Proceedings of the 6th International Conference on Mechanics and Materials in Design,
Editors: J.F. Silva Gomes & S.A. Meguid, P.Delgada/Azores, 26-30 July 2015

PAPER REF: 5642

QUANTITATIVE DETECTION OF CONTACT FAILURES IN COMPOSITES USING INFRARED THERMOGRAPHYAND THE RECIPROCITY FUNCTIONAL APPROACH

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ABSTRACT

Composite materials are found in many engineering applications such as aircraft walls, pipes, nuclear reactors, cooling of electronic components and many others. The evaluation and detection of adhesion failures at the interface between the layers of these materials have great importance for these applications. This work deals with the quantitative detection of adhesion failures in a medium composed of two layers, by estimating the temperature difference at the interface between these layers. This temperature difference is obtained solving an inverse heat conduction problem with the reciprocity functional approach. Previous work of the authors provided detailed analysis using simulated temperature measurements. This paper applies these methodologies to a case where real measurements are used. The results show that it is possible to identify and quantify contact failures through the proposed methodology using real measurements.

Keywords: Non-Destructive Inspection, Reciprocity Functional, Infrared Thermography.

INTRODUCTION

The scientific community has done a large effort in order to develop techniques to detect and analyze adhesion failures in composite materials. Several papers have been published using different methodologies, including infrared thermographic techniques, such as the lock-in thermography or pulse heating thermography (Meola and Carlomagno, 2004). Meola and Carlomagno (2004) presented a review paper, where the fundamental aspects of thermography and its applications were presented. In that paper, the particular characteristics of each application were also addressed, including agriculture, medicine, fluid mechanics and non-destructive techniques.

Regarding non-destructive techniques, recently an experimental apparatus was presented by Sultan *et al*. (2013), which allowed the qualitative detection of failures in composite materials. Good results were obtained for samples made of fiberglass with failures of different sides. Brown and Hamilton (2013) also presented an experimental apparatus to detect failures using thermographic images, but considering concrete.

Although there are several different methodologies to evaluate the adhesion between layers of a composite medium, such techniques, in general, rely on intrusive measurements or on some iterative techniques. In this work, we used a technique based on the reciprocity functional approach (Andrieux and Abda, 1993; Colaço and Alves, 2013; Abreu *et al*., 2014a; Abreu *et al*., 2014b) to estimate the temperature difference at the interface between two layers of a

composite material, which has a direct connection with the dimension and shape of the contact failures. This technique does not require any intrusive measurements and also does not rely on any iterative procedure. The only required measurements are the temperatures taken by an infrared camera, on the outer surface of the material.

Abreu *et al*. (2014c) proposed an experimental apparatus, where a controlled sample with known location and size of the contact failures was analyzed. In this work we used the technique previously developed by (Colaço and Alves, 2013; Abreu *et al*., 2014a; Abreu *et al*., 2014b), as applied to that experimental apparatus, in order to verify its applicability to real measured data.

PHYSICAL PROBLEM AND MATHEMATICAL FORMULATION

In this work we consider a steady state heat conduction problem in a composite medium with two layers, where the thermal conductivities (k_1 and k_2) are known constants in each material.

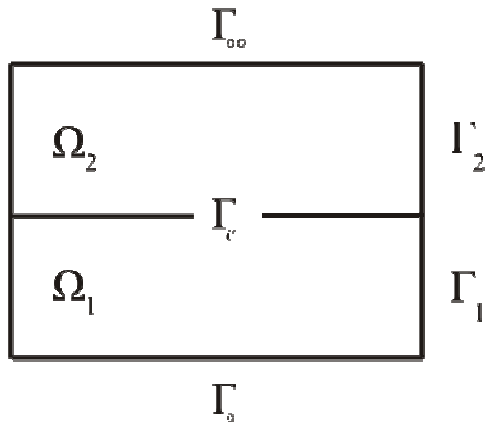


Fig. 1 - Geometry for a two-dimensional composite medium.

Let us consider a domain Ω, divided in three parts $\Omega = \Omega_1 \cup \Gamma_c \cup \Omega_2$ where Ω_1 is the first domain, Ω_2 is the second domain, and Γ_c is the contact surface between them. The lateral surfaces $\Gamma_1 \cup \Gamma_2$ are thermally insulated, the surface Γ_o is subjected to a prescribed temperature, and the surface Γ_{oo} is subjected to a prescribed heat flux. Figure 1 shows the geometry for this two-dimensional composite medium. For the direct problem, all boundary conditions, dimensions and physical properties are known. The mathematical formulation for this direct problem is given as (Özişik, 1993):

$$\nabla^2 T_{1,2}(\mathbf{x}) = 0, \qquad \text{in } \Omega_{1,2} \tag{1.a}$$

$$T_1(\mathbf{x}) = T_o = 0, \qquad \text{on } \Gamma_o \tag{1.b}$$

$$k_2 \partial_n T_2(\mathbf{x}) = q(x, y), \qquad \text{on } \Gamma_{oo} \tag{1.c}$$

$$k_1 \partial_n T_1(\mathbf{x}) = k_2 \partial_n T_2(\mathbf{x}), \qquad \text{on } \Gamma_c \tag{1.d}$$

$$k_1 \partial_n T_1(\mathbf{x}) = h_c \left[T_2(\mathbf{x}) - T_1(\mathbf{x}) \right], \qquad \text{on } \Gamma_c \tag{1.e}$$

$$k_{1,2} \partial_n T_{1,2}(\mathbf{x}) = 0, \qquad \text{on } \Gamma_{1,2} \tag{1.f}$$

where h_c is the thermal contact conductance, q is the imposed heat flux on Γ_{oo}, ∂_n denotes the normal derivative, and the subscripts 1 and 2 refer to the domains Ω_1 and Ω_1 respectively. The objective of this paper is to estimate the temperature jump (T_2-T_1) on Γ_c, using only external measurements taken on Γ_{oo} by an infrared camera. When such temperature jump tends towards zero, the thermal contact conductance rises to infinity, allowing the identification of contact failures. Thus, the determination of (T_2-T_1) allows a qualitative and quantitative analysis of the failure.

To estimate the temperature jump, (T_2-T_1), on Γ_c, Abreu *et al*. (2014b) proposed an inverse problem approach, using the reciprocity functional approach, in a methodology similar to the one presented by Colaço and Alves (2013). In Abreu *et al*. (2014b) a Laplace auxiliary problem was used, together with the reciprocity functional approach, to estimate the temperature jump using simulated measurements. In this work, we will consider the same methodology, but using real measurements, taken by an infrared camera. The mathematical details will be omitted here, but the reader is advised to consult our previous works (Colaço and Alves, 2013; Abreu et al., 2014a; Abreu et al., 2014b) for the complete description of the technique.

Following our previous works, the application of the reciprocity function approach (Colaço and Alves, 2013; Abreu et al., 2014a; Abreu *et al*., 2014b), establishes that the temperature jump (T_2-T_1) on Γ_c can be obtained as

$$\left(T_2 - T_1\right)_{\Gamma_c} = \sum_{j=1}^{N} \xi_{v_2}^{j} \phi^{j} \tag{2}$$

where ξ is the solution of the following linear system

$$\left\langle \phi^{i}, \phi^{j} \right\rangle_{L^2(\Gamma_c)} \xi_{v_2}^{j} = R\left(v_2^{j}\right) \tag{3}$$

In Eq. (4), R is the reciprocity functional, written as

$$R\left(v_2^{j}\right) = k_2 \int_{\Gamma_{oo}} \left(\Psi^{j} q - Y \partial_n \Psi^{j}\right) d\Gamma_{oo} = \left\langle T_2 - T_1, \phi^{j} \right\rangle_{L^2(\Gamma_c)} \tag{4}$$

where Y is the measured temperature on Γ_{oo}, and Ψ^{j} is the jth component of a Fourier basis system obtained from the solution of the following auxiliary problem (Abreu *et al*, 2014b)

$$\nabla^2 v_1^{j}(\mathbf{x}) = 0, \quad \text{in} \quad \Omega_1 \tag{5.a}$$

$$\nabla^2 v_2^{j}(\mathbf{x}) = 0, \quad \text{in} \quad \Omega_2 \tag{5.b}$$

$$\partial_n v_1^{j}(\mathbf{x}) = 0, \quad \text{on} \quad \Gamma_1 \tag{5.c}$$

$$\partial_n v_2^{j}(\mathbf{x}) = 0, \quad \text{on} \quad \Gamma_2 \tag{5.d}$$

$$v_1^j(\mathbf{x}) = 0, \qquad \text{on} \quad \Gamma_o \tag{5.e}$$

$$v_2^j(\mathbf{x}) = v_1^j(\mathbf{x}), \qquad \text{on} \quad \Gamma_c \tag{5.f}$$

$$k_1 \partial_n v_1^j(\mathbf{x}) = k_2 \partial_n v_2^j(\mathbf{x}), \qquad \text{on} \quad \Gamma_c \tag{5.g}$$

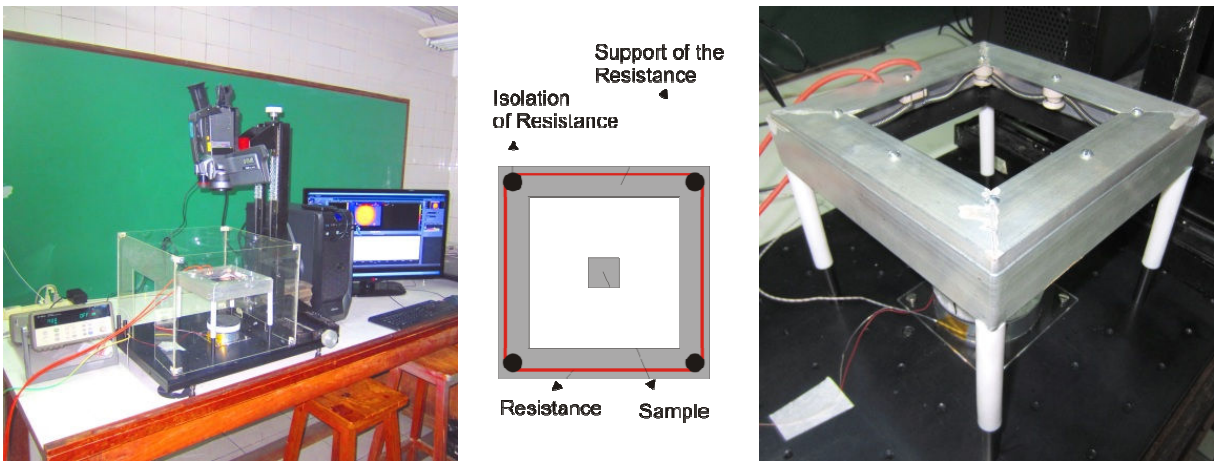
$$v_2^j(\mathbf{x}) = \Psi^j, \qquad \text{on} \quad \Gamma_{oo} \tag{5.h}$$

Equations (5) must be solved N times to represent the temperature jump according to Eq. (2). It is interesting to notice that this auxiliary problem does not depend on the unknown quantities on the interface boundary. Thus, it can be solved in advance and used to recover different functions, for different materials. The only restrictions are the geometry and the thermal conductivities that must remain the same for the different samples. From Eqs. (2)-(4), it is also possible to verify that, besides the result of the auxiliary problem, only the applied heat flux q and the measured temperatures Y, both taken on the external boundary, are needed to reconstruct the unknown temperature jump at the internal interface. Therefore, the method is non-intrusive. Also, from the previous equations, one can verify that the entire procedure is non-iterative, making it very attractive for the fast estimation of the sought function.

EXPERIMENTAL SETUP

In order to validate the numerical procedure discussed in the previous section, an experimental apparatus was built. This apparatus is shown in Fig. 2 (Abreu *et al*., 2014c) and it is composed of a FLIR A300sc thermographic camera, electrical resistances to be used as heaters, a support for the samples, a microcomputer and an acquisition system (Agilent) to monitor the temperatures at the lateral and lower surface of the sample.

The infrared camera has a resolution of 240x340 pixels and can measure temperatures in the range varying from 0°C to 350°C. The imposed heat flux q on the top surface was obtained by the thermal radiation of a 22 Ω electrical resistance, enclosed by an aluminum support, as shown in Fig. 2(c). This support was used to dissipate the heat in the aluminum block and emit the thermal radiation more uniformly on the sample top surface. The distance between the aluminum support and the sample was taken as 0.20 m.



(a) (b) (c)

Fig. 2 - (a) Experimental apparatus, (b) Schematic representation of the thermal resistance used as heat source, and (c) Support used for the thermal resistance .

As reported by Abreu *et al*. (2014c), this setup is able to produce a uniformly distributed heat flux on the sample surface. The electrical resistance was constructed in such way that there is an opening view that allows the temperature measurement on the top surface of the sample by the infrared camera, while the sample is being heated. Samples are placed over an aluminum block with high thermal conductivity, in order to ensure that the temperature on their bottom surface is approximately constant and equal to the temperature of the aluminum block. This temperature was monitored during the experiment using five type-E thermocouples.

In this work, samples with known contact failures were used (Fig. 3) in order to validate the proposed procedure. These samples were made of Polymethylmethacrylate (PMMA) with 0.04 m of length, in a square shape. The thickness was equal to 0.002 m for each layer. A single layer sample with no defects (Fig. 3b) was also used to identify the imposed heat flux.

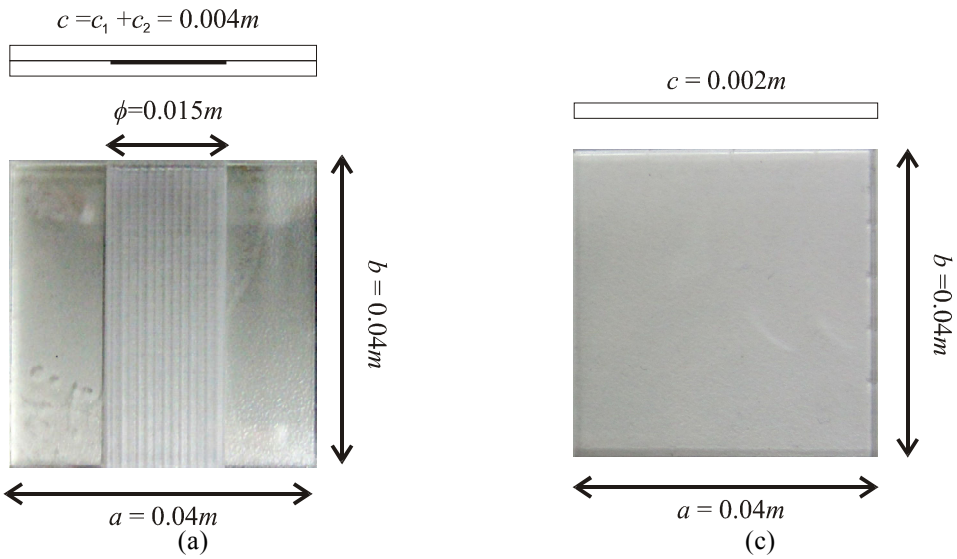


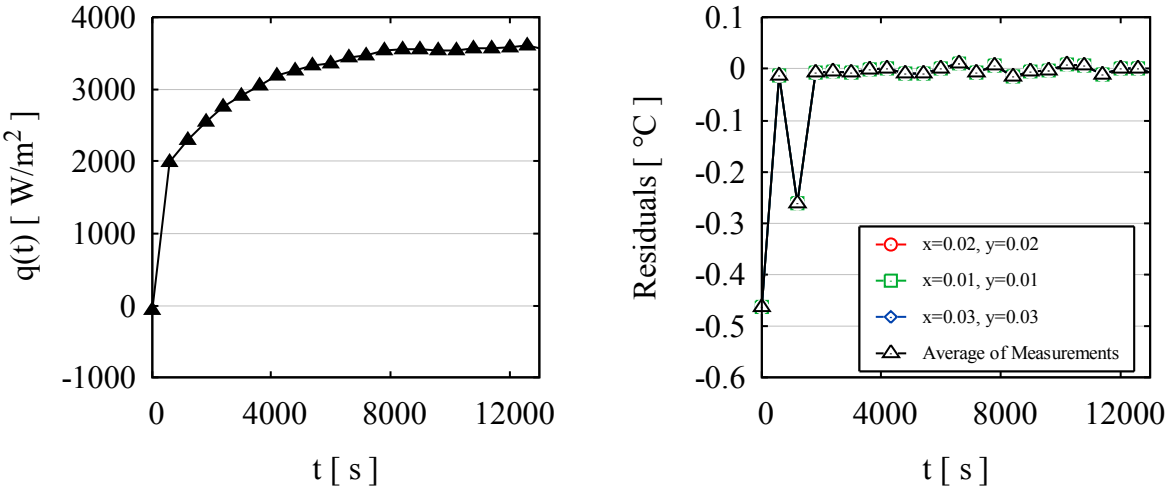
Fig. 3 - Samples made of Poly(methyl methacrylate) (PMMA).

RESULTS

Initially the applied heat flux was estimated, considering the sample presented in Fig. 3.b, which is supposed to be free of failures. The experimental procedure was composed of the following steps:

1. The temperature acquisition system was started;
2. Initial temperature measurements were taken during 120 seconds, which were used to calculate the standard deviation of the measurements;
3. A voltage of 80 volts was applied to the 22Ω resistance, resulting in a power dissipation of 323W.
4. Temperature measurements were then taken at a frequency of 1 measurement every 10 seconds, during 14000 seconds.

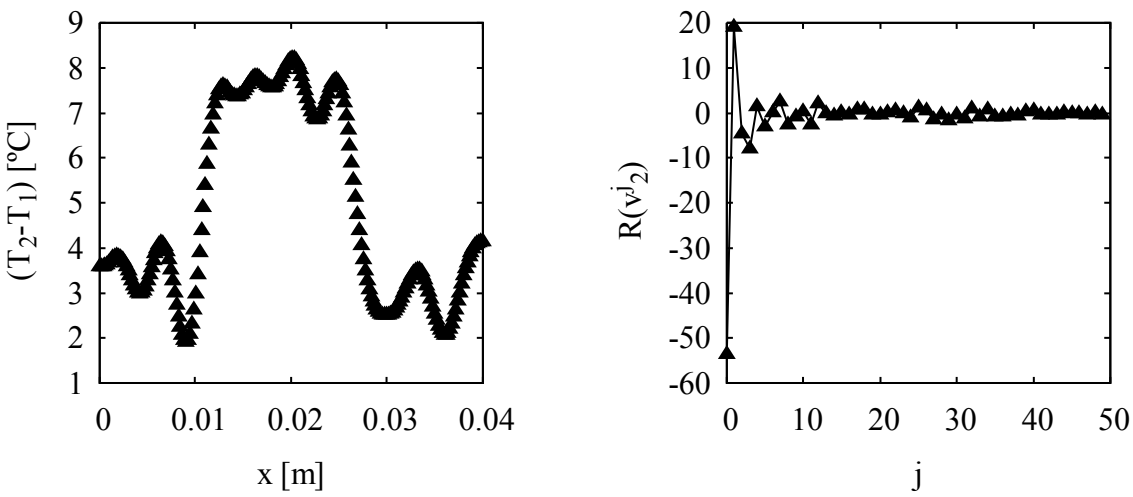
The Markov-Chain Monte Carlo Method (MCMC), following the methodology proposed by Mota *et al*. (2010), was used to estimate the applied heat flux on the top surface of the sample. This methodology uses a Markov Random Field non informative prior information. The estimated heat flux is shown in Fig. 4, where it can be noticed that it is approximately constant and equal to 3,500 W/m^2, once the steady state regime was reached. Figure 5 shows the difference between the averaged measured temperature and the estimated one at several different locations on the top surface of the sample. Results show that the heat flux is approximately constant after 10,000 seconds of experiment, and the temperature is uniform over the top surface of the sample.



(a) (b)

Fig. 4 - (a) Heat Flux estimated using MCMC method. (b) Residual analysis.

Finally, Fig. 5a shows the recovered temperature jump at the inaccessible boundary. Comparing this figure with the sample shown in Fig. 3a, it can be verified that the shape of the recovered function agrees well with the shape of the failure. The entire estimation procedure takes a fraction of second to be completed and can be also expanded to other physical problems. Fig. 5b shows the convergence of the reciprocity functional, Eq. (4).



(a) (b)

Fig. 5 - (a) Estimated function by the Reciprocity Functional, (b) Convergence of the method.

CONCLUSIONS

In this paper we applied the reciprocity functional approach, previously investigated by the authors, to the experimental identification of failures in a double-layered material. An experimental setup was presented, where the sample was heated by the thermal radiation emitted from an electrical resistance and temperatures were measured using an infrared camera. The estimated function presented a very good agreement with the sample failure showing that it is possible to identify the location of failures using this technique. The computational time is extremely low, and the entire procedure takes a fraction of second to be completed.

ACKNOWLEDGMENTS

The authors would like to thank the following Brazilian agencies for the fostering of science: *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq), *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES), *Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro* (FAPERJ), and *Programa de Recursos Humanos da Agência Nacional de Óleo, Gás Natural e Biocombustíveis* (ANP/PRH37) for the financial support for this work. The authors also thank the support of the Portuguese agency FCT. The authors acknowledge also the support of LABMEMS/COPPE/UFRJ for the manufacturing of the samples used in this work, in special of Mr. José Martim and Prof. Carolina Naveira-Cotta.

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