

PULSE PHASE THERMOGRAPHY FOR KISSING DEFECT DETECTION

R. C. Waugh^{*}, J. M. Dulieu-Barton and S. Quinn

University of Southampton, Southampton, UK

**rcw1n09@soton.ac.uk*

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Abstract

An investigation into the application of pulse phase thermography (PPT) to identify kissing defects in adhesive bonds has been undertaken. Kissing defects are zero volume debonds that occur in adhesive bonds. Where there is a lack contrast between defect and bulk material properties, such as in the case of kissing defects, traditional non-destructive evaluation (NDE) techniques fail to identify the defects. It has been shown that the addition of a non-destructive load may be used to open such defects thus creating thermal contrast and allowing kissing defects to be detected using PPT. While initial work demonstrated that this was feasible using a laboratory based test machine further work has shown that vacuum loading may also be used thus creating a far more portable and industrially relevant technique.

1. Introduction

Adhesive bonds offer more uniform load transfer across the joint when compared to their mechanical counterparts. For adhesive bonds to be used in primary structural roles and load bearing applications it is necessary for all types of defects that occur in adhesive bonds to be identified in a reliable manner.

A range of defects occur in adhesive bonds [1, 2]. Generally defects such as voids or inclusions have a finite volume. The change in defect density or heat transfer properties enables detection using NDE approaches such as ultrasound or thermography. Kissing defects have zero volume and hence cannot currently be reliably detected. A kissing defect is found where all the components of a bond are present and in contact however there is improper adhesion between adhesive and adherend resulting in a reduction of strength from that expected from that joint [3]. Kissing defects are known to cause joints to fail via adhesive failure [4]. The exact cause of kissing defects is unknown however there are several theories including environmental factors, abnormalities in the curing cycles, contamination, residual stress and moisture ingress [5]. Previous research has been undertaken into how to recreate kissing defects where they have been predominantly categorized as dry contact or liquid layer [6, 7]. The present work uses the liquid layer approach to produce simulated kissing defects. A thin layer of silicon grease is added to the surface of the adherend during joint manufacture where the thickness of the silicon is much less than that of the adhesive layer. This method has been shown to be successful for creating defects that cannot be detected by traditional NDE but cause a significant reduction in the strength of the bond [8].

Pulse phase thermography (PPT) is an active thermographic approach that can identify regions of differing thermal properties within a component [9]. A pulse of heat is applied to the surface of a component, the surface is then monitored using a sensitive infrared (IR) detector as the heat front propagates through the component. In the current work, heat is added via a photographic flash lamp. Where the thermal properties below the surface are uniform across the component the heat front will propagate uniformly, however where there is a region of differing thermal properties the heat front propagation will be perturbed. Variation in the rate of heat transfer below the surface affects the decay of the surface temperature directly over that region thus a subsurface defect may be identified by monitoring the surface temperature. Pulsed thermography directly assesses the thermal data recorded whereas in PPT the surface temperature data is then processed using a fast Fourier transform

$$F_n = \sum_{k=0}^{N-1} T(k) e^{2\pi i k n / N} \quad (1)$$

$$= \text{Re}_n + i \text{Im}_n$$

using the number of images processed, N , the processing frequency increment, n , and the temperature data at pixel (x, y) for thermal image k . The transformed values are used to produce phase values, ϕ , using

$$\phi_n = \arctan \left(\frac{\text{Im}_n}{\text{Re}_n} \right) \quad (2)$$

Phase data enables deeper probing into materials as surface effects and the influence of uneven surface heating are removed [10].

The current work focusses on the application of PPT to identify kissing defects in adhesively bonded joints. It is shown that by loading bonded joints kissing defects can be identified using PPT. Initial work focusses on single lap joint samples loaded in a servo-hydraulic test machine before moving on to demonstrate the feasibility of using a vacuum loading to provide a more versatile approach.

2. Methodology

2.1. Creation of simulated kissing defects

Single lap joint specimens were constructed from carbon fibre reinforced polymer (CFRP) in a cross ply layup of $[0, 90]_s$. The total joint thickness was 1 mm with a bonded area of 30 x 30 mm. Silicon grease was added to the central 10 x 10 mm of the bonded area between the front lap and the adhesive. The adhesive used was two part Araldite fast acting epoxy adhesive. Non-destructive loading parameters were established by taking 5 samples to failure. Failure of several samples also gave assurance that the silicon grease contamination was remaining where deposited in the bond line and that the correct failure mode was obtained. Figure 1 demonstrates that there was minimal grease smearing and the lap joint failed through adhesive failure as described in the literature [4].

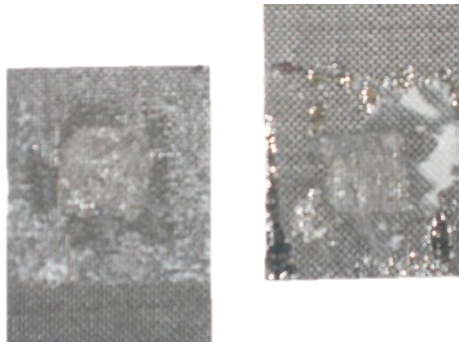


Figure 1. Silicon grease contaminated CFRP lap joint loaded to failure to inspect contamination and find loading conditions.

2.2. Experimental setup

PPT set up is shown in figure 2. The flash lamp used in the current work was a Nikon Speedlight SB600 and the IR detector used was a FLIR SC6000. The first series of experiments used this set up arranged around a servo-hydraulic test machine which was used to impart a static load into the lap joint samples. A load of 3 kN was applied to the samples. The detector to specimen distance was 350 mm and the heat source to sample surface distance was 180 mm. A data collection frequency of 383 Hz was used which was suitable to capture the surface temperature decay in the CFRP. The FFT processing was carried out using a frequency range of 0.001-1 Hz with an interval of 0.05 Hz.

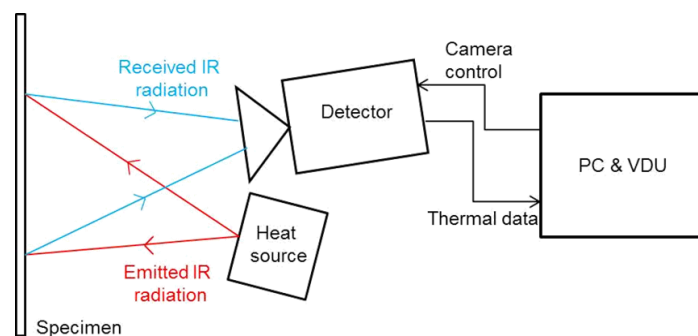


Figure 2. Schematic of pulsed and pulse phase thermography experimental setup.

3. Initial laboratory based study

Initial work focussed on a laboratory based study applying a load to a CFRP lap joint using a tensile load. A finite element model was then used to predict the necessary air gap thickness required to enable a kissing defect to be detected.

3.1. Lap joints

PPT phase data is presented for the CFRP lap joint containing silicon grease contamination for both the loaded and unloaded states, as shown in figure 3a and b where the defect location is indicated by the red square in the unloaded image. It is shown that when the lap joint is unloaded it is not possible to identify the silicon grease contamination using PPT. When load is applied defects within the lap joint are revealed. A real defect is revealed at the upper edge of the lap where bending is opening the defect and creating an air gap. The same is true for the silicon grease contamination where the defect becomes identifiable due to the introduction of an air gap. The phase contrast profiles in figure 3c, taken horizontally across the centre of the defect, reveal that in the unloaded state there is no phase contrast between the defect and surrounding bonded region however when the 3 kN load is applied the defect creates a phase

contrast of around 6°. Once unloaded both the silicon grease defect and the defect at the upper edge of the lap became no longer visible and the specimen is still fully in tact thus emphasising the non-destructive nature of the load applied.

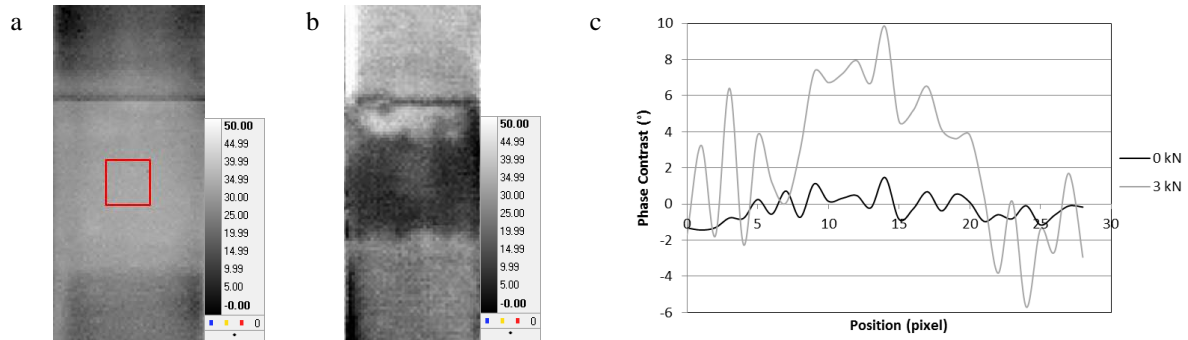


Figure 3. Silicon grease contamination in CFRP lap joint results a) PPT phase data (0 kN) and b) PPT phase data (3 kN) and c) a phase profile plot taken across the centre of the defect region for unloaded and loaded states.

3.2. Air gap prediction

It has been demonstrated the application of a non-destructive load is able to open a defect a sufficient amount for it to become detectable. A finite element model previously developed by the authors [11] has been used to predict how large of a gap must be created to provide sufficient thermal contrast to detect a kissing defect within the CFRP lap joint. A range of gap thicknesses were used and the resulting maximum thermal contrast, ΔT_{\max} , produced during a pulsed thermography test modelled. The threshold for detectability was taken as the detector sensitivity of 20 mK. The results from the model predict that the defect must be opened to approximately 75 nm for it to be detected within the lap joint, see figure 4. These results indicate that only a small opening is required to create a sufficient gap so only a small load needs to be applied. While using a servo-hydraulic test machine was successful at opening the defect in the CFRP lap joint it should be noted that using this means of loading restricts the application of the technique for identification of kissing defects to the laboratory. Work now focusses on methods of loading components without the use of a test machine.

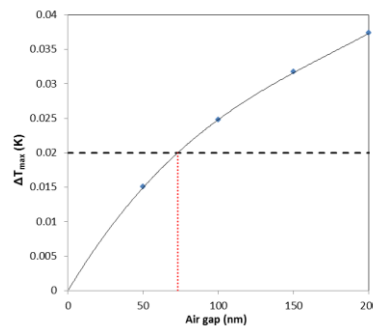


Figure 4. FEA results showing air gap thickness required to a defect to be identified within the CFRP single lap joint.

4. Feasibility study

A feasibility study of the application of a vacuum load to one side of a sample to open a kissing defect was investigated. A larger panel of 350 x 150 mm was constructed by bonding together the same CFRP lay-up as used above and Triplex material [12]. The Triplex consisted of a layer of glass fibre, a thin piece of aluminium and a final layer of glass fibre, the total thickness of the Triplex was 0.7 mm. The Triplex material was adhered to the rear of

the CFRP and the sample was tested from the front side of the CFRP. The Triplex material was selected for the feasibility study of the technique as it was ideal to have a mismatch in the stiffness's of the materials to allow a simplified case study. The Araldite adhesive used in the lap joints was also used for this sample. The CFRP/Triplex bonded sample was subjected to a vacuum load on the triplex side of the bond. A vacuum chamber of 120 mm diameter was attached to the sample and the pressure varied between atmospheric and vacuum pressure using a vacuum pump, while the CFRP surface was heated and surface temperature monitored. The modified setup for this experiment is shown in figure 5.

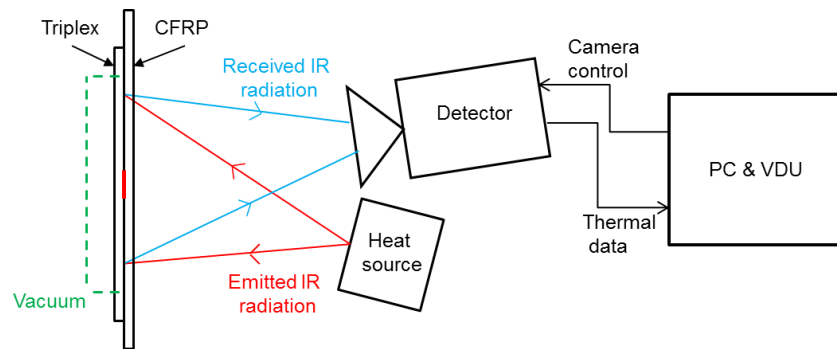


Figure 5. PPT setup with the addition of vacuum loading to the rear of the sample.

4.1. Feasibility study results

Figure 6a and b show the PPT phase results of the same region with and without load applied. The lighter circular ring visible in the edges of the images is due to the presence of the aluminium vacuum chamber attached to the rear of the sample. It is clear that without the addition of load the silicon grease contamination is not visible in the phase data, however with the addition of the vacuum it is clearly able to be identified. This is emphasised in the profile data taken horizontally across the centre of the defect position, as shown in figure 7. The profile plot also demonstrates that the regions away from the defect, i.e. the well bonded regions, are unaffected by the application of the vacuum. It should be noted that the unloaded image is taken after the full vacuum was applied showing that permanent damage has not been caused by the vacuum loading.

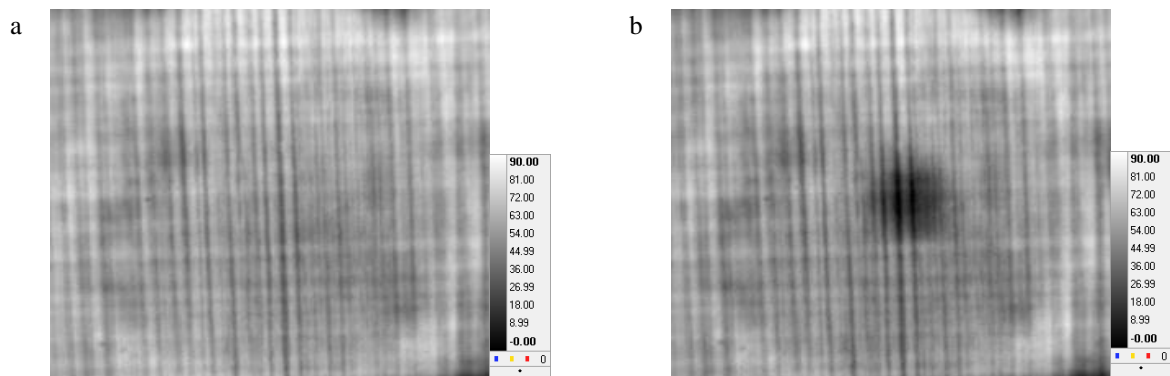


Figure 6. PPT phase data for the CFRP/Triplex bonded sample a) unloaded and b) vacuum loaded on the rear of the sample.

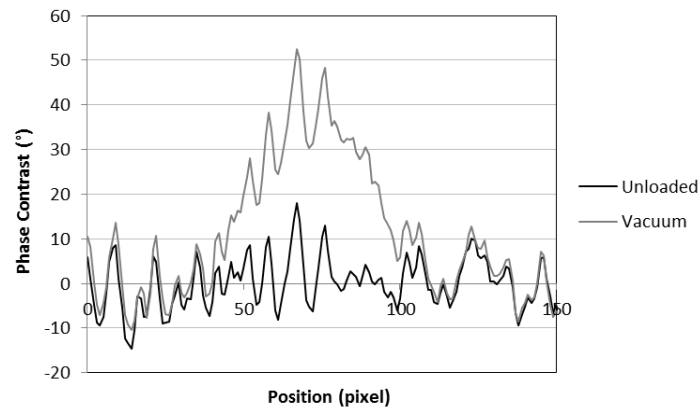


Figure 7. Profile plots taken horizontally across the defect region for the CFRP/Triplex bonded sample for the vacuum loaded and unloaded data.

5. Conclusions and future work

Through the use of CFRP lap joints loaded in tension it has been shown that it is possible to apply a load to a bonded joint sufficient to open defects within the bond without damaging the remainder of the joint. It is the bending moment created when loading a single lap joint that has enabled the defects to open so it is a force normal to the bond line that would be most effective at revealing such a defect. Finite element modelling has revealed that the thickness of the air gap necessary to be created is only 75 nm for the 10 mm square defect in CFRP lap joint considered in the lap joint configuration. Should loading via a test machine be required the technique shall always be confined to the laboratory, hence work has progressed to investigation of loading by application of a vacuum. The feasibility study was carried out on a CFRP plate with a more flexible material adherend. Through the addition of vacuum loading to the rear of this sample a silicon grease defect that was previously undetected was identified without damaging the remainder of the bond. Ongoing work shall investigate the application of the vacuum loading to less flexible adherends and partial vacuum pressures.

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