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Damage Detection on Frescoes Paintings by Active IR-Thermography Soft-Sensing

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Abstract **– Active thermography is a Non Destructive Technique (NDT) for composite materials testing, largely applied in aeronautics applications. Some previous works have also demonstrated its power for damage detection in frescoes and paintings. Active thermography is based on the measurement of the 2D thermal emission of an object surface when the object is exposed to a thermal flux. The thermal flux propagation inside the object affects its surface temperature and emissivity, which can be measured by an Infra-Red (IR) thermal camera. The presence of defects inside the object, as detachment between different layers, modify the propagation of the heat flow and consequently the surface temperature distribution, which can be used for the damage identification.**

Unfortunately, damage detection is often based on the subjective identification of discontinuities in the thermal maps that typically relies on the operator expertise. To make the identification objective, simplified mono-dimensional models have been used for the detachment modelling and for grounding their recognition and localization on a correlation between experimental thermograms and modelled ones.

This paper proposes a new approach linking the experimental 2D measurements to a FE model of the element under test in order to update the model with the measured data and optimise its inputs, i.e. the thermo-mechanical characteristics of the object, to be able to localise a potential damage and its depth.

In this work, the authors have performed a feasibility analysis of the method, have optimised the computational effort and have experimentally determined the properties of the material, which the object under test is made of, that have a strong influence on the uncertainty of the method itself.

The 3D extension of the model is under evaluation and it will be included in a future work.

Keywords: active IR thermography, paintings detachments, soft-sensing, NDT, damage detection

I. INTRODUCTION

Infrared thermography is nowadays an established non-destructive method for the detection of thermal bridges and discontinuities or defects (like delamination and layer detachment) and for the investigation of thermal performances of building elements.

The most exploited and robust application of such method is the active or Pulsed-Thermography (PT) which is based on the observation of the heat conduction across the stratigraphy of the building element by imposing a thermal load to the element itself. Common radiators are in the visible range (e.g. flash or halogen lamps) but also infrared emitters or lasers. Several applications of PT can be found in literature for both defect diagnostics (a standard exists for the quality control of composite materials [1]) and thermal performance assessment ([2], [3], [4]). The analysis of the surface temperature of the loaded element by means of IR thermography allows detecting inhomogeneities in the stratigraphy because the surface temperature decays as long as the heat can flow off into the interior. If an air inclusion is present due to a delamination the heat is trapped into the air cushion and the temperature cannot further decrease. The reconstruction of building element morphology can be therefore performed in a qualitative way.

In order to improve the accuracy of the analysis and to have a quantitative information about the defect location or extent the experimental data must be coupled with models that can be analytic like the ones based on physical laws, like the 1-D heat equation or more complex numerical FEM models of the heat conduction within the element. A simple 1D thermal wave model has been implemented in [5] while optimization methods, allowing iterative reconstruction of a wall thickness, have been proposed in [6] and [7] for the identification of corrosion areas. This kind of approach based on experimental data used as objective function for an optimization problem funded on a numerical model of the physical phenomenon can be also called soft-sensing procedure since it exploits both software (i.e. numerical model) and sensors (i.e. the IR thermography data).

In this work the validation of an optimization algorithm has been presented based on a numerical model exploited for both generating synthetized data emulating an IR thermal map and reproducing the heat flow within an unknown geometry in order to reconstruct the correct stratigraphy of the element under test. The numerical model and the optimization method are presented in Section II and the discussion of results in session III.

II. NUMERICAL METHOD FOR THE RECONSTRUCTION OF THE WALL GEOMETRY AND DISCONTINUITIES

The optimization method or soft-sensing approach has the objective to extrapolate information that could not be obtained from a thermographic image by itself. The added value is given by the use of a FEM model of the building element tested developed in COMSOL Multiphysics that, starting from an unknown geometry, is updated until the difference between the temperature simulated on the element surface and the one measured on the tested element surface is minimized. This minimization process has been implemented in Matlab thanks to the facility own by Comsol called LiveLink for MATLAB. In order to validate the process the measurement data have been synthetized numerically by means of a FE model accurately reproducing the building element under test. The optimization procedure is summarized in Fig. 1.

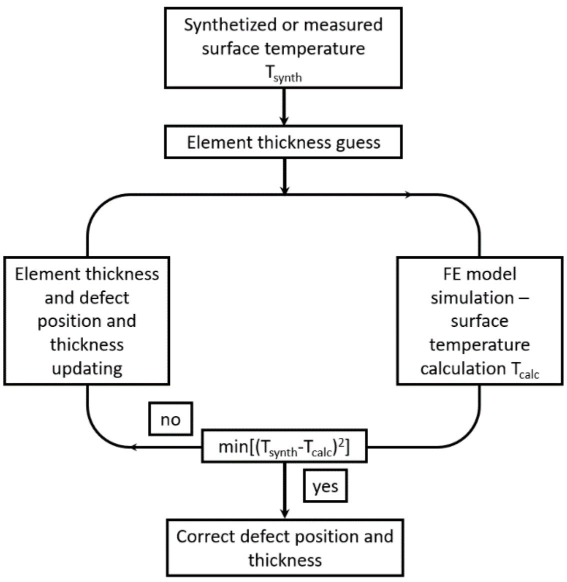
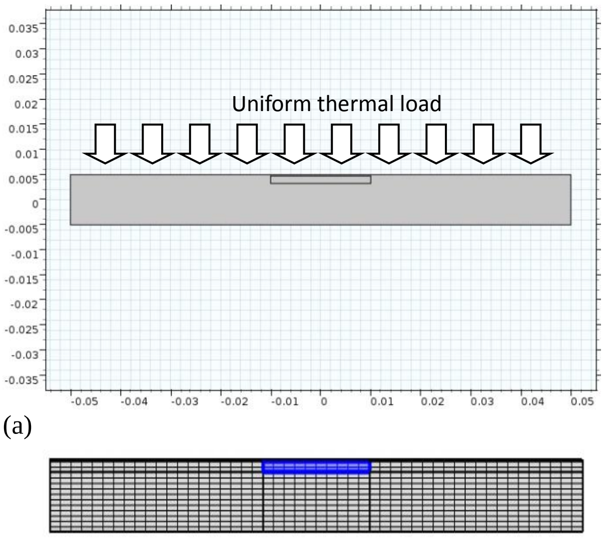


Fig. 1 Optimization procedure

A. FE model for surface temperature data synthesis

A 2D FE model has been developed with the aim of evaluating the thermal flow in the surface wall normal direction. The modeled geometry is a rectangle representing the building element of width 0.1 m and thickness of 0.01 m, see Fig. 2a. The material considered for this element is concrete. The defect is represented by a 20x1.5 mm rectangle full of air placed at 0.25 mm from the top surface (e.g. it is a sub-superficial defect) and it is located close to the loaded wall surface, i.e. where the heating id applied. The finite elements have been reproduced by using a mapped structured mesh, as reported in see Fig. 2b.



(b)

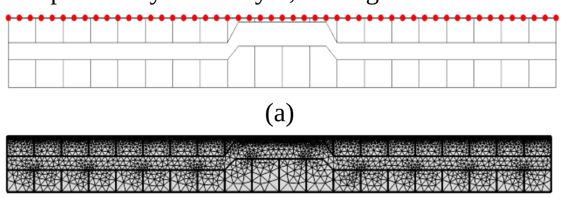
Fig. 2 FE model geometry (a) and mesh (b)

The model physics is the heat transmission, the initial condition is uniform temperature of 293.15 K for air and concrete and the boundary conditions are:

- uniform heating of the wall top surface from an external source of 5000 Wm^{-2} with a step load of 10 s duration
- perfect insulation of the wall bottom surface (convective flow neglected).

B. Optimization model

The model used to reconstruct the building element geometry has been created considering two concrete layers separated by an air layer, see Fig. 3a.



(b)

Fig. 3 Optimization FE model (a) and mesh (b)

The mesh of the model is structured triangular (Fig. 3b), with a number of nodes in the wall top surface (red dots in Fig. 3a) equal to the one of nodes of the synthesis model in order to have the same sampling in the thermal data on the wall surface. Once obtained the temperature from the synthesis model (T_{synth}) and the optimization one (T_{calc}) the optimization is realized when the objective function (*f*) is minimized, which is:

$$\boldsymbol{f} = \sum_{t=0..Tacq,N} (\boldsymbol{T}_{synth} - \boldsymbol{T}_{calc}) \qquad (1)$$

where the sum considers all the time samples syntheses (from 0 to the time interval *Tacq*) and all the nodes in the wall top surface (red dots in Fig. 3a).

An important issue of the optimization model is the initial guess of the wall thickness and the defect depth starting from the measured thermogram, synthetized in this case). A manner for the first estimation of the back wall geometry is the so-called echo defect shape method [8]. This method takes into account that the reflection of the thermal wave in the defect interface, when returning towards the wall top surface, produces an increase of the temperature in the surface itself and that the time evolution of this temperature can be fitted by an exponential curve.

III. DISCUSSION OF RESULTS

In order to test the sensitivity of the optimization process to different parameters (e.g. spatial resolution, initial knowledge of the thickness), it has been ran in three different configuration:

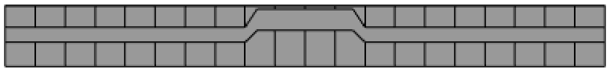
- Model with 20 elements in the building element width direction (low resolution model),
- Model with 40 elements in the building element width direction (model with improved spatial resolution),
- Application of the echo defect shape method for the calculation of the thickness initial guess (model with thickness initial guess calculated with the echo defect shape method).

The results of the three process are reported in the following section.

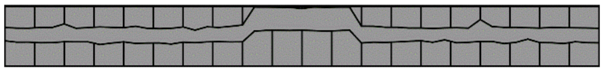
A. Low resolution model

The geometry of the model used for the superficial temperature synthesis and the one reconstructed by the optimization process are reported in Fig. 4. The position, thickness and depth of the defect are accurately identified.

The top surface temperature reconstruction after optimization (red dotted line) is reported in Fig. 5 together with the real temperature profile (i.e. the temperature synthetized by the synthesis model, blue line) and the temperature calculated by the numerical model before starting the optimization (black line).



(a) Synthesis model



(b) Optimized model

Fig. 4 Geometry of the building element model

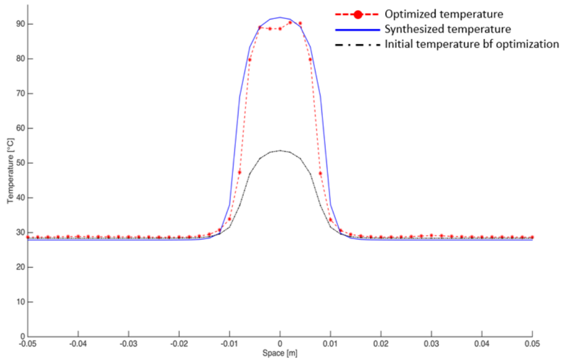
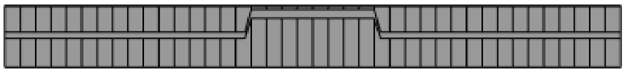


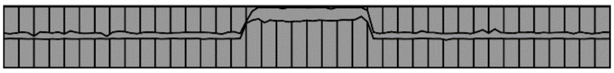
Fig. 5 Top surface temperature profiles at the time instant of 10 s

B. Model with improved spatial resolution

By improving the spatial resolution as evidenced in the models geometry (Fig. 6) the accuracy of the top surface temperature profile reconstruction improves (Fig. 7).



(a) Synthesis model



(b) Optimized model

Fig. 6 Geometry of the building element model

A. Model with thickness initial guess calculated with the echo defect shape method

This method starts with an initial value calculated analytically, i.e. from the synthetized top surface temperature data, as described in [8]. The initial geometry obtained using the echo defect shape model and the optimized one are illustrated in Fig. 8, where a close up around the defect is presented.

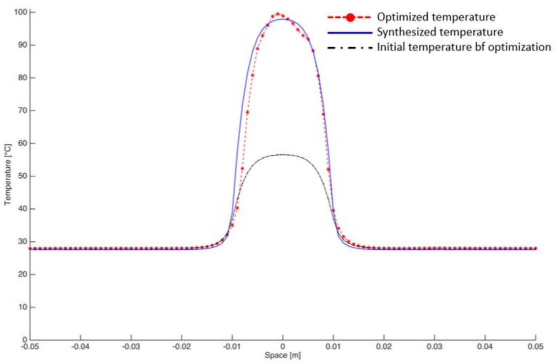
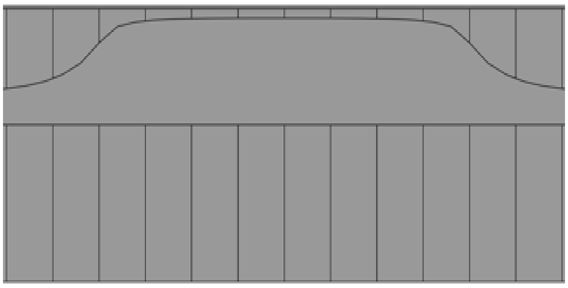
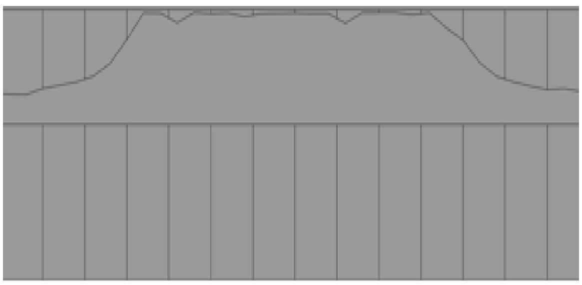


Fig. 7 Top surface temperature profiles at the time instant of 10 s



(a) Initial geometry



(a) Optimized geometry

Fig. 8 Geometry of the building element model – close up around the defect

The accuracy of the top surface temperature profile reconstruction improves further if the thickness initial guess is closer to the real one (Fig. 9).

IV. CONCLUSIONS

A hybrid experimental based numerical model has been presented with the aim of reconstructing multi-dimensional shapes. This model, using as input the thermal profile of a building element surface, allows evaluating the thickness of the element and the presence of a defect inside it. The critical aspects of the method are:

- Long calculation time if high accuracy and spatial resolution are required,
- Parallel calculation impossible to be implemented,
- Even longer calculation time if 3D modelling is needed.

A specific software code will be developed in a future work to solve those issues. The main idea is to develop an iterative model for limiting the resolution in the region far from the defect and increase it in the neighbor pixels. The accuracy of the quantitative result increases also if the simulation parameters are accurate in turn, as the material physical properties, the thermal load power and its spatial distribution. Those parameters must be measured and introduced into the model to improve the final results.

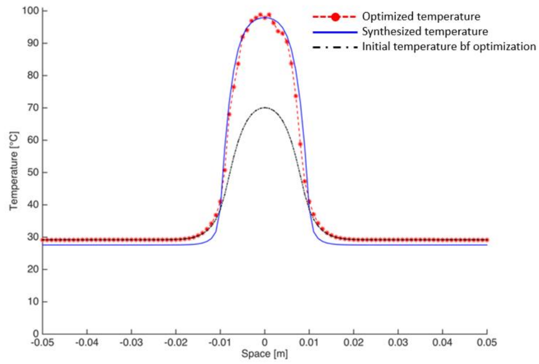


Fig. 9 Top surface temperature profiles at the time instant of 10 s

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