From thermal inspection to updating a numerical model of a race bicycle

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Abstract

There are many advantages of using thermography for updating numerical models. These include the fact that it can be performed in-situ, it can cover large areas and it is a quantitative method. In this paper, a numerical model of a bicycle frame will be updated and optimized by the surface temperature distribution captured with pulsed thermography. These results will be compared and benchmarked against FRF measurement data as reference. The chosen temperature decay measurement to be used as reference data will be of key importance. Both updating techniques will be compared with respect to measurement time and accuracy.

Keywords: finite element model, pulsed thermography, optimization, Inverse Problem

1. Introduction

The study of Pulsed Infrared Thermography (PT) has become an important aspect of non-destructive evaluation technique (NDE) for damage detection in metallic structural elements, as well as CFRP (Carbon Fibre Reinforced Polymer) and GFRP (Glass Fibre Reinforced Polymer) composites [1]. There are many advantages of thermography, these include the fact that no coupling is required, it can be performed in-situ, it can cover large areas and it is a quantitative method. A disadvantage is that there is a limit on the thickness of the structure being monitored [2]. On the other hand, computer simulation and virtual modelling tools are an economical and fast way to determine and simulate material behaviour. The next step in integrating the non-destructive PT tests and virtual modelling is the updating of the FE model [3], [4]. Computer simulations are economically interesting and a fast way to determine and simulate material behaviour and to calculate worst case scenarios. Finite element (FE) analysis has been used as a verification tool in some applications involving infrared thermography [5]. Besides thermography, FE modelling has proven its success in multiple application areas for worst case simulation and quantitative failure detection. In conventional FE model updating procedures, frequency response function measurements and estimated modal parameters are used as reference data to be compared with the calculated output from the FE model [6]. The disadvantages are that there is a limit on the thickness of the structure being monitored [7]. In this paper, a finite element model of a bicycle frame will be updated and optimized by the surface temperature distribution captured with pulsed thermography. These results will be compared and benchmarked against thermal measurement data to be used in an FE updating procedure [8]. The chosen temperature decay measurement to be used as reference data will be of key importance. In this paper, the aim is to update the FE model with respect to the temperature distribution measured by the thermography non-destructive method applied on a carbon race bicycle frame. Both updating techniques will be compared with respect to measurement time and accuracy.

2. Pulsed thermography

Pulse thermography (PT) is one of the most popular thermal stimulation method in IR thermography. One reason for this popularity is the quickness of the inspection relying on a thermal stimulation pulse, with duration going from a few ms for high thermal conductivity material inspection (such as metal parts) to a few seconds for low thermal conductivity specimens (such as plastics, graphite epoxy components). Such quick thermal stimulation allows direct deployment on the plant floor with convenient heating sources. Moreover, the brief heating prevents damage to the component (heating is generally limited to a few degrees above the initial component temperature).

In PT experiments, measurement of the temporal evolution of the surface temperature is done by using an infrared (IR) camera to reveal the presence of defects under the surface [2]. Qualitatively the principle is as follow: absorption of energy from the thermal pulse causes surface temperature to change rapidly, a thermal front is thus launched under the surface where it propagates by diffusion. Presence of zones having different thermal properties (defects) with respect to the bulk of material changes the diffusion rate so that defect positions can be seen on the front surface as areas having different temperatures, after the thermal front reaches them. Problems associated with PT are

generally weak contrasts, detection limited to shallow defects, sensitivity to surface artifacts of the specimen, need to know the localization of a "defect-free" location to compute thermal contrast (e.g. [2], eq. 6.28). On the other hand, as for NDE applications, PT has many known advantages: - non contact, -quick, - ease of deployment, etc.

3. Measurement Set-up

The bicycle frame is heated by two heat sources of 1 000W each. The sources are positioned straight to the wall as shown in Figure 2. The Xenics Gobi camera is placed on the center-to-center distance between both halogen spots. The heating time is 10 seconds and a measured cooling time has been used. There is opted to use a pulsed thermography measurement set-up in order to perform a fast and 'simple' measurement.


Fig. 1. Experimental setup for IR measurements.

The microbolometer has a field-of-view of 42.6°. This means the camera needs to be placed about 1.3m from the bicycle frame in order to capture the complete frame in the camera image. The reflection can be ignored as Germanium has a reflection rate of less than 1% between a wave length of 7-12µm. In order not to have an influence of the wall behind the set-up, the bicycle frame will be placed at a distance of 1m from the wall, in order to avoid that the wall heats up due to the light bulb excitation [1,3]. For this reason, the wall reflection will not have an influence on the heat measurements. In addition, the camera will be placed symmetrically between the light bulbs (Figure 1). The halogen light bulbs and microbolometer camera are placed perpendicular to the bicycle frame in order to capture the complete frame at equal distance but also in order to avoid that occurring reflections are not coinciding with the measured bicycle frame.

4. Measurements

During the analysis of the images, it was clear that a pulsed heating of 8 seconds is sufficient to heat up the bicycle frame and to make a temperature analysis possible for updating purposes. As already discussed, a pulse thermography measurement procedure is used to perform the measurements. As seen on Figure 2, visualizing a thermal image of the bicycle frame, a contrast over the structure surface is clearly visible and ready for analysis and post-processing.
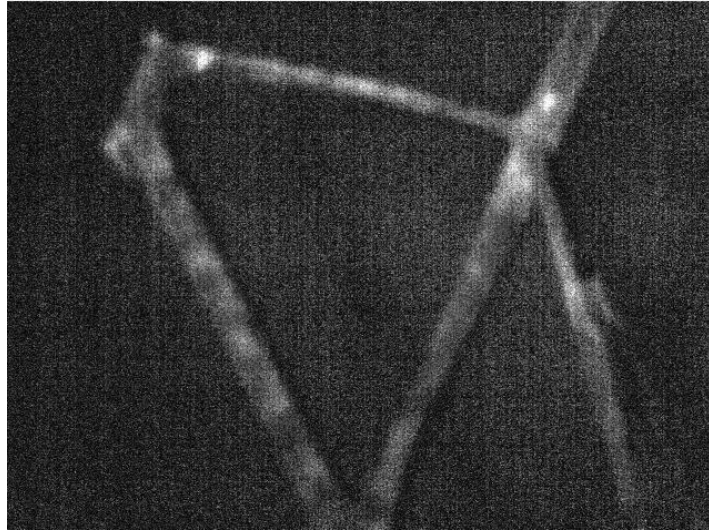
Fig. 2. Measured thermal image of bicycle frame.

4.1 Measurement parameters

For the thermal measurements, a Xenics Gig-E Gobi camera is used. The images are captured with a sample frequency of 10 Hz and a resolution of 640x480 pixels. The Noise Equivalent Temperature Difference (NETD) of the camera equals 50 µK which is a measure for the camera sensitivity.

Different measurement points are chosen over the bicycle frame. These measurement points are visualized in Figure 3, representing a thermal image with a fixed frame number. The measurement points to be used for updating purposes are chosen in the vicinity of the frame where steering stem should be placed. These points are chose in such a way that the updating results are resulting in an accurate prediction of the frame thickness and material properties on this location.
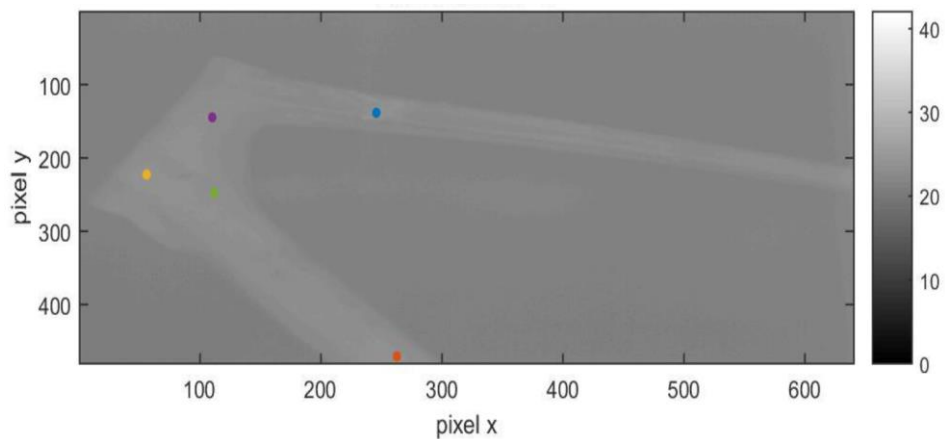
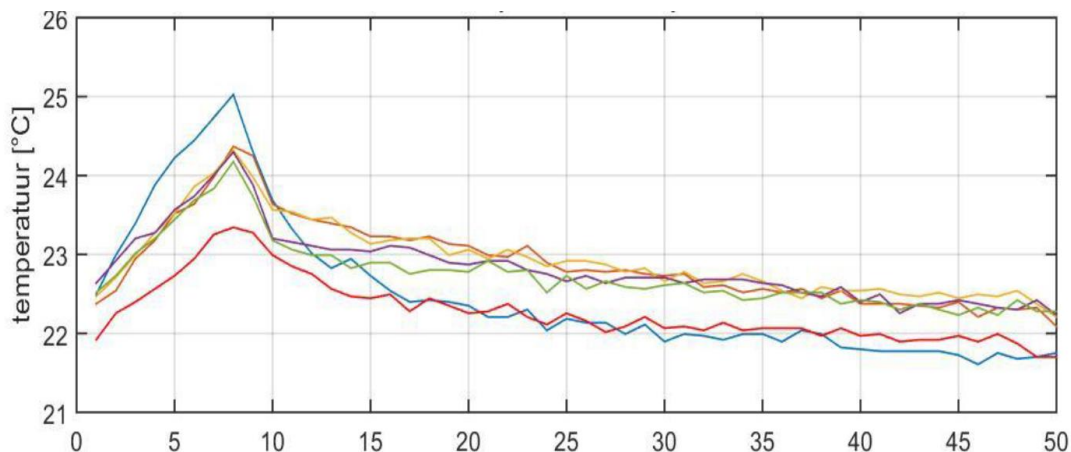**Fig. 3.** Thermal image with fixed frame number (frame 8)

Fig. 1. *Temp. profile versus time.*

The measured temperature evolution over time (over different measurement frames) is visualized in Figure 4. The heating of the structure surface is clearly visible during the first 8 seconds. Afterwards, the structure's temperature is decreasing over time and the temperature decay in the case of pulsed thermography is measured. The different measurement points over the bicycle frame follow the same temperature evolution over time. The ambient temperature is 22 °C. During the pulsed excitation, the structure is heated a few degrees Celsius. Also on Figure 4, it can be noticed that a difference in material thickness, depending on the location of the measurement points, is resulting in different maximum temperature values. These temperature values will be compared with the simulation results, discussed in Section 5.

5. Finite Element model

The bike frame model (Fig.1) is built in Autodesk Inventor and simulated in Siemens NX. The composite layer is defined in NX Laminate Composites, a module for NX Advanced Simulation that allows to design and analyze laminate composites. The composite model created reflects all geometry and physical aspects of the composite frame. Mesh convergence of the finite element was checked, using 11 241 linear tetrahedral elements.

5.1 Thermal simulation property values

The finite element model is defined with the material properties of a CFRP composite. De material property values of the four-layer laminate are defined with equivalent density value of 1350 kg/m^3. The used heat capacity is a constant value and thermal conductivity and expansion coefficient are temperature dependent values. The used values in the thermal simulation are listed in Table 1.

Property	Value
Heat source [W]	300
kmat [W/(mK)]	0.2
Cpmat [J/(kgK)]	1050
rhomat [kg/m^3]	1350
epsmat	0.8
Start pulse [s]	1.5
Tambient [K]	295.15

Table. 1. Thermal simulation property values

5.2 Mesh

For the surface of the light bulbs, a 2D QUAD4 surface mesh is chosen with element size = 10mm and thickness=1mm. The light bulbs are modeled in such a way that the temperature difference is negligible over the bulb model surface. For the frame meshing itself, a 3D Tetra volumetric mesh is chosen with element size equal to 5mm.
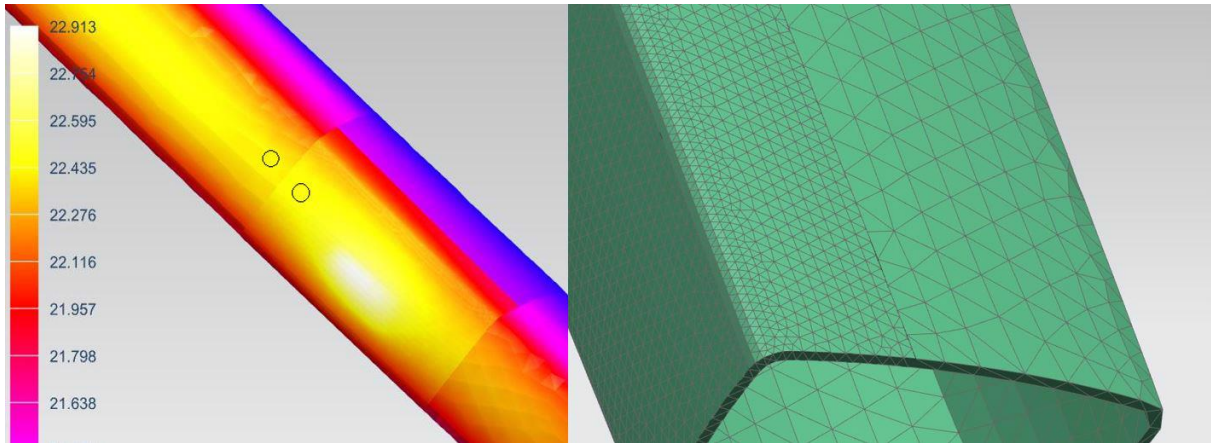

Fig. 5. Bicycle frame mesh and simulated temperature distribution.

5.3 Heat flux light bulbs

A power of 1000W is defined for the heat sources. As the structured is excited by a pulsed block wave in the case of pulse thermography measurement process, the same heating process is simulated. However, in order to achieve a perfectly flat block rectangular block wave in the heat simulation, a temperature constraint is defined in combination with a variable pulse length in order to optimize the heating of the bicycle frame. An initial excitation pulse length of 8s is initially used (Fig. 6). In order to transmit the thermal energy onto the bicycle frame, radiance but also convection is defined in the thermal simulation.
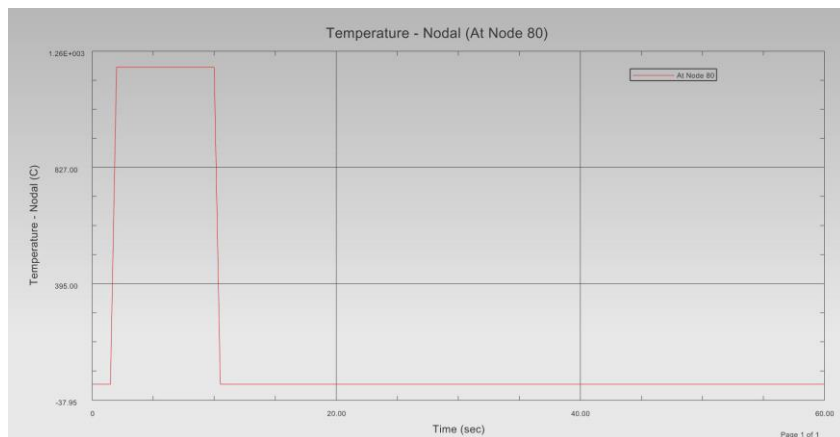

Fig. 6. Heat excitation pulse of flash light bulb during defined in the FE simulation.

Parameter	Range
Thickness [mm]	1-10
Heat transfer coefficient [W/mK]	2-100
Pulse duration [s]	2-10

Table. 2. Parameter ranges during optimization routine

6. Optimization results

For the FE updating algorithm an adaptive response surfaces optimization approach will be used [8] where the experimental data is used as target for the FE model. The listed parameters (in Table 2) of the frame are the parameters that will be optimized. Figure 1 and Figure 4 present the experimental and numerical results of the first measurements. Figure 4 shows the temperature evolution when applying a pulsed heat source. This difference will be reduced in the optimization algorithm over a time interval. The finite element simulation approximates the experimental setup, which is used to simulate with the correct properties. The updated FE models could be used to assist NDT methods in damage localization and detection.

(a)   (b)
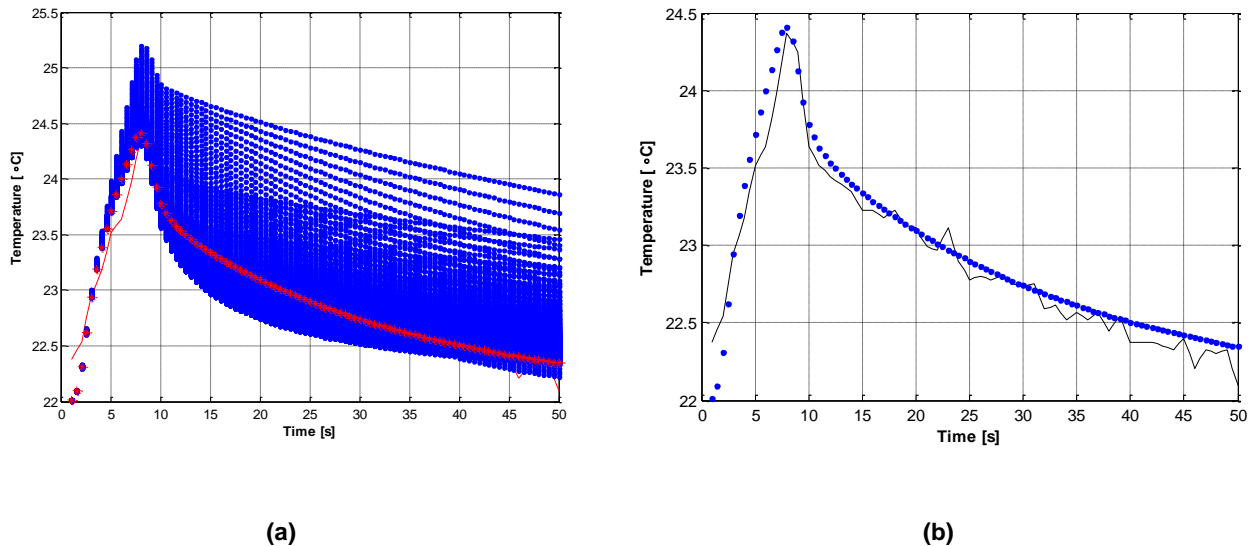
Fig. 7. Updating of simulated temperature evolution over time with measured decay (full line) and optimized temperature decay (dotted line).

The evolution of the simulated temperature evolution over time is visualized in Figure 7(a) with the red dotted line the temperature decay optimally representing the measured temperature decay, plotted in full red line. Both curves are also visualized in Figure 7(b). In this figure it can be clearly seen that the dotted line (simulated temperature) represents the measure temperature decay (full line) very well. The squared error equals a value of 1.4826. The optimized set of parameter values is listed in Table 3.

Parameter	Optimal Value
Thickness [mm]	3
Heat transfer coefficient [W/(m.K)]	50
Pulse duration [s]	8

Table. 3. Optimal parameter values after updating finite element model with temperature measurement.

CONCLUSIONS

In this paper, a numerical model of a bicycle frame is updated and optimized by the surface temperature distribution captured with pulsed thermography. From initial updating and optimization results it can be concluded that a temperature decay measurement can be used as reference data in order to determine the correct set of updating parameters. In this case study, the most important parameter value to be identified is the local thickness value of a composite bicycle frame. By making use of a finite element model characterizing and simulating the thermal measurement, one is able to identify the correct thickness, excitation period and convection coefficient.

ACKNOWLEDGEMENTS

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