermal Conductivity (W/m.k)
Easy Composites	Easy Core 75G	PVC Closed Cell Foam	75	0.033
Diab	Divinycell H-100	PVC Closed Cell Foam	100	0.033
Diab	Divinycell H-250	PVC Closed Cell Foam	200	0.049

Table 1: Core materials tested

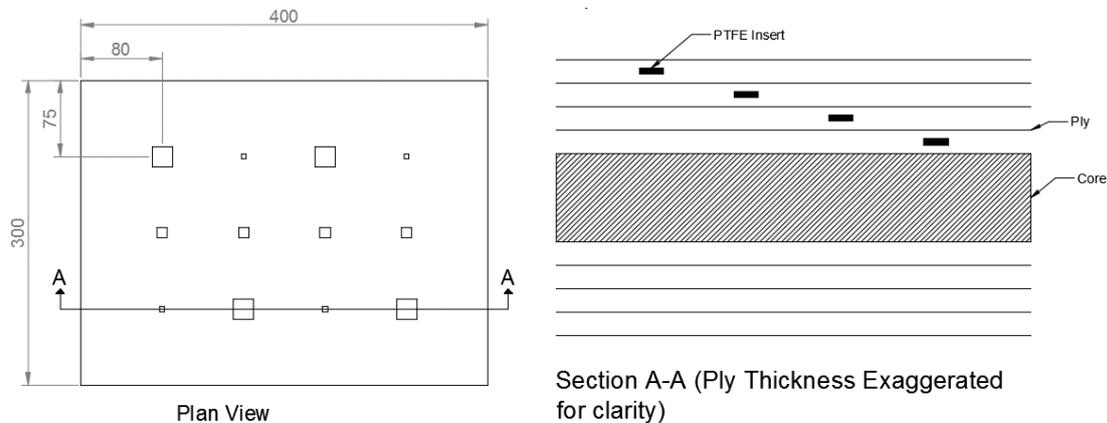


Figure 1: Simulated Delamination Location

The panels containing simulated contamination defects were manufactured differently. The face sheets were manufactured using resin infusion and secondarily bonded to the foam core using SA-80 film epoxy adhesive. This was because the silicon grease would not stay in position during the vacuum infusion.

It was also found during testing of the interfacial defects that PT was not able to penetrate deep enough into the laminate to identify defects beyond 1.8 mm. The overall thickness of the laminate was therefore reduced to 1.4 mm so that all NDE techniques could be tested and compared. All simulated defects were placed at the core/face interface. Silicon grease and PTFE inserts were placed both below the adhesive at the adhesive/core interface and above the adhesive at the face sheet/adhesive interface. A third set of defects were simulated by removing portions of the adhesive film to create areas which lacked adhesion. Two sizes of defect were simulated for the silicon and adhesive removal methods, 10 and 20 mm diameter were used. Once the samples were inspected in the ultrasound bath, matt black paint was used to increase the emissivity of the surface of the specimens.

3 EXPERIMENTAL METHODOLOGY

The PT experiments were set up in reflection mode whereby the photon detector and heat source are positioned on the same side of the test specimen. A photographic flash was used to produce a broad spectrum thermal pulse. An infra-red detector was used to monitor the thermal decay of the surface of the panel which is recorded by a computer. The specification of the flash and IR detector used are given in Table 2 below.

Equipment	Description	Specification
FLIR SC5000 Photon Detector	Operating Temperature	77 K
	Thermal Sensitivity	20 mK
	Number of Pixels	320 x 256
	Frame Rate	383 Hz
	Infrared Spectral Range	3.6-5.1 μm
Bowens 1000 Pro Photographic Flash	Power	1000 Ws
	Flash Duration at full power	1/2100 s

Table 2: Experimental Equipment Specification

The FLIR Systems proprietary data acquisition software Altair was used to collect the thermography data. Altair was also used to control the camera, in conjunction with CIRRUS which was used initially to set up camera parameters and perform a non-uniformity correction. The IR detector was positioned at approximately 180 mm from the panel at 10° angle slightly off perpendicular to reduce camera cold spot reflection. The camera stand-off distance was chosen to obtain a useful spatial resolution while viewing a single simulated defect with each test. The flash was positioned at approximately 130 mm stand off from the panel. The PT data were obtained by selecting the maximum contrast frames from the thermal data recorded, where thermal contrast is the difference between the defect and non defective areas. Post processing and PPT was carried out in Matlab R2016a, using a Fast Fourier transform to convert the PT data from time domain to frequency domain. Ultrasonic testing was carried out in an immersion bath containing distilled water as a coupling fluid. Three axis probe movement was provided by precision stepper motor driven lead screw actuators, with a 0.02 mm minimum step size. The transducer and movement control are connected to a computer, with the transducer communicating through a 200 MHz analogue to digital converter. The software used was USL Scanner 4.16 provided by Ultrasonic Science Limited. A variety of probes were tested, and 2.25 MHz and 10 MHz transducers were found to provide the best results.

4 RESULTS

The experimental work initially considered the single shot resin infused panels with PTFE inserts, using PT, PPT and UT. Figure 2 shows the PT data for the three cores tested, at the shallowest depth of 0.6 mm where all techniques were capable of identifying the PTFE inserts. As shown in Figure 3, the contrast between defective and non-defective areas was reduced with increased depth. At 1.8 mm depth, it is difficult to identify the PTFE insert without knowledge of its location. Processing the thermal data to phase data allowed deeper probe depth, as shown in Figure 4 the characterisation is improved. It was also shown that the smaller PTFE inserts were more difficult to detect in all cases. The 5mm inserts were difficult to identify with increased depth and as shown in Figure 5, were poorly characterised, with lateral heat conduction causing the edges of the insert to become less well defined.

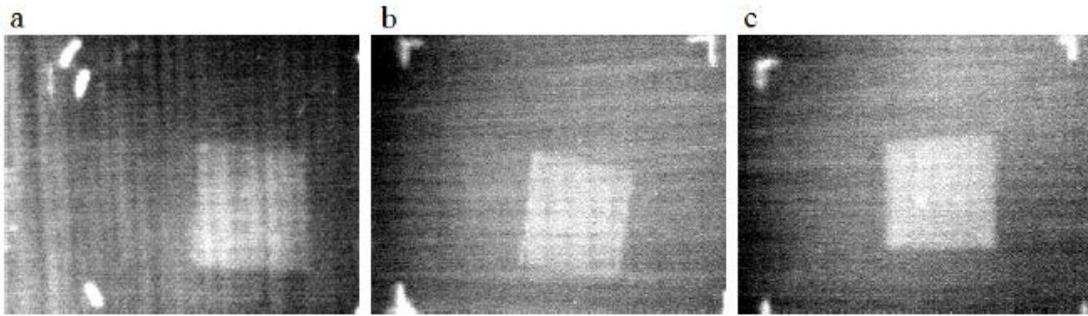


Figure 2: Experimental PT Data for 20 mm PTFE inserts at 0.6mm depth a) Easy Cell 75G, b) Dinvincell H-100, c) Dinvincell H-250.

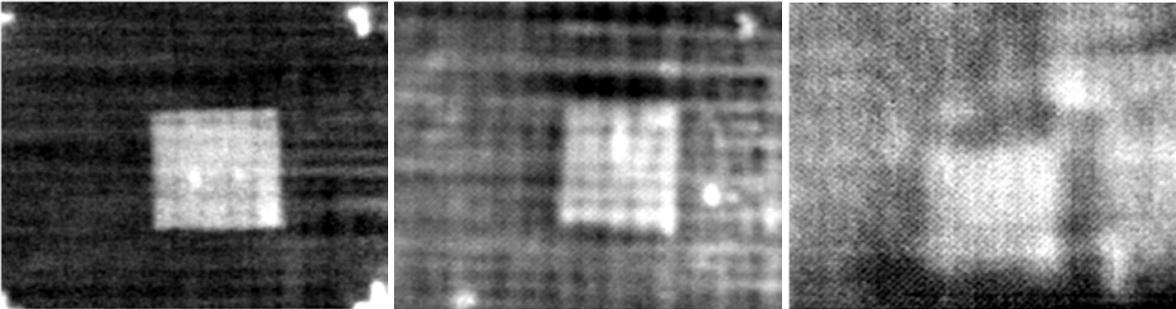


Figure 3: PT Data for 20 mm insert increasing laminate thickness at a) 0.6 mm b) 1.2 mm c) 1.8 mm

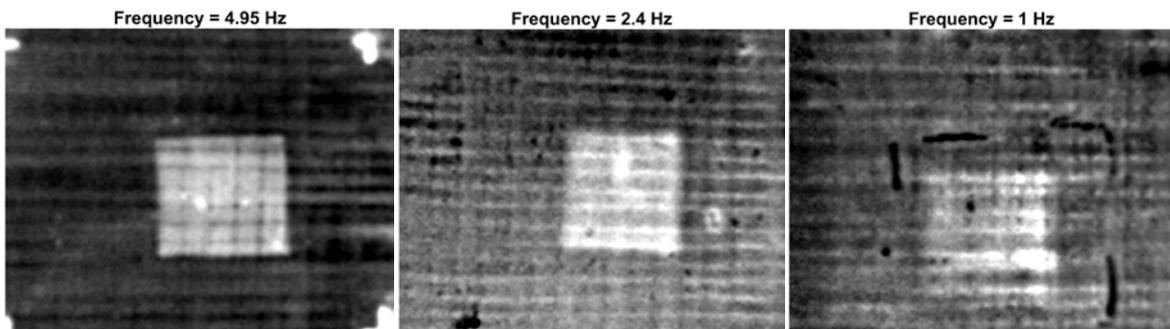


Figure 4: PPT Data at increasing laminate thickness for 20 mm PTFE Insert at a) 0.6 mm b) 1.2 mm c) 1.8 mm

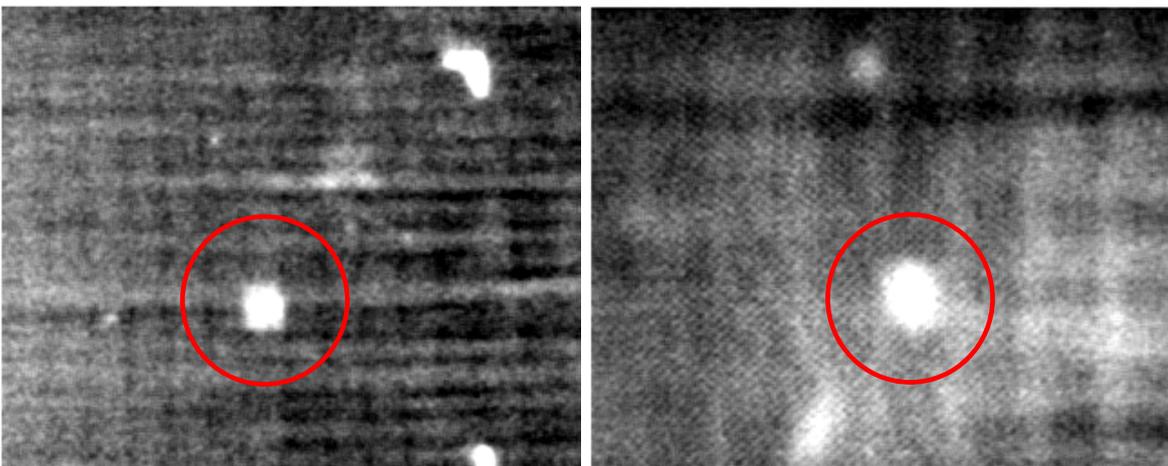


Figure 5: PTFE 5 mm defect at a) 0.6 mm b) 1.2 mm

The results shown in Figure 6 were obtained from the secondary bonded test panels which differ from those used in the above results, as discussed previously. All techniques were able to identify the largest PTFE inserts between the face sheet and the adhesive. The PT data provided low contrast, but the insert could be more accurately characterised in PPT. The UT data showed a clear definition of the insert using a 10 MHz transducer. PTFE inserts placed at the interface between the adhesive and the core were difficult to identify with all techniques. PT was unable to identify any size of insert, and PPT phase data revealed the PTFE insert, however the edges were not well defined and the contrast was low. The UT data was able to detect the largest insert, but similarly, edges were not well defined.

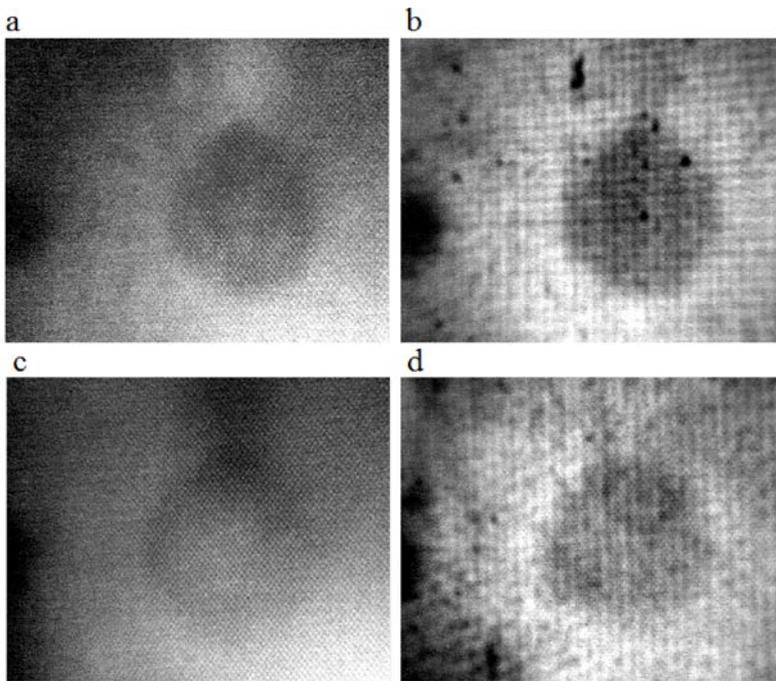


Figure 6: Silicon Inserts Between Adhesive Film and Face Sheet a) PT Data H-100 Core b) PPT Data H-100 c) PT Data H-250 Core c) PPT Data H-250 Core

All techniques could consistently identify the silicon placed at the face sheet/adhesive interface. As shown in Figure 6 the core material used has an influence on the contrast obtained. Current results appear to show an increase in thermal and phase contrast with increased core thermal conductivity. Further testing is underway to confirm this conclusion. Silicon artefacts between the adhesive film and the core were very difficult to detect with all techniques. Using PT only the largest silicon defect of 20 mm was visible. The PPT data showed that both 10 mm and 20 mm silicon artefacts were identifiable, however the boundaries were not well defined. UT provided good edge definition at the face sheet/adhesive interface and was able to identify the silicon insert between the adhesive and core but the defect was poorly characterised. All techniques were able to clearly identify areas where adhesive was removed with high contrast.

5 CONCLUSIONS

The experimental data shows that it is possible to detect simulated interfacial and contamination defects with all techniques used. However it has been shown that PT is only consistently effective for the detection of shallow defects. UT is an effective tool for probing deeper into the laminate, and can identify interfacial defects in relatively thick laminates. However defects which occur close to the core, or at the core to face sheet interface are particularly difficult to identify using UT. At these

locations it is difficult to distinguish the reflections from the core and the defects as they are detected almost simultaneously. PPT is capable of identifying and characterising defects in thicker laminates compared to PT, including at the core/face sheet interface. The location of the defect relative to the adhesive has an effect on the accuracy of PPT, where defects placed between the adhesive film and the core material being more difficult to identify than those placed, between the adhesive and face sheet. The effect of core density has been investigated, and core density is shown to affect thermal and phase contrast, with increased contrast obtained for increasing core thermal conductivity. Further work investigating different materials would be required to confirm this. It has however been shown in this work that thermography and in particular PPT is a useful NDE technique for the identification and characterisation of delamination and de-bond defects in composite sandwich structures.

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