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Modelling and evaluation of pulsed and pulse phase thermography through application of composite and metallic case studies

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ABSTRACT

A transient thermal finite element model has been created of the pulsed thermography (PT) and pulse phase thermography (PPT) experimental procedure. The model has been experimentally validated through the application of four case studies of varying geometries and materials. Materials used include aluminium, carbon fibre reinforced plastic (CFRP) and adhesively bonded joints. The same four case studies have also formed a basis for comparison between three experimental techniques: PT, PPT and the more established ultrasonic (UT) c-scan.

Results show PPT to be advantageous over PT due to its deeper probing as it is less influenced by surface features. Whilst UT is able to reveal all the defects in these case studies, the time consuming nature of the process is a significant disadvantage compared to the full field thermography methods.

Overall, the model has achieved good correlation for the case studies considered and it was found that the main limiting factor of the PT model accuracy was knowledge of thermal material properties such as conductivity and specific heat. Where these properties were accurately known the model performed very well in comparison with experimental results. PPT modelling performed less well due to the method of processing the PT data which aims to emphasise small differences. Hence inaccuracies in inputted values such as material properties have a much greater influence on the modelled PPT data. The model enables a better understanding of PT and PPT and provides a means of establishing the experimental set-up parameters required for different components, allowing the experimental technique to be appropriately tailored to more complex situations including bonded joints or structures where several materials are present.

The paper ends with a section on defect detectability based on thermal diffusivity contrast between the defect and the bulk material. It shows that in aluminium, because of its higher conductivity, greater thermal contrast is achieved for small differences in diffusivity. Regions where the diffusivity ratio between defect and bulk materials was insufficient to provide thermal contrast for defect identification were found. PPT phase data is shown to reduce the extent of such regions increasing the detectability of defects. Effusivity is introduced as a means of determining the thermal contrast between the defect and non-defective areas and hence establishing the defect detectability.

1. Introduction

Adhesively bonded joints are often preferable to their mechanical counterparts due their ability to decrease the weight of the joint. Bonded joints enable a more even distribution of load transfer through the joint, avoiding the high stress concentrations typically associated with mechanical fastenings. The increased use of fibre reinforced composite materials, where machining the material for mechanical fastenings has the potential to initiate damage, has led to an increase in the use of adhesive joints in engineering structures. There is also an increasing trend towards the use of adhesively bonded composite patch repairs on damaged structures as a means of reinforcement [1].

Adhesive bonds are prone to several types of defect which have previously limited the range of application of such joints. To enable more widespread use of adhesive joints in structural applications all types of defects must be accurately and reliably detected. Defects typically found in adhesive joints may be

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categorised in three groups; voids, inclusions and kissing defects [2]. A void is the inclusion of air in the adhesive layer. Air may be introduced into the resin during the mixing of a two-part adhesive or during joint construction where a lack of contact occurs between the adhesive and adherend, resulting in an air gap in that area. Inclusions involve the physical inclusion of a foreign material of relatively large volume when compared to the bond line thickness. Kissing defects are a reduction of adhesion between the adhesive and adherend without affecting the thickness of the adhesive layer, hence there is no gap between the adhesive and the adherend. Such defects currently cannot be reliably and consistently detected [3,4].

Established NDE techniques typically used in industry for material assessment today include ultrasonic testing [5], radiography [6], shearography [7,8] and thermography [9]. The drive to apply adhesive joints in a wider range of applications is increasing the demand for the development of new NDE techniques suitable for their efficient and effective assessment. Many current NDE methods are able to identify defects; however, no individual technique is able to reliably identify the reduced adhesion associated with kissing defects. Research has been carried out investigating advanced ultrasonic methods which has shown promise for identification of kissing defects [10,11], however, this remains a point by point process and as such is not ideal for large scale applications. Thermographic techniques have the advantage of being full field, non-contact and fast. Previous studies have shown the potential use of thermography for identification of defects in adhesive bonds [12]. Most studies have focussed on specific applications or specific material or joint configurations. This work aims to develop a model that is able to simulate pulsed thermography (PT), and pulse phase thermography (PPT) through processing of the data, which can be tailored to specific components. As experimental parameters in PT and PPT change for different components, the use of such a model will allow experimental parameters to be tailored to the application without the need for extensive, time consuming and potentially expensive preliminary experiments. Finite element approaches have been used previously to model pulsed thermography. In [13] carbon–carbon composites with voids are considered and in [14] steel plates with flat bottom holes are considered by using a secondary heat source as the defect in the FEA. Both models are developed for a specific experimental set up and only a single test case is shown. The current work aims to expand upon this, presenting a series of case studies of various materials and configurations. Although kissing defects are not explicitly studied in the current work, the development of the modelling methodology enables the limits of defect identification to be focused on, in terms of their thermal properties. It should however be emphasised that if there is no thermal contrast between a defect and surrounding material then it cannot be identified by thermography alone; this is the subject of a future paper [15] where it is shown the application of a small load can help enhance thermal contrast and hence aid identification of kissing defects.

As a significant amount of research, e.g. [16], is being carried out into the use of ultrasonic techniques for detection of defects in composite materials, water coupled ultrasound (UT) c-scans of each defect have been included for comparison of different experimental techniques. While it is acknowledged that other forms of UT are more frequently used in the field, these images allow a representative comparison of UT and the thermographic techniques considered.

2. NDE techniques

Three NDE techniques have been studied for the detection of defects. Comparisons of experimental results are drawn between the three approaches of PT, PPT and UT.

2.1. Pulsed and pulse phase thermography

PT and PPT make use of highly sensitive infra-red detection systems and are carried out in either transmission or reflection mode. In transmission the heat source is on the opposite side of the component to the infra-red detector. The work described in the present paper focuses on reflection mode where the heat source and the detector are on the same side of the component. Thus reflection mode is a much more useful tool for industrial applications where only one side of a component or structure may be accessible.

In PT the surface of the component under investigation is exposed to a pulse of thermal energy. The thermal decay of the surface is then monitored as the heat conducts through the sample, see Fig. 1. If the material under the surface is uniform across the region of interest then the temperature of the front surface will decay uniformly. However, if the thermal front meets a region of different thermal properties, such as a subsurface defect, the surface temperature directly over the defect will be at a different temperature to the surrounding surface as the heat transfer has been perturbed in the region of the defect. For example, an air gap in aluminium has lower thermal conductivity than the aluminium and so the propagation of the thermal front is slowed in this area and is detected as a hotspot in the surface data during the thermal decay.

In reflection PT and PPT the surface of a component is monitored using an infra-red photon detector. A thermal pulse is impinged on the surface of the component by means of a heat source such as a flash lamp. A sequence of thermal images of

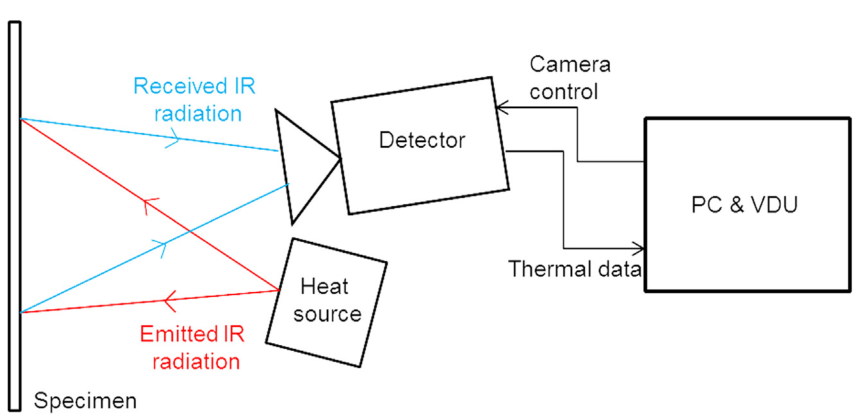

Fig. 1. Experimental apparatus for pulsed and pulse phase thermography showing heat pulse application and thermal decay data collection.