Efficient modeling and post-processing approaches for weakbond detection in CFRP composite using the integration of DS and PPT techniques

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Abstract

This paper shows the ability to model realistic weak bond defect in CFRP composite for the simulations of digital shearography (DS) and pulsed phase thermography (PPT)-based NDT, and to enhance the defects images obtained from DS and PPT testing using image fusion algorithm. This will help providing useful guideline for experimental setup. This study proves the ability of using the integration of DS and PPT techniques for weakbond detection in CFRP composite.

Keywords: CFRP, weakbond defects, digital shearography, pulsed phase thermography, modeling and simulation, fusion algorithms

1 Introduction

The carbon fibre reinforced polymer (CFRP) composites are used extensively in many industries, especially in aerospace. However, some defects such as delamination, weakbond, and fibre damages on the composites could be developed over time that may lead to a significant disaster if they are not detected timely. Weakbond within CFRP is one of the most challenging defects to be detected by current state-of-the-art non-destructive testing (NDT) technologies. Combining digital shearography (DS) and pulsed phase thermography (PPT) techniques are potentially viable to detect such kind of defect. Simulation technology has proved to be crucial for explaining physical phenomena, providing useful guidelines and fine-tuning the experimental setup to improve the detectability and system performance. This indeed helps to obtain optimal mechanical and thermal responses of defects to external loads for DS and PPT, respectively. However, the computer models for the simulations of DS and PPT-based NDT with weakbond defects detection in CFRP requires not only a Finite Element Method-based multi-scale modeling, but also to have an efficient approach to deal with weakbond layers. The conventional modeling method is to represent weakbond defects in CFRP using thick layer ETFE/PTFE release films (50um) inserted between the plies of the composite at different depths [1-4].

In this work, we have implemented an efficient approach to model a vacuum grease-based weakbond defects at different CFRP layers, which have near-zero-thickness produced after hot press process, representing realistic weakbond in composite. In the model, the stability needs to be controlled for the implementation of contact surface instead of thin layer in cohesive zone modeling. The developed
models have been fine-tuned with actual data from experiments to account for accurate material properties and specs, e.g. pulse duration and power of laser heat, of the experimental setup. Besides defect properties, top surface characteristics of composite such as convection property, surface roughness will also be incorporated to investigate the impact on the output response. Furthermore, to enhance the clarity of defect images obtained from DS and PPT simulations, wavelet-based fusion algorithms have been developed providing clearer image by taking into consideration best features from individual DS image (shape) and PPT image (intensity). The developed algorithm is also able to deal with image contaminated with noises to reduce artifacts and achieve better fusion. The results obtained from simulations of 8-layer CFRP with vacuum grease-based weakbond defects demonstrate the ability of our developed DS and PPT models. The output responses are inputted into fusion algorithm that can greatly improve the clarity of each individual image.

2 Methodology

2.1 Simulation of mechanical and thermal responses of weak bond defects to external loads

The multi-scale finite element modeling for a CFRP with defect/weak bond has been developed as CFRP consists of multi-layer anisotropic material representing heterogeneity. This multi-scale problem can be solved by employing homogenization approach with transient solver (i.e. structural analysis and heat transfer). We have specifically investigated the ability of improving defect detection via thermal and mechanical responses under various external excitation conditions. In the models, various parameters, e.g. defect size and thickness, heat flux magnitude and profile, can be varied to study the impact on the output response. Noted that the cohesive zone modeling (CZM) is used for representing zero-thickness weak bond at different CFRP layers in DS model. The defect model is constructed representing near-zero-thickness of vacuum grease based weak bond in CFRP. The interaction of the sample with the surrounding environment must be included in setting up the boundary condition by fixing all four sides of CFRP sample in DS model; the initial condition of the PPT model assumed the sample and surroundings is in thermal equilibrium. The excitation is modelled using thermal pulse excitation with uniformly irradiate heat flux on top surface, where the excitation power, pulse duration, beam diameter, wavelength, cooling duration, camera frame rate, etc. are the parameters to be optimized. In the developed models, material properties available in the literature supplemented with experiments: anisotropic CFRP with tensor physical mechanical and thermal properties, density of carbon fiber and epoxy matrix. Output of interest is out-of-plane deformation and outer surface temperature distribution for DS model and PPT model, respectively.
2.2 Development of algorithms for image fusion

Image fusion is a process of combining the relevant information from a set of images of the same scene into a single image. Fused image preserves all relevant information and should not introduce artifacts. We have proposed using wavelet transform-based fusion, where the peak signal to noise ratio parameter can be used to evaluate fused image quality. Though the fusion approach can greatly improve the clarity of each individual image, we’ve observed that fused image enhancement is not the case when applying to DS and PPT image. It is suspected that artifacts introduced due to noise from particular DS image will deteriorate the quality of fusion. In order to deal with such image contaminated with noise, we will employ different enhanced image techniques such as contrast adjustment, image filtering, e.g. Wiener filter and Otsu-based segmentation, for reducing artifacts and achieving better quality of fused images. However, there still exist some noises that cannot be simply removed by using the above algorithms. Hence, we have proposed a general framework for image fusion taking into consideration of noise removal as shown in Figure 2 [5-8].
3 Results and Discussions

The simulation models of 8-layer CFRP with alternate fiber orientation is presented. In DS model, the stability needs to be controlled for the implementation of contact surface instead of thin layer in cohesive zone modeling. In the PPT model, both conduction and convection mechanisms have been implemented as radiation mechanism is not taken into account due to little impact on the results. The grease defect with various size located under 2nd, 4th, 6th, and 8th layers. The thickness of CFRP and adhesive are 127μm and 20μm, respectively. The simulation models are fine-tuned using practical material properties and excitation specifications. Indeed, the power density of the heating flux used in the simulation is calibrated with the experimental data heated by the 1kW halogen lamps. It should be noted that output power of flashing lamps/laser beam is represented by Gaussian heat flux. As vacuum grease based weak bond defects expecting to have near-zero-thickness produced after hot press process, the defect model is constructed representing thickness of 10μm. Noted that the parametric investigation of weak bond thickness on the detection sensitivity needs to be conducted.

The strain response under the heat flux excited on top of surface is evaluated using the developed model. The heat flux is uniformly excited on top of the CFRP for 3s and cool down to 10s. The edge of the model is fix support and set to ambient temperature. Figure 3 shows the logarithmic strain response along z-direction at different time frames. At time step of 1.1s, the strain response starts to be saturated in the heating process. The saturated response is continued until time step of 4.2s and the defects with different depth and size are clearly identified at 4.3s in the cooling process. In our simulation, the strain
resolution limit is $3.8 \times 10^{-5}$, while the displacement limitation is $3.8 \times 10^{-10}$ m in $z$-direction. The simulated temperature distributions on the top surface of the specimen in the heating and cooling process are clearly shown in Figure 3. It has been seen that the temperature at the defect area is higher than that at the non-defect area. The results show promising defect detection for PPT with resolution contrast up to $\sim 0.07$ K; however, it is not the case for DS, which is less sensitivity for detection of defects at deeper layers since the noise level is high.

To demonstrate the improvement of fused image by using the noise removal algorithm in the proposed fusion framework, the results obtained from simulations of 8-layer CFRP with weak bond defects using both DS and PPT are taken for fusion. We first compute the phase map from these simulation data. After conducting image fusion, it has been shown in Figure 4 that this provides clearer and better image by taking into consideration best features from individual DS (shape) and PPT image (intensity).
4 Conclusions and Future works

We have developed DS and PPT models for realistic weak bond defects in CFRP composite as well as an effective process to fuse DS and PPT images. Modeling and simulation provides faster and cost-effective to assess the outcome when changing configuration of CFRP with defects as well as profile of thermal pulse excitation. The results obtained show that the thermal resolution of the defect is up to 0.07K, while the mechanical displacement is limited to 0.38nm. We have also evaluated the response of the defect due to external excitation variation, e.g. excitation duration and heat flux density. A moderate heat flux power of 1kW is recommended for short duration of 3s. The result shows that the system will unable to detect the defect buried under the 16th layer. To achieve a holistic simulation model, besides studying defect properties, e.g. thickness, depth and material properties, we will also investigate the top surface characteristics such as convection property, surface roughness etc. In addition, different excitation models will be incorporated, e.g. eddy current, vacuum etc. This could help experiment adjusting equipment parameters accordingly in order to achieve the desired sensitivity. A general framework for DS and PPT images fusion emphasizing on noise removal has been proposed in order to enhanced input data for fusion algorithms. We can see that the success of fusion depending on the specific problem; and input data plays a very important role. This study proves the ability of using the integration of DS and PPT techniques for weakbond detection in CFRP composite.

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References


