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Investigation of defect characteristics and heat transfer in step heating thermography of metal plates repaired with composite patches

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HIGHLIGHTS

- Infrared thermography of repaired metal plate with composite patch has been modeled.
- Effect of defect type, size and depth on the detection ability has been investigated.
- Appropriate heating method to enhance the probability of detection has been found.

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ABSTRACT

Nowadays, composite patches are widely used in different industries to repair damaged metal structures. Inspection of such repaired structures is always considered as a challenging task. Different thermography methods such as step heating are commonly used to inspect repaired structures. Some parameters such as defect features or heating procedure play major roles in defect detection. In this work, in order to investigate such effects, step heating thermography of an aluminum plate repaired with a composite patch is modeled and tested. The main goal of this study is to evaluate the effects of defect type (delamination and disbond), size and depth on the detection ability of the test. Moreover, regarding the heat transfer process obtained from the simulation, the appropriate heating procedure for inspecting the repaired metal structures is determined. To validate the simulation outputs, experimental results corresponding to the temperature variations are compared with those predicted from the simulation.

1. Introduction

Repair of damaged structures has been always the concern of different industries. Currently, composite patches are used to repair damaged plates in such industries. Since, disbond between the patch and damaged plate results in malfunction of the repaired structures, therefore, creating a perfect bond is of great significance. Delaminations of the patch layers as well as disbonds between the patch and damaged plate are common defects of repaired structures. For an existing defect, a knowledge of the size and position of disbond and delamination helps to determine the life time of structure. Therefore, using an effective type of non-destructive inspection approach such as thermography seems necessary.

Thermography techniques are continuously updating and the capabilities and limitations of such procedures have been the focus of many researches [1–3]. These techniques have been widely used to inspect composite structures. Previously, some studies [4,5] have focused on composite thermography and investigated the effect of defect size and depth. According to their results, smaller and deeper defects are harder to be detected as they cause less temperature differences on the surface temperature profile. Thermography methods have been also utilized to inspect repaired structures [6,7] and it has been demonstrated that as well as deep defects in composites, application of thermography techniques to detect disbonds is associated with some limitations [8,9]. Furthermore, similar results have been reported in the case of using step heating thermography for composite inspection [10]. It seems that further researches are still needed to show the ability of thermography techniques in inspection of repaired structures and composites. Different methods of numerical modeling can be utilized to overcome some of the mentioned limitations.

Some studies [11–15] have been previously performed to simulate heat transfer in anisotropic multilayers as well as composites. In the case of complicated structures and anisotropic material properties, numerical solutions such as finite element (FE) methods are preferred rather than the analytical approaches. FE

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methods [16] have been shown to be powerful numerical solution methods in heat transfer modeling specially for composites. FE simulation can be applied to calculate 3D temperature distribution in an anisotropic solid that may contain subsurface defects or features. Such FE modeling [17,18] has been recently reported to allow the investigation of some unpredicted parameters such as the effects of lateral diffusion around a defect and heat diffusion through the thickness specially when simulating thermal behavior in complex components. Additionally, as stated in some studies [18,19] the capacity of defect characterization based on experimental data is limited by the experimental setup conditions. Therefore, a numerical modeling can be utilized to provide information about the test as well as the heat transfer mechanism. For instance, modeling of defects such as delaminations and disbonds in a repaired structure will further improve the prediction of all subsurface defects and will help to find the best test procedure as well as the heating method required for an appropriate defect detection and analysis.

Since, defect characterization of repaired structures and composite patches have not received enough attention in the literature, in this study, step heating thermography of a repaired aluminum plate with composite patch was simulated by the commercial FE software, Abaqus. Step heating thermography is a method in which, heating duration is larger than pulse thermography and detection can be performed in both heating and cooling steps. 15 defects (including both delaminations and disbands) with various dimensions and positions were considered for modeling to investigate the effects of defect type (delamination and disbond), size and depth on the detection ability of test. Moreover, regarding the surface temperature variations in simulation, the effects of metal on the heat transfer process were investigated so as to find an appropriate heating method to enhance the probability of defect detection. An experimental set up was also utilized to investigate the correctness of the simulation outputs. For this purpose, the experimental values of surface temperature and temperature variations related to the defects were compared with the corresponding simulation results. Followings are some correlations representing the basic heat transfer equations.

2. Heat transfer principles

The model contains ten layers (one aluminum layer, one adhesive layer and eight composite layers). Due to the presence of symmetric planes in the model, the coefficients of layer heat conductivity, kij matrix, are reduced to 5 none zero components as in Eq. (1) (Considering z-axis as the out-of-plane direction):

$$\begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \rightarrow \begin{bmatrix} K_{xx} & K_{xy} & 0 \\ K_{yx} & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix} \tag{1}$$

Each layer separately satisfies the transient heat transfer equation, which is shown in Eq. (2).

$$k_{xx}\frac{\partial^2 T}{\partial x^2} + k_{yy}\frac{\partial^2 T}{\partial y^2} + 2k_{xy}\frac{\partial^2 T}{\partial x \partial y} + k_{zz}\frac{\partial^2 T}{\partial z^2} = \rho c_p \frac{\partial T}{\partial t} \tag{2}$$

where K is the heat conductivity ratio and c_p is the heat specific capacity. For each contact surface between the nth and $(n+1)th$ layers, Eq. (3) is established.

$$T_n(x, y, h/2) = T_{n+1}(x, y, -h/2)$$

$$K_{zz}^{n}\frac{\partial T_n}{\partial z}\left(x, y, \frac{h}{2}\right) = -K_{zz}^{n+1}\frac{\partial T_{n+1}}{\partial z}\left(x, y, -\frac{h}{2}\right) \tag{3}$$

where h is the layer thickness. For each free surface, being in contact with air, one can write Eq. (4) as the boundary condition.

$$\begin{aligned} -\left(k_{xx}\frac{\partial T}{\partial x} + k_{xy}\frac{\partial T}{\partial y}\right) &= h_1\left(T_\infty - T\left(\mp\frac{L}{2}, y, z\right)\right) \\ &\quad + \alpha\sigma\left(T\left(\mp\frac{L}{2}, y, z\right)^4 - T_\infty^4\right) \\ -\left(k_{yy}\frac{\partial T}{\partial y} + k_{yx}\frac{\partial T}{\partial x}\right) &= h_2\left(T_\infty - T\left(x, \mp\frac{L}{2}, z\right)\right) \\ &\quad + \varepsilon\sigma\left(T\left(\mp\frac{L}{2}, y, z\right)^4 - T_\infty^4\right) \\ -\left(k_{xx}\frac{\partial T}{\partial x} + k_{xy}\frac{\partial T}{\partial y}\right) &= h_1\left(T_\infty - T\left(\mp\frac{L}{2}, y, z\right)\right) \\ &\quad + \alpha\sigma\left(T\left(\mp\frac{L}{2}, y, z\right)^4 - T_\infty^4\right) \end{aligned} \tag{4}$$

Eq. (3) consists of six equations corresponding to six free surfaces. In Eq. (4), T_∞ is the ambient temperature, h is the convection coefficient of the air, ε is the emissivity of the composite surface and α is the Stephan–Boltzmann constant.

In order to calculate thermal conductivities in composite layers, one can use transformation tensors to transform heat transfer coefficients from the reference axis to any desired axis. The components of off-axis conductivity matrix can be expressed as Eq. (5), in which K_1, K_2 and K_3 are the principal heat conductivities of the composite layer:

$$\begin{Bmatrix} K_{xx} \\ K_{yy} \\ K_{xy} \\ K_{zz} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 \\ n^2 & m^2 & 0 \\ mn & -mn & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} K_1 \\ K_2 \\ K_3 \end{Bmatrix} \tag{5}$$

where $m = \cos\theta$, $n = \sin\theta$ and θ is the angel between fiber direction and x-axis, being here equal to zero. Therefore:

$$\begin{Bmatrix} K_{xx} \\ K_{yy} \\ K_{xy} \\ K_{zz} \end{Bmatrix} = \begin{Bmatrix} K_1 \\ K_2 \\ 0 \\ K_3 \end{Bmatrix} \tag{6}$$

Solving all mentioned equations together, temperature profile of the model is calculated. However, the temperature of the surface facing thermo-camera is recorded and used to find defects during experiments. In the following section, FE simulation will be discussed in detail.

3. Description of the simulation

As mentioned earlier, the model consisted of ten layers: An aluminum layer with a thickness of 2 mm, an adhesive layer with a thickness of 0.125 mm and a carbon-epoxy multilayer with stacking sequence of $[0_8]$ and thickness of 0.25 mm. The model has been shown in Fig. 1.

In defect sites, air property was assigned. Table 1 shows the thermal properties of all materials used in the simulation.

The predefined temperature of model was 25 °C. The heating supplier was assumed to be a 2 KW source (a 2 KW lamp in the experimental setup) and the surface area exposed to heating was equal to 0.12 m^2. As almost 90% of the source energy was absorbed with the model, the applied heat flux to the model surface was 15 KW/m^2. Since composite properties may be affected at temperatures above 80 °C, the heating time was estimated to be about seven seconds to avoid any damage to the composite. The heat flux