



Defect depth estimation using through-transmission pulsed thermography: A numerical and experimental investigation

Zain Ali , Sri Addepalli *, Yifan Zhao

Faculty of Engineering and Applied Sciences (FEAS), Cranfield University, Cranfield, MK43 0AL, United Kingdom

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ABSTRACT

Through-transmission pulsed thermography is widely recognised for offering higher defect resolution than reflection mode, yet its development has been hindered by challenges such as quantifying defect depth. This study addresses the depth quantification gap by introducing a novel depth estimation technique based on the relationship between defect depth and the Fourier number. The method is validated through both finite element modelling and laboratory experiments using calibration samples with embedded air-gap defects at known depths. Results show that depth estimation accuracy improves as defects approach the backwall, consistently across both simulation and experimental environments. Finite element analysis also demonstrates that the proposed technique outperforms the log second derivative method typically used in reflection mode. These findings advance the capability of through-transmission thermography for precise subsurface defect characterisation.

1. Introduction

Ensuring the thermal and structural integrity of components is essential in sectors such as aerospace, energy and transportation, where subsurface defects can significantly influence reliability and service life. As materials become more advanced and geometries more complex, there is increasing demand for non-contact inspection methods that can provide rapid and reliable information on internal features. Infrared thermography has gained particular attention for this purpose because it offers fast full-field measurements and a strong sensitivity to thermal transport phenomena [1,2].

Within this field, through-transmission pulsed thermography is especially useful for the evaluation of deeper subsurface defects such as delamination in carbon fibre reinforced polymers [3]. By placing the heat source and infrared detector on opposite sides of the specimen, heat is forced to diffuse through the full thickness of the material, which improves detectability and lateral resolution compared to reflection-mode configurations [4]. Through-transmission measurements are also widely used for thermal diffusivity evaluation, where they provide a more direct representation of heat flow through the sample [5]. However, a key limitation remains. Through-transmission thermography cannot reliably quantify defect depth, which restricts its use to qualitative interpretation rather than quantitative assessment. Recent works, such as Wang et al., have demonstrated that defect depth

can be quantified in pulsed thermography through nonlinear modelling of peak surface temperature features [6], but these approaches are formulated in the reflection mode. Other studies have addressed physics-guided thermography and automated inspection to improve defect detectability and data quality [7,8], however, depth quantification in through-transmission pulsed thermography remains unaddressed.

A further challenge is the lack of realistic defect standards for method validation. Many studies simulate defects using low-conductivity inserts such as PTFE or resin-based inclusions [9,10]. These approaches do not accurately represent the thermal behaviour of air-filled porosity, which is a critical defect type in both metallic and composite materials and often initiates fatigue damage in aerospace structures [11,12]. More representative calibration samples are therefore required to improve the interpretation of transient thermal responses.

This study addresses these limitations by introducing a new experimental design in which internal cavities are drilled into a steel specimen and sealed with matching steel plugs while maintaining a controlled 1 mm air layer. This configuration provides a more realistic representation of subsurface porosity. Finite element modelling is combined with pulsed thermography measurements to analyse heat diffusion around defects located at multiple depths.

The main contribution of this work is the development of a first-of-its-kind defect-depth quantification approach for transmission-mode

* Corresponding author.

E-mail address: p.n.addepalli@cranfield.ac.uk (S. Addepalli).

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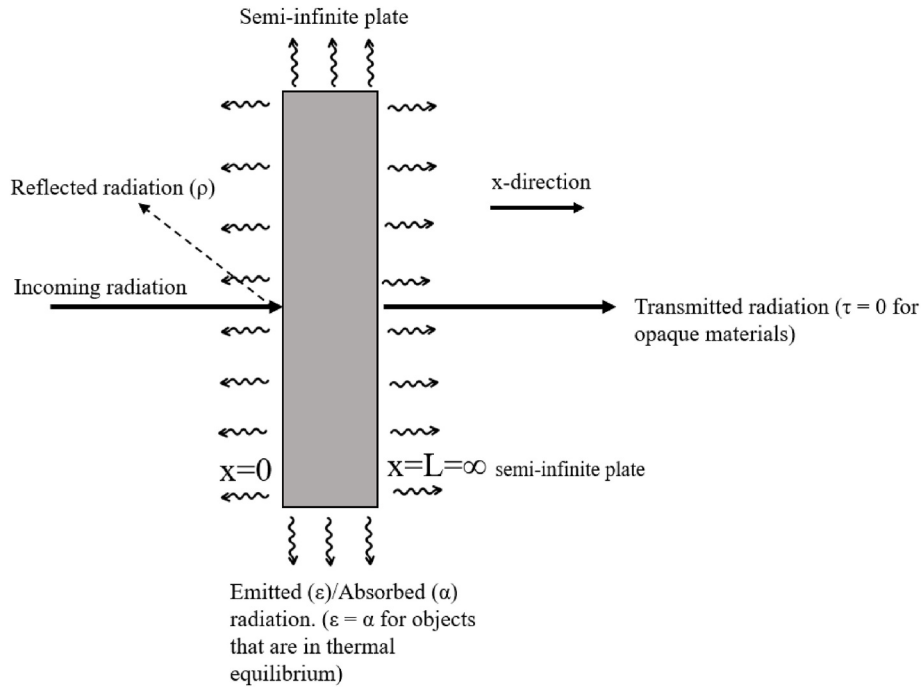


Fig. 1. Schematic describing an objects response to incoming electromagnetic radiation.

Table 1

Input parameters for the sample being inspected.

Defect size and shape	16 mm diameter circle	8 mm diameter circle	16 mm length square
Defect depth (mm)	1	3	5

Table 2

Number of experimental runs for a full factorial DoE.

Run	Defect size and shape	Defect depth (as measured from the backwall)
1	16 mm length square	3
2	8 mm diameter circle	5
3	16 mm diameter circle	3
4	16 mm length square	5
5	16 mm diameter circle	5
6	8 mm diameter circle	3
7	16 mm length square	1
8	8 mm diameter circle	1
9	16 mm diameter circle	1

thermography based on the Fourier number. Although the Fourier number has previously been used to describe transient thermal behaviour and to support defect characterisation [13], its potential for predicting defect depth in through-transmission configurations has not been examined in detail. The correlation established in this study, supported by strong agreement between modelling and experimental measurements, demonstrates that the method is reliable, repeatable and reproducible across multiple defect depths. These findings provide a pathway toward quantitative defect evaluation using transmission-mode thermography.

2. Theory

The purpose of this section is to familiarise readers with the fundamental principles of the techniques employed in this study. This understanding will, in turn, clarify the rationale behind the selection of materials and methods used in the development of the technique.

2.1. One dimensional heat transfer

Fig. 1 shows an object which has been subjected to electromagnetic radiation. Here the x-direction is the direction parallel to the sample thickness. Part of the radiation is reflected, and the other two parts are either absorbed or transmitted. For opaque materials, the transmitted radiation is zero. The amount of radiation that is either reflected or absorbed is dependent upon the materials reflection and absorption coefficients respectively. The sum of these coefficients will always equal to 1. Fig. 1 also states that the absorbed radiation is equal to the emitted radiation. This is Kirchoff's law of thermal radiation that states the amount of radiation absorbed by an object at any wavelength is equal to the amount emitted provided that the object is in thermal equilibrium.

The equation that governs the temperature distribution within the material is from the classic heat diffusion theory in solids also known as the Fourier equation.

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (1)$$

Where T is the temperature (K), t is the time (s) $\alpha = \frac{k}{\rho C}$ is the *thermal diffusivity* of the material (m^2/s); k is the thermal conductivity (W/mK); ρ is the density (kg/m^3); and C is the specific heat ($\text{J}/\text{kg K}$).

2.2. Pulsed thermography

For pulsed thermography, Parker et al. employed the one-dimensional heat transfer equation developed by Carslaw and Jaeger [14], addressing several challenges associated with obtaining analytical solutions [5]. Firstly, the issue of thermal contact resistance was mitigated through the use of flash heating. Secondly, surface heat losses were minimised by acquiring thermal measurements over a very short duration in the order of milliseconds. This resulted in the following equation:

$$T(L, t) = \frac{Q}{\rho CL} \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp \left(-n^2 \pi^2 \frac{\alpha t}{L^2} \right) \right] \quad (2)$$

Where L is the sample thickness (m) and Q is the excitation energy (J/

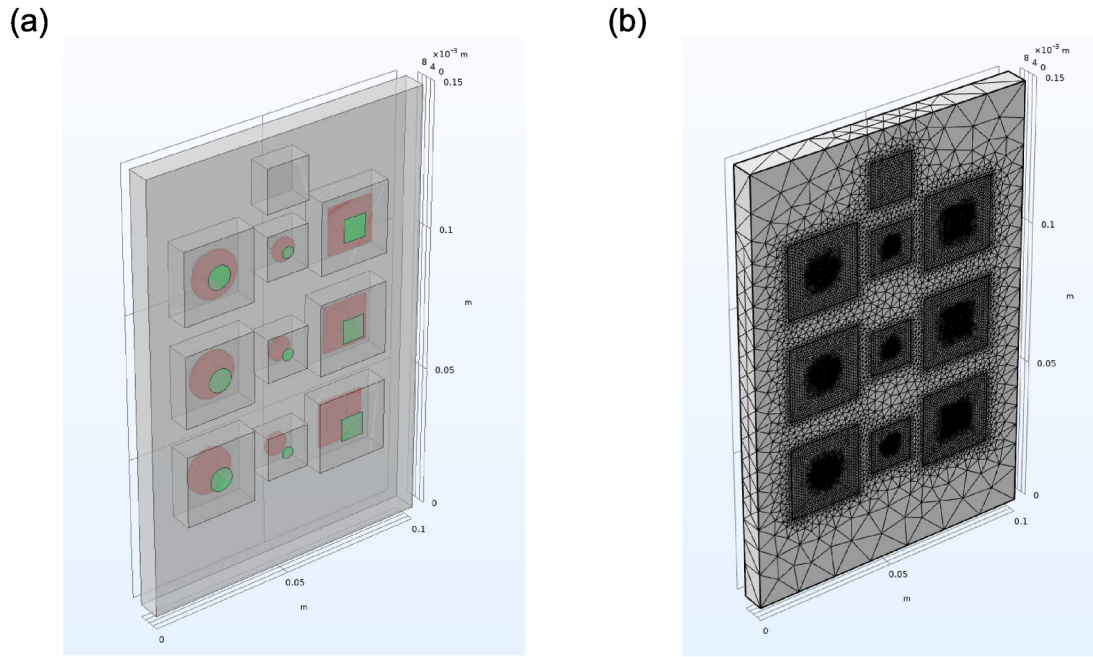


Fig. 2. Geometry created in pulsed thermography of a stainless steel 304 plate with subsurface defects a) the red regions are the defects, and the green regions are the area from which the surface temporal information was extracted b) the meshed geometry. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Input parameters for the finite element model on COMSOL.

Material Thermal Properties	
Specific Heat Capacity (J/kg.K)	500
Density (kg/m ³)	7930
Thermal Conductivity (W/m.K)	16.2
Plate Geometry	
Height (mm)	150
Width (mm)	100
Defect size and shape	16 mm diameter circle, 8 mm diameter circle, 16 mm length square
Defect Depth (mm)	1, 3, 5
Heat Transfer Physics	
Initial Temperature (K)	293.15 (Applied to the entire body)
Pulse energy (J)	500
Pulse Width (ms)	2
Heat flux q_0 (W/m ²)	((Pulse Energy/Pulse width)/(Width*Height))*B(t)
Convective heat transfer coefficient h (W/m ² .K)	5
Emissivity ϵ	0.95
Meshing Parameter (area of interest)	
Mesh size (uniform in all directions including through thickness)	Extremely fine
Maximum element size	0.001
Minimum Element size	0.00001
Maximum Element growth rate	1.3
Curvature factor	0.2
Resolution of narrow regions	1
Meshing Parameter (rest of the geometry)	
Mesh size (uniform in all directions including through thickness)	Normal
Maximum element size	0.015
Minimum Element size	0.0027
Maximum Element growth rate	1.5
Curvature factor	0.6
Resolution of narrow regions	0.5

m²). Two dimensionless parameters V and ω can be defined to make the equation independent of specific material properties and therefore Equation (2) can be re-written as:

$$V(L, t) = \left[1 + 2 \sum_{n=0}^{\infty} (-1)^n \exp(-n^2 \omega) \right] \quad (3)$$

where $V = T/T_M$ in which T_M is the maximum temperature that the backwall can reach and $\omega = \pi^2 \alpha t / L^2$ is the dimensionless time quantity. The equation describing the front wall temperature response is the same as in Equations (2) and (3) without the $(-1)^n$ term.

To find the thermal diffusivity of the material, Parker introduced the half-rise temperature method where in the time taken to reach half the maximum temperature is recorded. Using the previously defined dimensionless parameters, when $V = 0.5$, then $\omega = 1.38$ since $\omega = \pi^2 \alpha t / L^2$. Thus α can be determined as:

$$\alpha = \frac{1.38 L^2}{\pi^2 t_{1/2}} \quad (4)$$

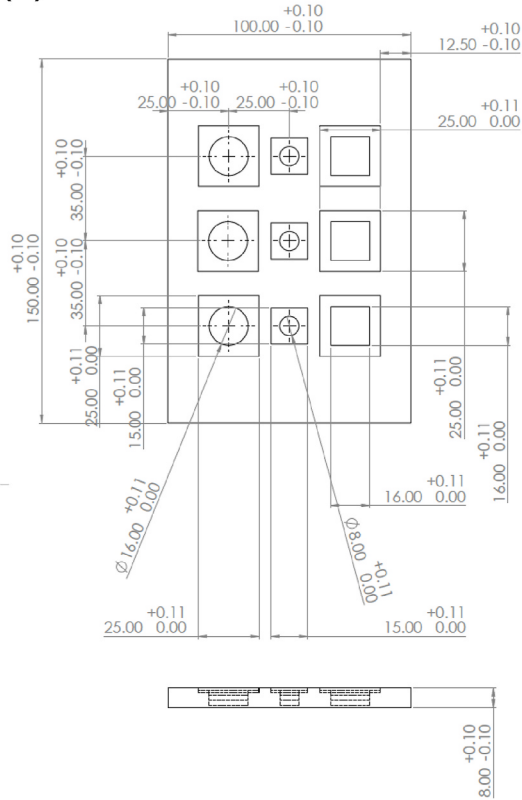
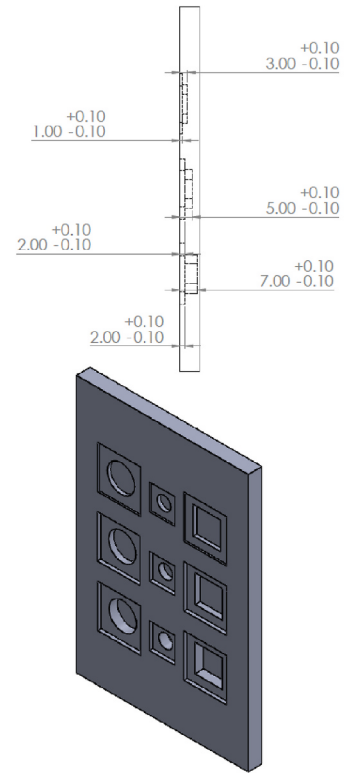
This method is the most accepted, the standard method used for thermal diffusivity estimation for both research and commercial instruments such as the LFA 427 [15].

2.3. New least squares fitting (NLSF) algorithm

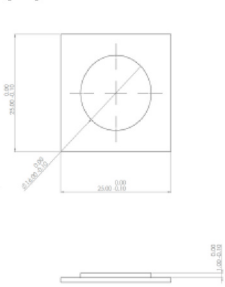
While Parker's half-rise method is widely used for estimating thermal diffusivity, it has key limitations. As noted by Chihab [16], it overlooks heat losses at the front and back surfaces and requires data acquisition immediately after the flash event ($t = 0$). This is not an issue in reflection mode, where both the flash and IR radiometer are on the same side. However, in transmission mode, shielding is required to prevent direct heating of the backwall, which also blocks the radiometer from detecting the flash event. This can be resolved with a synchronised system that records the flash frame.

Another limitation is the method's assumption of no subsurface defects, implying a thermal reflection coefficient of 1. In reality, as Lau et al. show, this value ranges between 0 and 1 [17]. This variation arises

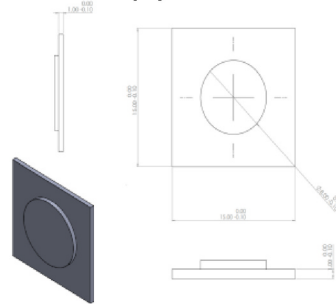
(a)



(b)



(c)



(d)

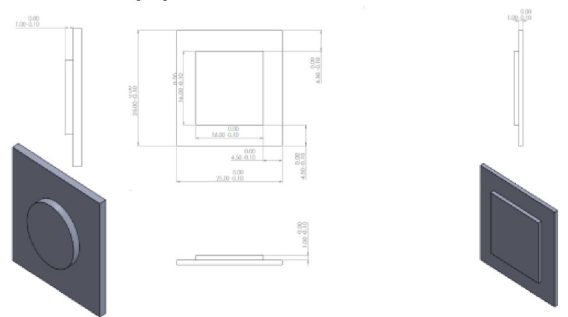


Fig. 3. a) Substrate with machined holes at different depths b,c,&d) Plugs for the first three holes showcasing all the different defect shape and sizes (all dimensions are in mm).

because heat transfer across a defect involves material–air–material interfaces, lowering the effective diffusivity, as described by Maierhofer et al. [4]. Accurate measurement therefore requires adjusting the reflection coefficient in Equation (2).

To address these issues Sirikham et al. (2017) introduced the New

least squares fitting algorithm (NLSF) [18]. Improving on the previously introduced Least squares fitting algorithm by Sun [19] which assumed the R to be 1, the authors introduce a new analytical mode as follows:

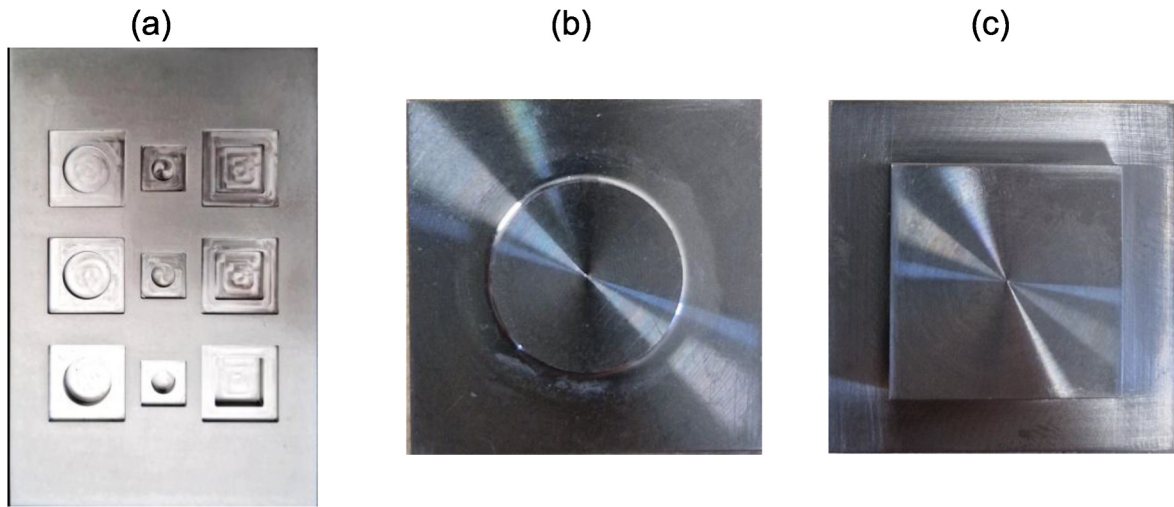


Fig. 4. a) Machined substrate based on the CAD model b) Machined plug for the circular hole c) Machined plug for the square hole.

Table 4

Impact energy samples with varying levels of impact energy.

Sample ID	Impact Energy (J)	Repeat number
4J P1 S2	4	1
4J P3 S25	4	2
4J P3 S27	4	3
8J P2 S11	8	1
8J P2 S13	8	2
8J P2 S15	8	3
12J P1 S21	12	1
12J P2 S21	12	2
12J P1 S22	12	3

$$T(t, B, W, R, t_s, s) = \frac{B}{\sqrt{t + t_s}} \left[1 + 2 \sum_{n=1}^M R^n \exp \left(-\frac{n^2 W}{t + t_s} \right) \right] - s(t + t_s) \quad (5)$$

Where $B = \frac{Q}{\sqrt{(\pi \rho c k)}}$, $W = \frac{L^2}{\alpha}$, t_s is the starting time for sampling, M is a large iteration number, and s represents the slope of the linear portion of the temperature time curve. The addition of t_s is unique in this case at it allows for taking data segments that don't necessarily start at $t = 0$. The *lsqnonlin* function available in MATLAB is used to solve this 5-parameter optimisation problem based on the following relation:

$$\min_{B, W, R, s, t_s} \|\tilde{T}(t) - T(t)\| \quad (6)$$

This method has successfully been implemented in the reflection



Fig. 5. CFRP samples that have undergone impact damage at energies of 4J (left) 8J (middle) and 12J (right).

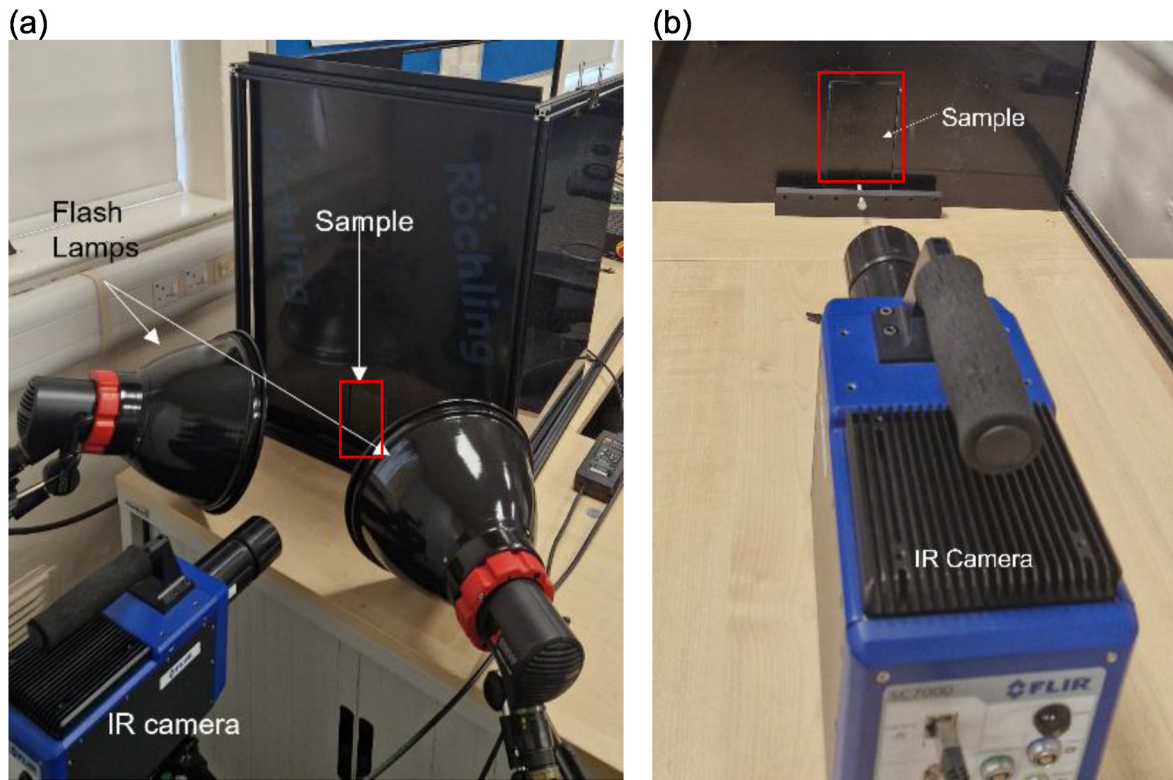


Fig. 6. Experimental configurations of the a) reflection mode and b) transmission mode.

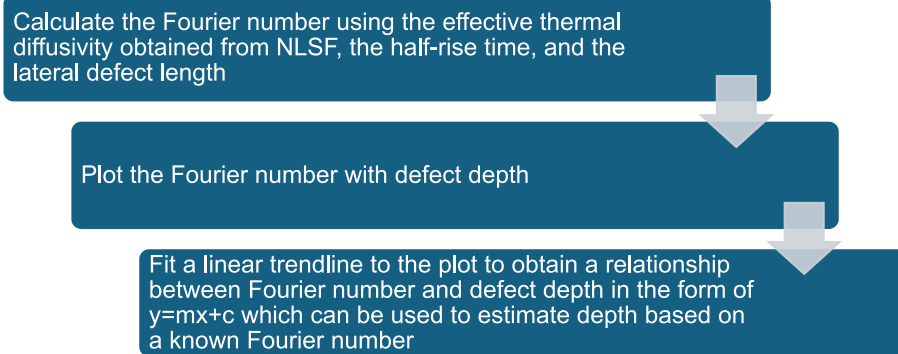


Fig. 7. A step-by-step procedure to estimate defect depth in the transmission mode.

Table 5

Estimated thermal diffusivity (sound region) and effective thermal diffusivity (defect regions) using the NLSF algorithm for the sound and defect regions using backwall temporal information.

Defect type	Defect depth		
	1 mm	3 mm	5 mm
Sound Area (note that defect depth is not applicable for this region)	3.92 (mm ² /s)	3.92 (mm ² /s)	3.92 (mm ² /s)
8 mm circle	2.66 (mm ² /s)	2.63 (mm ² /s)	2.94 (mm ² /s)
16 mm circle	1.47 (mm ² /s)	1.38 (mm ² /s)	1.48 (mm ² /s)
16 mm square	1.33 (mm ² /s)	1.21 (mm ² /s)	1.29 (mm ² /s)

Table 6

Estimated input flash energy using the NLSF algorithm for the sound and defect regions using backwall temporal information.

Defect type	Defect depth		
	1 mm	3 mm	5 mm
Sound Area (note that defect depth is not applicable for this region)	515.47 (J)	515.47 (J)	515.47 (J)
8 mm circle	518.78 (J)	520.53 (J)	519.47 (J)
16 mm circle	511.89 (J)	518.18 (J)	517.46 (J)
16 mm square	510.17 (J)	518.14 (J)	517.32 (J)

mode but was not used for the transmission mode until recently [20]. Moreover, α is assumed to be known a priori in the equation above. However, as mentioned in Section 1, the reflection mode's sensitivity to

noise reduces its reliability in measuring the thermal diffusivity which is why the transmission mode needs to be used. The methodology is similar except in this case Equation (2) was used. The optimal parameters can be determined in a similar manner to Equation (6) as shown below:

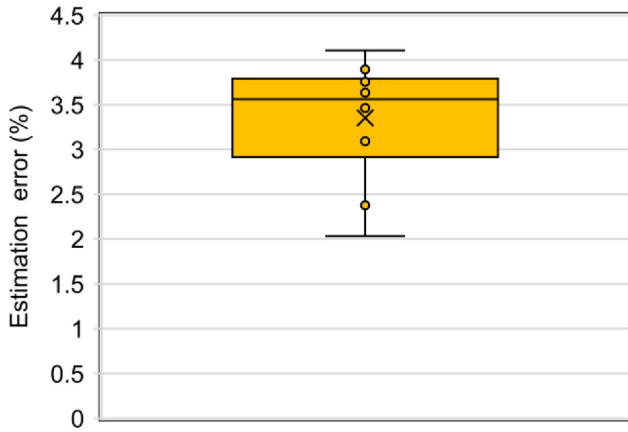


Fig. 8. Variation of the input energy estimation error in the sound and defect regions.

$$\min_{W,R,\alpha,t_g} \|\tilde{T}(t) - T(t)\| \quad (7)$$

In this case the parameter $W = \frac{Q}{\rho C}$. The 5-paramter optimisation problem has been reduced to a 4-paramter optimisation problem in the transmission mode with α included as one of the unknowns.

3. Materials and methods

Now that the fundamental theory has been covered, this section presents a detailed methodology that has been used to obtain the results. Based on previous work it has already been established that there has been a lack of transparent methodologies that can reliably provide the temporal information required to evaluate thermal material properties [21]. A follow up study addressed this gap by implementing a full factorial design of experiments to observe the effect of changing sample thickness and pulse energy on thermal material property evaluation [20]. This work builds on the conclusions presented previously by examining a sample with subsurface defects at different depths.

3.1. Design of experiments (DoE)

In single-input, single-output (SISO) systems, even black-box models allow for a clear relationship between input x and output y , enabling straightforward sensitivity analysis. However, in multi-input, single-output (MISO) systems, the presence of multiple inputs and their potential interactions complicates the analysis. To address this, a structured approach like full factorial design of experiments (DoE) is essential. This method systematically varies inputs to quantify both main and interaction effects, enabling a more comprehensive and accurate sensitivity analysis.

For the purpose of this study, three input factors are considered with three levels. The three factors are the geometric features of the defect. The three levels are the depths at which these defects are located. Table 1 shows the different factors (Defect size and shape) and the three levels (Defect depth). Note that the defect depth is measured from the side which have not been covered by plugs in the actual sample (See section 3.3.). To remove any confusion going forward in this study, the side without the plugs will be referred to as the “rear side” and the side with the plugs will be the “front side”. The sample dimensions were set to $150 \times 100 \times 8$ mm, following a previous study that used specimens of comparable size [22]. These depths were chosen to span the full range of interest, allowing for the evaluation of thermal behaviour at both shallow and deep locations within the material. This ensured that the pulsed thermography analysis captured how defects at varying depths, both near the surface and further beneath it affect the captured thermal

response.

For the defects two circles with a height of 1 mm and different diameters are chosen to observe the effect of the defect diameter on the temporal response. Earlier research [23] had indicated that the defect size had a greater influence on the temperature contrast i.e., the temperature difference between the defect and defect-free areas. However, that study did not perform physical experiments. Moreover, the type of DoE conducted was a Taguchi design and not a full factorial design. While Taguchi offered a more practical DoE protocol, it did not perform as well a full factorial design [24]. Furthermore, the study by Ali et al. also revealed that the shape of the defect influences the temperature contrast [23]. For 3 factors at 3 levels, a full factorial design will have a total of nine runs as shown in Table 2. Since all the defects are on the same sample, the temperature information from each zone can be acquired from a single data capture.

3.2. Finite element modelling

To simulate pulsed thermography on a sample with subsurface defects, the heat transfer module in COMSOL (v.6.0) was used. First a stainless steel 304 plate was created using the in-built CAD module. The dimensions of the plate were set to $150 \text{ mm} \times 100 \text{ mm} \times 8 \text{ mm}$ in-line with the manufactured sample. The motivation for choosing stainless steel was that it was the material that will be used in the experimental part of this study (See section 3.3) so that a like-to-like comparative analysis can be undertaken. All the defects were modelled as air gaps embedded within the same plate making up to a total of nine defects.

For the mesh, the geometry was partitioned so that only the defect-zones can be finely meshed. To record the temperature information for the sound area, a small region at the top of the plate ($15 \times 15 \text{ mm}$) was partitioned for the fine mesh. The rest of the geometry had a coarser mesh. The justification behind finely meshing parts of the geometry and not the whole geometry is to save computational time. For the 16 mm diameter circle and 16 mm length square defect, the area that was finely meshed was a $25 \times 25 \text{ mm}$ square and for the 8 mm diameter circle the area was $15 \times 15 \text{ mm}$ square. The reason for choosing these areas slightly greater than just the defect areas is to avoid any edge effects that might adversely affect the boundaries of the defect which has a fine mesh inside and a coarser mesh outside. For the fine mesh, the element size was gradually reduced until further refinement produced no noticeable change in the resulting temperature profile. This confirmed that the solution had reached mesh independence.

Fig. 2 illustrates the finite element model. The red regions in Fig. 2a are the defects and the green regions are the ones where the surface temporal information has been extracted from (both front and back walls). Fig. 2b shows the meshed geometry showcasing the regions of fine and coarse mesh.

While there have been previous finite element models that have simulated pulsed thermography [25,26], they have focused only on the reflection mode. Moreover, they do not delve into the details of how the simulation is setup which makes it slightly challenging to recreate the model. For this reason, Table 3 inspired by Vora et al. [27], has been created to provide more transparency for the FEM. Lastly for the time step, it was set to 0.02s to mimic the frame rate of the IR camera.

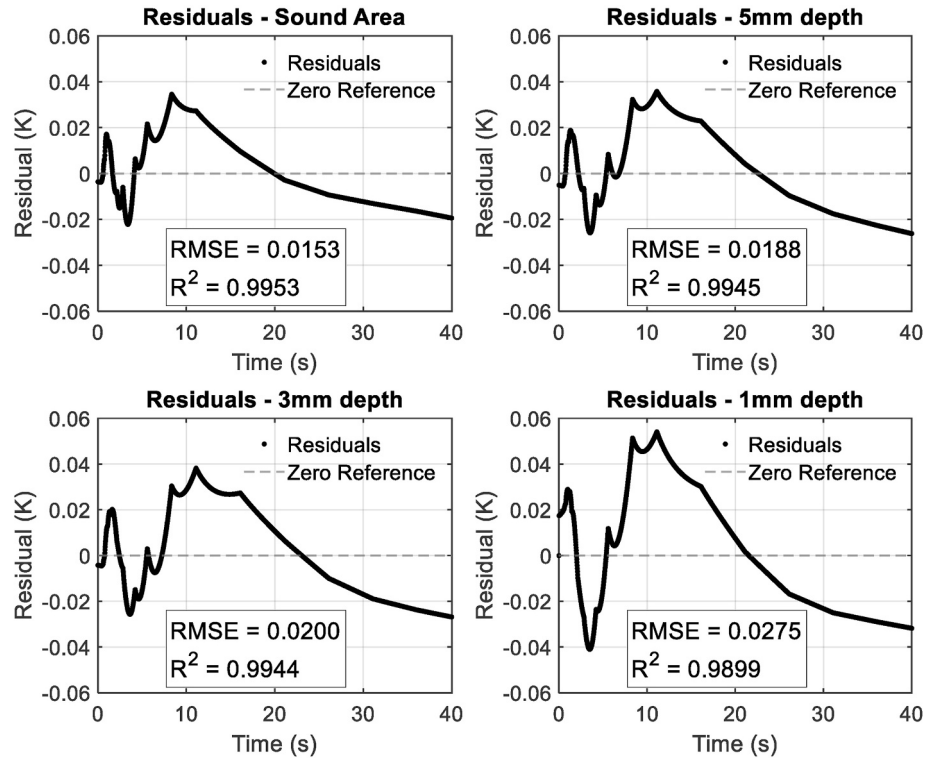
3.3. Experimental work

For the laboratory experiments, a control sample made from steel and a carbon composite laminate both with defects were identified, their specifications are summarised in the sub-section below.

3.3.1. Steel samples with subsurface airgap defects

For the physical experiments, first a 3D CAD model of the stainless steel 304 sample was developed. A substrate with holes would need to be machined. These holes will be plugged in by metallic plugs of the same material. The depth of the plugs has been designed such that they would

(a)



(b)

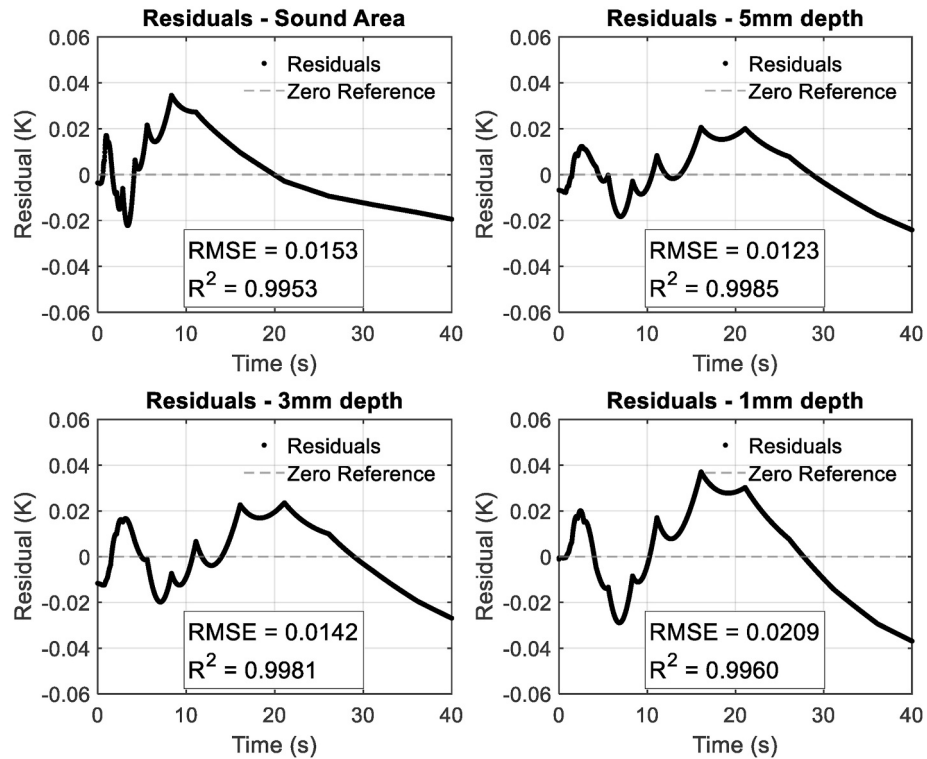


Fig. 9. Residual plots for the sound and defect regions in the FEM a) 8 mm circle defect b) 16 mm circle defect and c) 16 mm square defect. The horizontal dashed grey line represents the zero reference.

completely enclose the holes in the substrate leaving a 1 mm (± 0.01 mm) air gap at different depths for the various defects machined in the substrate regardless of their lateral size. Fig. 3 shows the CAD model of

the substrate and the plugs that were used to plug the holes in the substrate. The fabrication process for the steel substrate and plugs was carried out in Langstone Engineering Ltd, which is a company based in

(c)

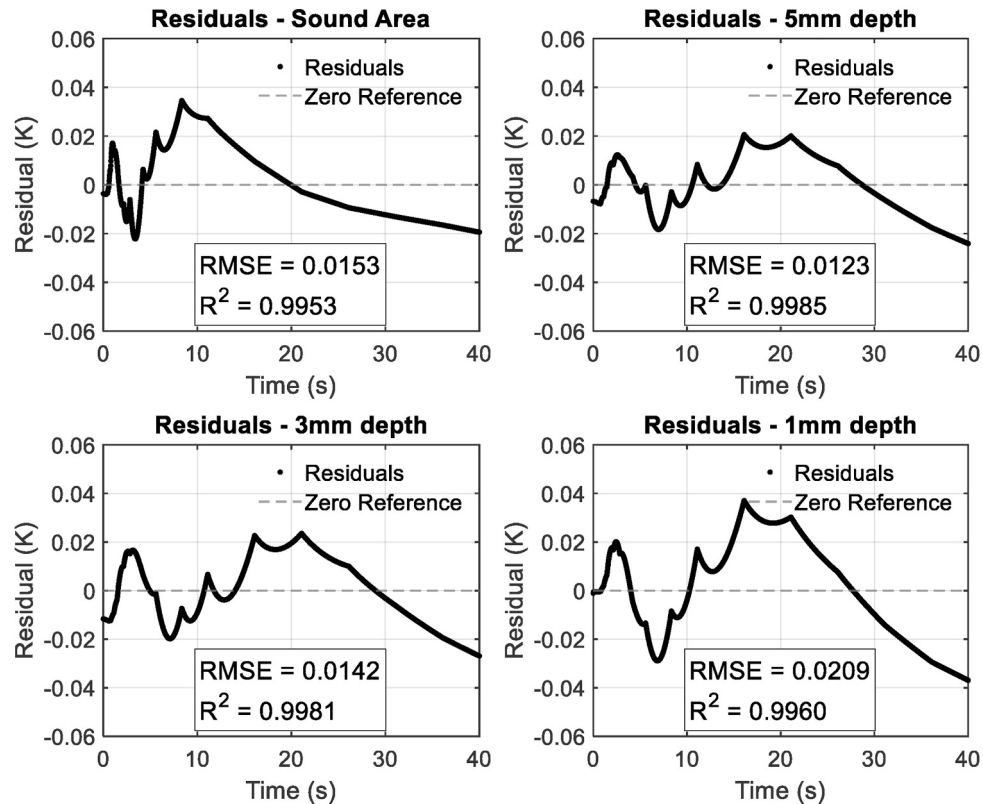


Fig. 9. (continued).

Portsmouth, United Kingdom. The dimensions for the substrate and the plugs were manufactured with tolerances specified by ISO 286 standards [28]. It is important to note that all the dimensions used for the CAD model match the ones used in the FEM so that a like-to-like analysis can be performed. The actual machined samples can be seen in Fig. 4.

3.3.2. CFRP samples with impact damage

For the CFRP samples four 750 mm × 750 mm × 3 mm plates were hand-laid and cured. These plates were then cut into 150 mm × 100 mm × 3 mm smaller samples bringing the total number of samples to 140, 35 samples from each plate. Impact testing with predetermined energy levels was performed on all the samples. Although the samples were impacted at 4, 6, 8, 10, and 12 J, only a small sub-set of the 4J, 8J, and 12J energy levels were selected for detailed analysis in this study. This selection was made to ensure a clear and representative distribution across the full range of impact energies exist and can serve as a verification of the developed through-transmission method. It is important to mention that these samples were made for a previous study [29] which had different objectives in terms of knowledge offering. Nine samples were randomly selected from the full set, comprising three samples for each energy level as repeats. The inclusion of repeats enables assessment of the variability inherent in the manufacturing process of CFRP plates. Although all samples were fabricated under the same standards, slight differences between them are expected. By repeating measurements across multiple samples at each energy level, the analysis can better distinguish true effects of the energy level from random variation, reducing the influence of confounding factors and increasing the robustness of the results. Table 4 shows the various samples impacted at different energy levels. The sample ID shows the impact energy (J), plate number (P#) and sample number (S#).

The surface subjected to the impact test was designated as the front side, and both the front and back surfaces were monitored by the IR

camera in the reflection and transmission configurations as done previously by Maierhofer et al. [4]. Therefore, the configurations going forward in analysis will be the same as the ones used in Ref. [4] i.e., Reflection Front (RF), Reflection Back (RB), Transmission Front (TF), and transmission back (TB). The CFRP samples with different impact damage can be viewed in Fig. 5. It was mentioned in a previous study [20] that the peak spectral emission can cause discrepancies in the estimated values for thermal diffusivity. To test this, the entire set of experiments were repeated using a FLIR a655sc longwave camera. A 5x5 pixel circle was created for both the sound and defect areas to capture the temperature information.

3.3.3. Pulsed thermography system

For the pulsed thermography inspection system, the IR camera used is the SC7600, a mid-wave camera with an indium antimonide (InSb) cooled detector that has a spectral range of $\approx 1.5\text{--}5.1\ \mu\text{m}$. For the synchronisation system, an IRT controller from Visioimage Inc (which is a company based in Quebec, Canada) is used that allows for syncing the flash lamps (also acquired from Visioimage). The flash lamps can provide variable levels of energies. The pulse duration is dependent on the energy level required and according to the manufacturer it offers 1/175s at 4.8 kJ, 1/300s at 2.4 kJ, 1/500s at 1.2 kJ, 1/900s at 0.6 kJ, and 1/1425s at 0.3 kJ. For this study the energy delivered from each lamp was set to 4.8 kJ giving a combined energy of 9.6 kJ for two lamps. The data acquisition was through the FLIR Research Studio software. The camera was triggered externally together with the flash using a MATLAB code that sent a signal to the IRT controller via a telnet server.

The temperature curves in the experiments were obtained from the side of the sample that did not contain plugs (the rear side); in other words, the sides with plugs (the front side) never faced the IR camera. In the reflection mode experiments, the rear side was exposed to flash heating, while in the transmission mode, the front side was exposed to

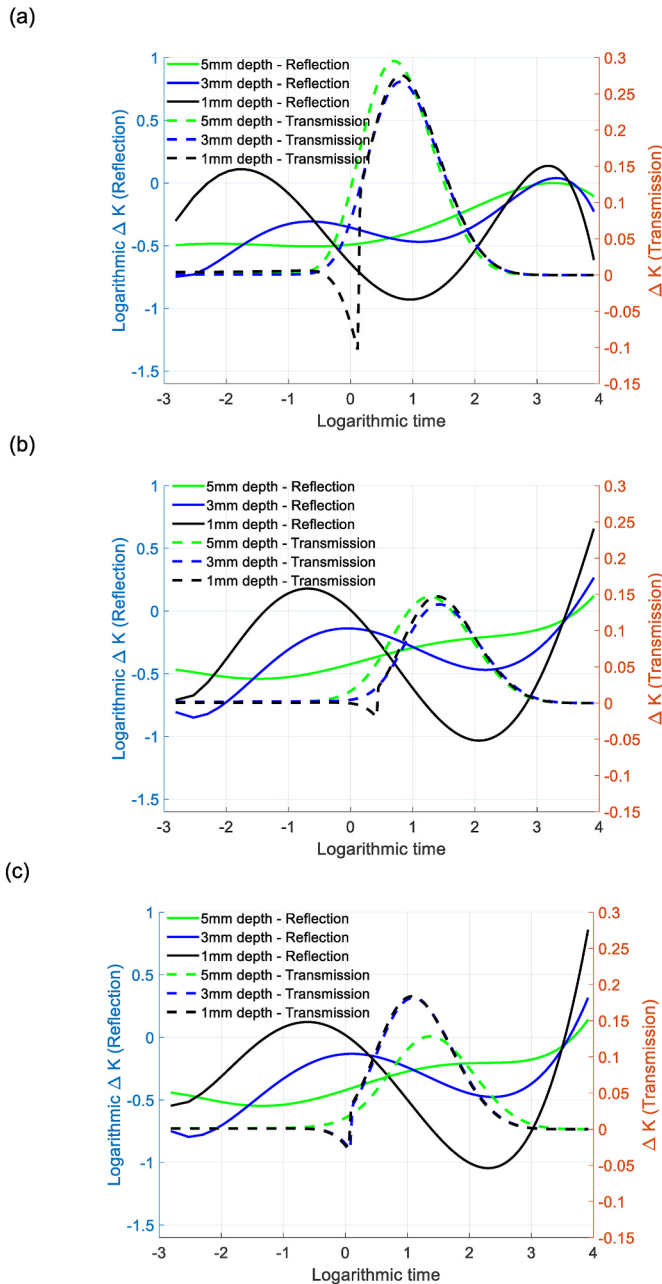


Fig. 10. Double axis plots for the first derivative of both the reflection and transmission modes. a) 8 mm circle defect b) 16 mm circle defect and c) 16 mm square defect. (Excitation energy is 500J).

the flash and the temperature was recorded from the rear. Similarly, in the simulations, transmission mode temperature data were obtained by thermally exciting the front side, whereas for reflection mode, the rear side was thermally excited. Fig. 6 shows the experimental configurations of the reflection and transmission modes. The black sheets were added in the setup to ensure that the flash does not reach the IR camera in the through-transmission configuration.

3.4. New method for depth quantification in the transmission mode

The current understanding in through-transmission pulsed thermography is that the depth quantification is a challenge since the distance travelled by the thermal wave in the defect and defect free regions is the same [1]. Additionally, exclusive analysis of the temperature contrast curves, as done in Ref. [23], shows that they are influenced by

depth. Yet the sensitivity to variations in lateral size is much higher, making these changes easier to distinguish, whereas depth variations are more subtle and therefore more difficult to quantify. Moreover, as it will be shown in Sections 4.1 and 4.2, effective thermal diffusivity measurements in the defect regions show no clear correlation with defect depth either. However, the thermal property that has been overlooked in depth quantification is the Fourier number, a dimensionless quantity representing a ratio of a material's diffusive rate over its quantity storage rate, calculated using the following equation:

$$Fo = \frac{\alpha t}{L^2} \quad (8)$$

where α is the material thermal diffusivity (m^2/s), t is the time in seconds and L is the characteristic length. Existing studies show limited work exploring the variation of the Fourier number with changing defect size and depth [13].

Fig. 7 shows the step-by-step procedure on how defect depth is estimated using the Fourier number.

For the purpose of this study, the L was chosen to be the lateral defect length for the square defect and diameter for the circular defects. The justification behind choosing the lateral length can be seen from Table 5 where it is observed that the lateral defect size has a greater influence on the effective thermal diffusivity than the defect depth. However, it will be made apparent in the subsequent subsections that the sensitivity to defect depth is realised through the terms in the numerator of Equation (8) i.e., the product of the effective thermal diffusivity α and the half-rise time t which gives us a relationship between the Fourier number and defect depth (L is just a constant that only affects the magnitude of the Fourier number and not its trend with defect depth). The justification for using the half-rise time is based on Equation (4) where it is established that the half-rise time is vital in determining the thermal diffusivity of the material.

3.5. Measurement uncertainty

The experimental setup, instrumentation, calibration procedures, and data acquisition protocol employed in this study are identical to those used in the authors' previous work on through-transmission pulsed thermography, where a detailed uncertainty analysis was conducted for all primary and derived quantities [20]. In that study, measurement uncertainties arising from sample thickness, flash energy, emissivity, temporal resolution, and signal fitting were quantified and propagated to the estimated thermal diffusivity using established error-propagation principles. Since the present experiments use the same hardware, operating conditions, and signal-processing workflow, the uncertainty levels observed here are expected to be comparable.

4. Results and discussion

With the methods and materials clearly outlined, this section discusses the results obtained from the proposed methodology. First, the results from the finite element model (FEM) are presented, followed by those obtained from the laboratory experiments. A comparative analysis between the numerical and experimental results is then conducted, and finally the capability of the proposed method for assessing impact damage in CFRP samples is discussed.

4.1. Results from the finite element model

Table 5 shows the estimated thermal diffusivity by the NLSF algorithm using the backwall temperature curves and Table 6 shows the estimated input energy.

Based on theoretical calculations using the material's thermal conductivity, specific heat capacity, and density (Table 3), the thermal diffusivity was determined to be $4.09 \text{ mm}^2/\text{s}$. Although this value is

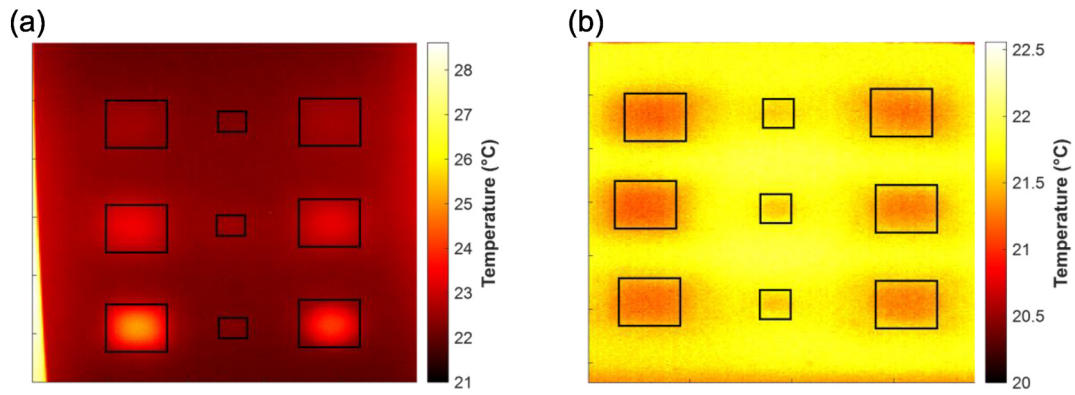


Fig. 11. Raw thermographs for the steel sample with subsurface defects in a) reflection mode (image taken 4 s or 200 frames after flash) and b) transmission mode (Image taken 9 s or 450 frames after flash).

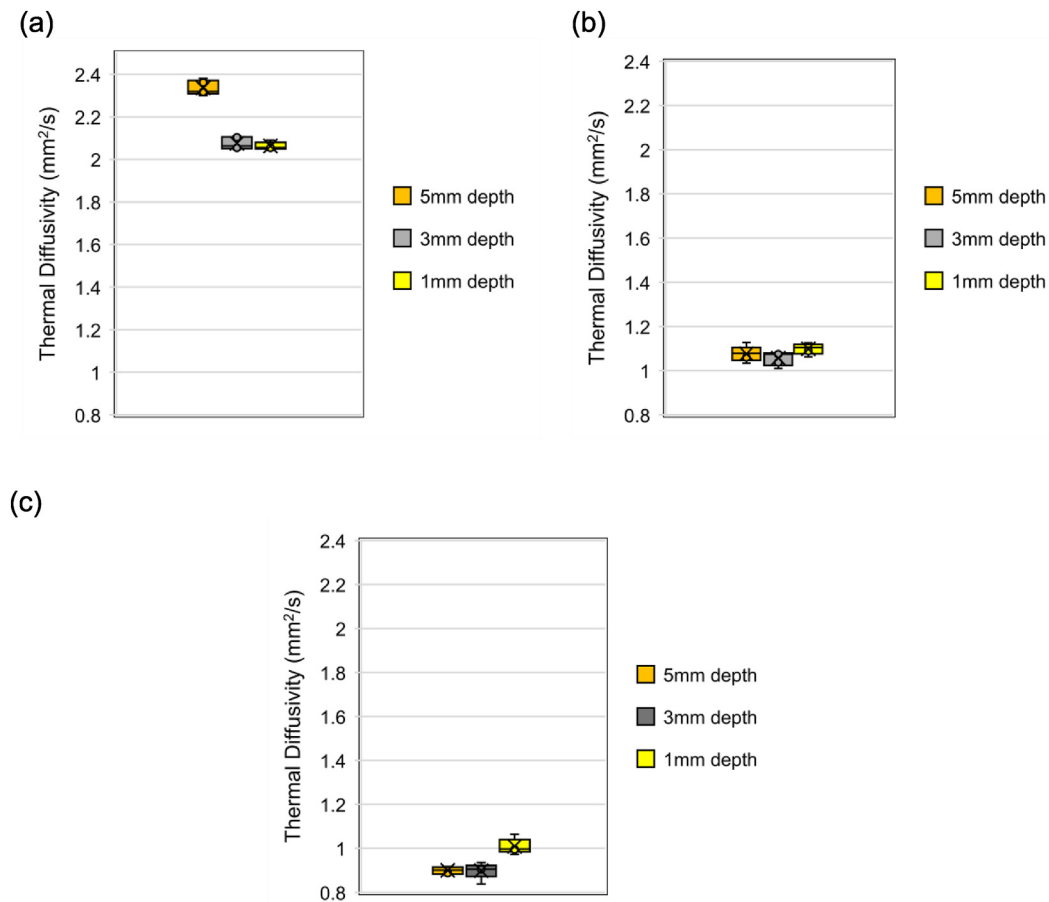


Fig. 12. Effective thermal diffusivity plots for defects at different depths a) 8 mm circle b) 16 mm circle c) 16 mm square.

lower than that of air ($\approx 22 \text{ mm}^2/\text{s}$), the much higher thermal conductivity of the material ($16.2 \text{ W/m}\cdot\text{K}$ compared to $\approx 0.026 \text{ W/m}\cdot\text{K}$ for air) dominates the heat transfer behaviour, resulting in a lower effective thermal diffusivity within the defect region. Consequently, the greater the contrast in thermal properties between the sound material and the air gap or defect, the higher the achievable resolution in thermographic defect detection. The estimated thermal diffusivity in the defect regions is therefore lower, as heat diffusion through the material thickness is reduced due to increased thermal contact resistance and lateral heat spreading around the defects. The term ‘effective’ is used here as it better represents the diffusivity of the defect regions. [4]. For the sound region, the estimated thermal diffusivity is the materials thermal

diffusivity. Comparing this value to the one obtained of the NLSF algorithm results in a 4.2 % error. This error can mainly be attributed to the low flash excitation energy and the 0.02s time step for the simulation. Previous work demonstrates that the using a higher excitation energy level and a smaller time step of 0.01s for the simulations yielded errors as low as 0.34 % [20]. However, the purpose here was to demonstrate the similarity between the FEM and laboratory experiments which is why a 0.02s time step was chosen to match the frame rate of IR camera that was used to acquire the experimental data. For the estimated energy levels shown in Table 6, the input flash energy in the simulation was 500J (to match the energy in the laboratory experiments) resulting in a maximum error of 4.1 % and a minimum error of 2.03 %. Fig. 8 captures

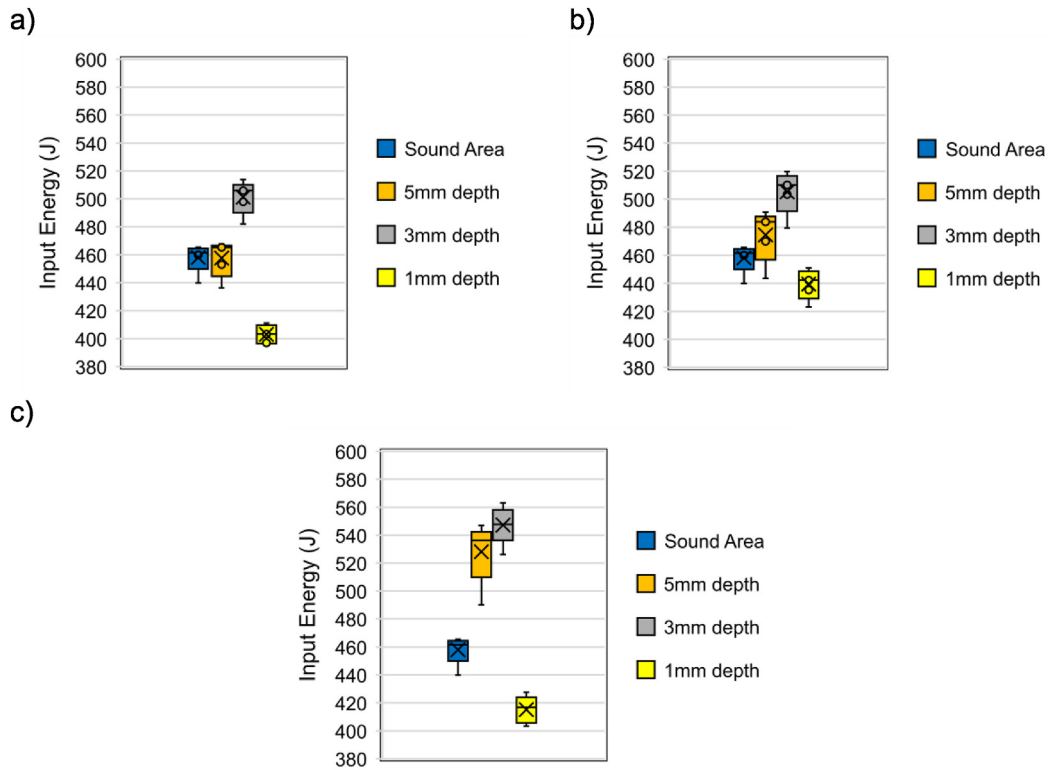


Fig. 13. Plots showing the heating variation between the sound and different defect regions a) 8 mm circle defect b) 16 mm circle defect and c) 16 mm square defect.

this error variation in the different regions (sound and defect areas)

It is important to note that in the transmission mode the front side of the sample was thermally excited (the side with the plugs in the experimental runs). If the depth is measured from the front side of the sample this depth is 6 mm. It shows that as the defect gets closer to the backwall the effective thermal diffusivity is higher than when the defect is in the middle of the sample i.e., the 3 mm defect. An interesting observation is that the results are consistent regardless of defect geometry. This phenomenon is something that has not been explored in literature and requires further investigation. A plausible explanation will need to consider lateral heat diffusion converting the one-dimensional heat transfer problem into a three-dimensional one.

To demonstrate how well NLSF algorithm captures the backwall temperature evolution, a combination of quantitative and visual assessment methods is employed. Metrics such as the root mean square error (RMSE) and the coefficient of determination (R^2) provide numerical summaries of the fitting accuracy, reflecting the overall discrepancy and the proportion of variance explained by the model. However, these metrics alone may not reveal underlying patterns or systematic deviations. Therefore, residual plots are used in conjunction with RMSE and R^2 to provide a more comprehensive evaluation. By visualising the differences between the measured data and model predictions over time, residual plots help identify trends, non-random structures, or outliers that could indicate model limitations. A good fit is typically characterised by residuals that are randomly scattered around zero with no discernible structure, reinforcing confidence in the suitability of the NLSF approach for modelling thermal response behaviour. This analysis is shown in Fig. 9 where the residual plots along with their corresponding RMSE and R^2 values are displayed. The fitted curves are in close agreement with the FEM generated backwall temperature curves as indicated by the R^2 value that exceeds 0.99 in each case and the low RMSE value which does exceed 0.0275 for all cases.

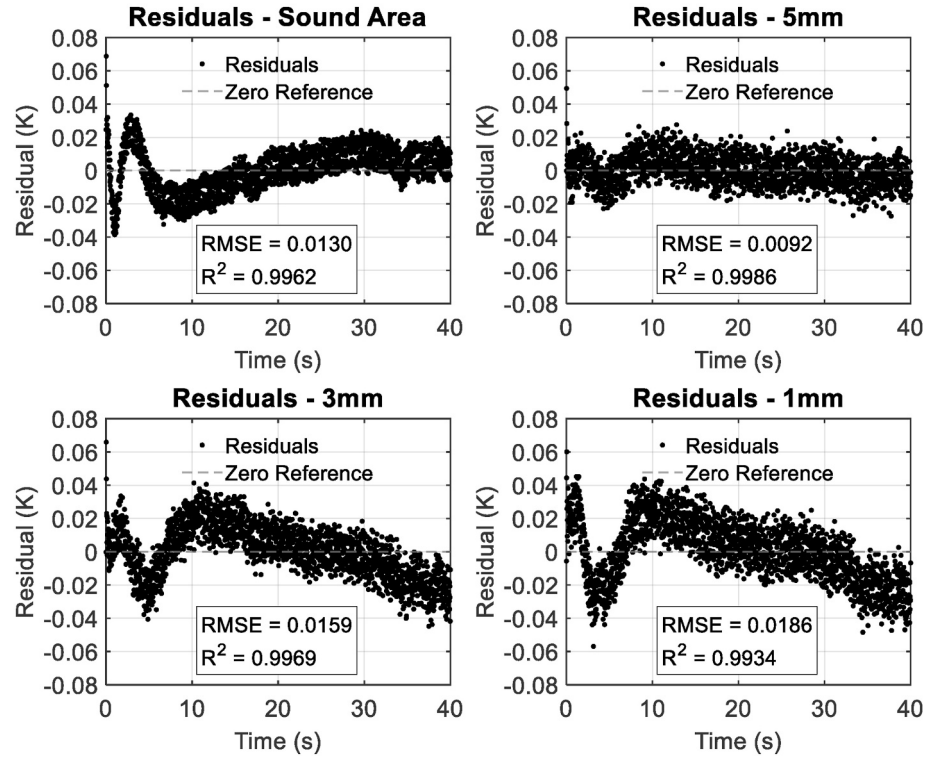
In terms of the plots, the residuals exhibit minimal drift from the zero reference (represented by the horizontal dashed grey lines in Fig. 9) and do not indicate any specific pattern i.e., the distribution is mostly

random. The residuals do exhibit some random oscillatory motion during the initial heating phase (0–10s) which could be due to some of the assumptions in the FEM model such as the interaction between the boundaries of solid material and the fluid airgap which does not completely align with the theoretical equation used for the fitting (Equation (2) assumes that the plate is semi-infinite and defect free), the meshing parameters used, and the time step used for the simulations. During the saturation phase (time ≥ 10 s for the sound area and ≥ 20 s for the defect areas) the theoretical equation slightly overshoots the actual temperature behaviour of the sample hence the decreasing values of the residuals towards the later stage of the simulated values. This is because the simulation exhibits a slight decrease in the backwall temperature profile indicating a gradual cooldown of the sample, something which Equation (2) cannot capture.

4.1.1. Dual mode analysis for the FEM

Most of the studies in existing literature either focus solely on the reflection mode or the transmission. Even the studies that explore both modes such as [4] conduct the data analysis of each mode separately. Developing a methodology that combines both the reflection and transmission curves is something that has not been attempted so far. While several reasons can exist explaining this, the most plausible reason could be the lack of calibration samples with fully enclosed defects at known depths. Current methods involve either using flat-bottom hole samples for the reflection mode [30] or adding inserts representing fully enclosed defects [9]. However, until now, no sample has been designed that contains fully enclosed air defects. Since this study addresses this critical challenge, a comparative analysis can now take place. First, the temperature curves of both the reflection and transmission modes need to be processed. For the reflection mode a polynomial fitting of order 6 is applied to obtain a smooth curve whereas the transmission mode temperature curves use the NLSF algorithm to apply the curve fitting. Next the first derivative plots are generated. For the reflection mode the data is plotted in the logarithmic domain for both the time and temperature and for the transmission mode only the time is

(a)



(b)

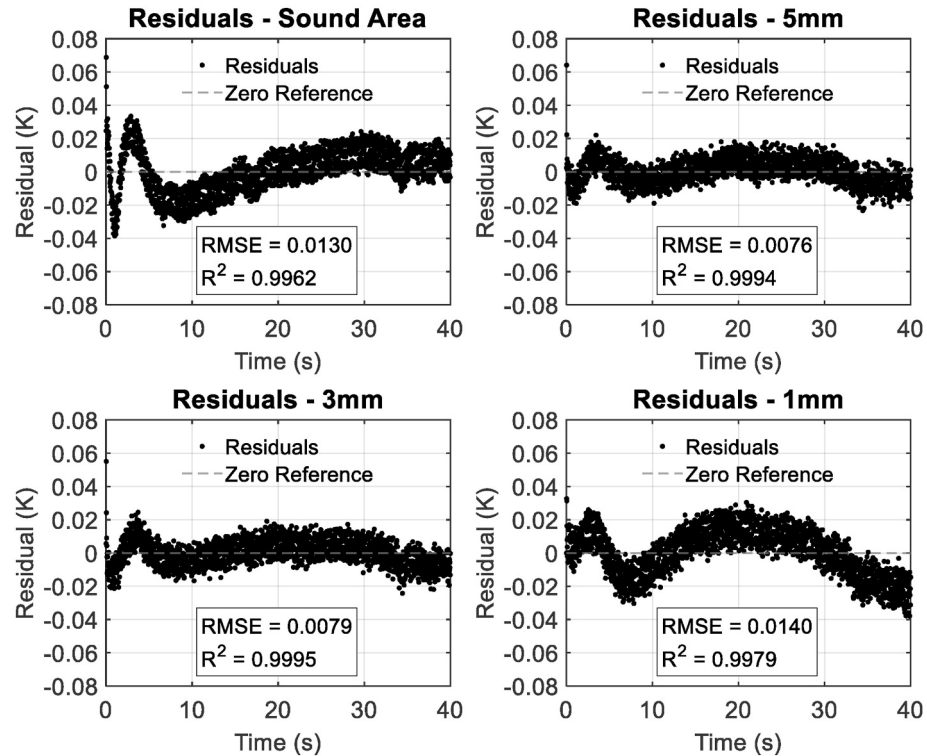


Fig. 14. Residual plots for the sound and defect regions in the FEM a) 8 mm circle defect b) 16 mm circle defect and c) 16 mm square defect. The horizontal dashed grey line represents the zero reference.

in the logarithmic domain. This is done to plot both the curves in a double y-axis plot so that a comparative analysis can be conducted. Fig. 10 shows the first derivative curves for both the reflection and

transmission modes.

For the transmission mode the first derivative peaks occur at relatively similar times. This can explain why defect depths are difficult to

(c)

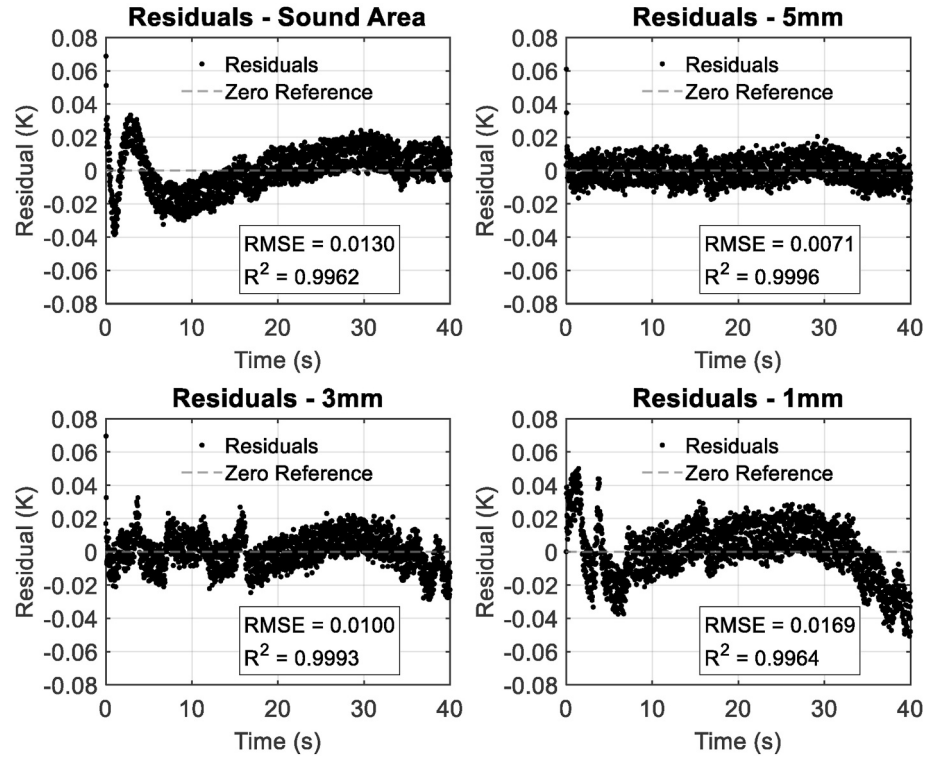


Fig. 14. (continued).

discriminate in the mode. Moreover, as indicated Table 5, by observing the effective thermal diffusivity values, the peak of the first derivative in transmission mode is higher for defects located closer to the back wall.

This indicates that the temperature rise at the backwall occurs at a faster rate in the region where the defect is closer to the backwall. On the other hand, the reflection mode clearly shows distinguishable peaks as the depth changes, with the exception of the 5 mm depth, where the peak is very faint, indicating a depth detection limit for the reflection mode. Analysing both curves individually reveal different limitations. However, observing both peaks that occur in the reflection mode and transmission mode simultaneously reveals an interesting insight. As the defect goes deeper into the substrate the first derivative peak of the reflection mode moves closer to its counterpart in the transmission mode. The peaks in question here are the first ones that occurs for the reflection mode. As the defect depth moves beyond the detection limits of the reflection mode, the transmission mode is still able to detect it. This means, for achieving a better estimate of the defect location within the sample it would be better to conduct a dual-mode inspection and observe the temporal behaviour of both the reflection and transmission modes.

4.2. Results from the laboratory experiments for the steel sample and comparison with FEM

Fig. 11 presents the raw thermograms acquired in both reflection (4 s or 200 frames after flash) and transmission modes (9 s or 450 frames after flash) for the steel specimen, which were utilised for temperature data extraction. Defect locations are indicated by black rectangles. A visual comparison of both thermograms reveals that the transmission mode successfully captures all defect features, irrespective of size or depth without the need of any visual enhancement algorithms. In contrast, the reflection mode exhibits limited sensitivity, with defects at 5 mm depth barely noticeable, and those with an 8 mm diameter also exhibiting low detectability. Although image processing techniques such

as TSR and Pulsed Phase Thermography (PPT) could enhance the spatial resolution and facilitate the detection of smaller and deeper defects especially in reflection mode, their application falls outside the scope of this study. Since the objective was to evaluate the effective thermal diffusivity, the raw thermograms were deemed sufficient due to the adequate temporal information they provided.

For the laboratory experiments a total of five repeats was undertaken for both the reflection and transmission modes to ensure repeatability of the results. This analysis was not performed for the FEM as every run would result in the same values. Fig. 12 shows the effective thermal diffusivity plots for all the defects at different depths. The thermal diffusivity of the sound area was not included in these plots as it is much higher therefore making it difficult to see the variation of the effective thermal diffusivities in the defective regions. The temperature information was extracted in a manner similar to the FEM, where the ROI size was set to half the defect area (circular ROIs for circular defects and square ROIs for the square defect), positioned at the defect centre. In terms of pixels, using the conversion factor of 1 pixel = 0.4 mm at a standoff distance of 300 mm, the ROI for the square defect was defined as a 20×20 pixel square (corresponding to an 8×8 mm area). For the 16 mm diameter circular defect, an ROI of 20 pixels (8 mm) in diameter was used, while for the 8 mm diameter circular defect, the ROI was a 10-pixel (4 mm) diameter circle. Based on five repeated measurements, the experimental repeatability (Type A uncertainty) was quantified using the standard deviation, yielding thermal diffusivity values of $3.96 \pm 0.047 \text{ mm}^2/\text{s}$ for the sound region and $2.34 \pm 0.034 \text{ mm}^2/\text{s}$, $2.08 \pm 0.029 \text{ mm}^2/\text{s}$, and $2.06 \pm 0.018 \text{ mm}^2/\text{s}$ for defect depths of 5 mm, 3 mm, and 1 mm, respectively. The corresponding coefficients of variation (CV) were low, ranging from approximately 0.9 %–1.4 %, indicating good experimental repeatability. The graphs follow a similar pattern to what was observed in the FEM in terms of the effective thermal diffusivity being slightly higher when the defect was closer to the backwall. The variation in the values can be attributed to the sample not being perfectly homogeneous and the usage of plugs that might have

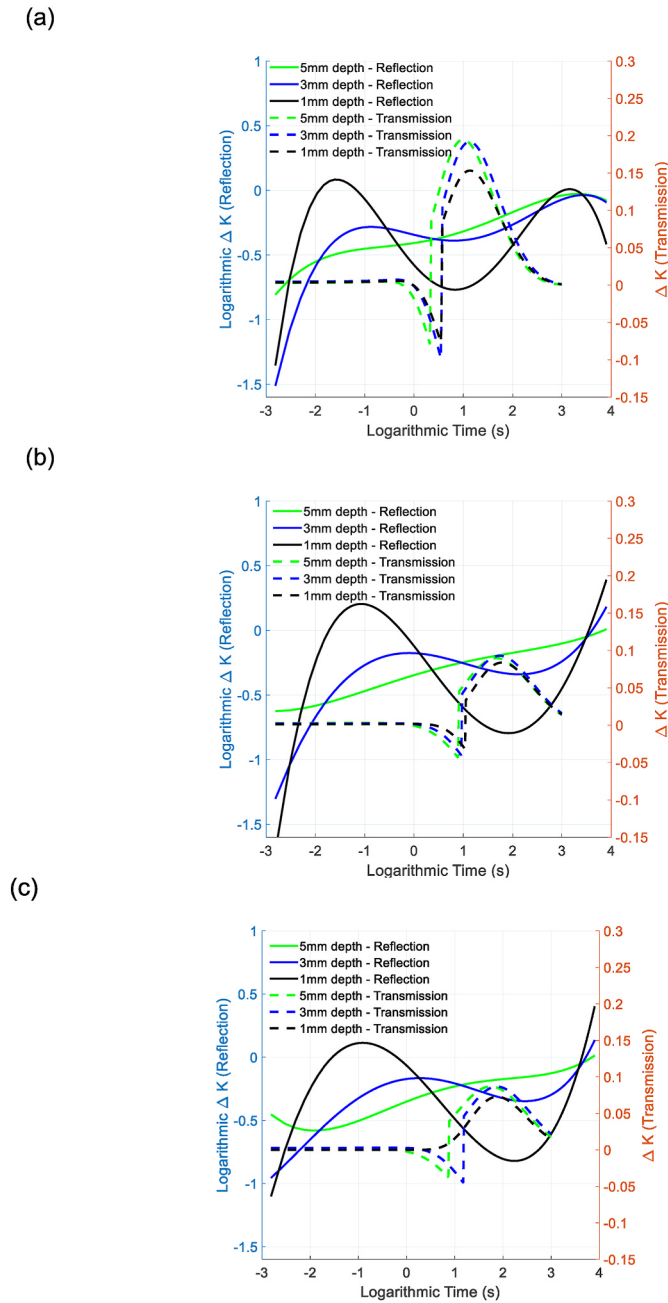


Fig. 15. Double axis plots for the first derivative of both the reflection and transmission modes obtained from laboratory experiments. a) 8 mm circle defect b) 16 mm circle defect and c) 16 mm square defect.

interfered slightly with the heat diffusion through the thickness of the materials.

Another potential source of variation in the results between the FEM and laboratory experiments can be attributed to the uneven heating of the surface. As seen in Fig. 6, open flash lamps were used. While a lot of effort was taken to minimise this effect by manipulating the position of the sample with respect to the flash lamps and IR camera, Fig. 13 shows the heating variation in the different regions. The sound area exhibits consistent energy input across repeated measurements, with an average heating energy of 458.1 ± 10.4 J. For the 8 mm circular defect, the applied heating energy was 457.7 ± 13.3 J, 501.2 ± 12.1 J, and 403.2 ± 6.7 J for defect depths of 5 mm, 3 mm, and 1 mm, respectively. For the 16 mm circular defect, the corresponding heating energies were 474.5 ± 19.0 J, 505.3 ± 15.6 J, and 439.5 ± 10.9 J. Similarly, for the 16 mm

square defect, average heating energies of 528.2 ± 22.2 J, 547.3 ± 13.5 J, and 415.2 ± 9.7 J were recorded for depths of 5 mm, 3 mm, and 1 mm, respectively. Across all regions, defect sizes, and depths, the applied heating energy exhibited low variability, with CV values in the range of approximately 1.7–4.2 %. Overall, the relatively low coefficients of variation indicate good repeatability of the applied thermal excitation and suggest that variations in heating energy are unlikely to significantly influence the observed thermal response or derived parameters. To obtain a like-to-like comparison with the FEM, the regions from which the temperature information was extracted was kept the same in the experiments. At a camera standoff distance of 300 mm, 1 pixel corresponds to approximately 0.4 mm. Using this conversion factor the regions of interest were created for the sound and defect areas. It can be seen that the maximum heat energy was concentrated around the 3 mm deep defects, which were positioned at the midpoint along the vertical axis of the 150 mm high sample. Moreover, it was observed that the minimum heat input occurred in regions where the 1 mm defects were located i.e., at the bottom of the sample. In addition to uneven heating caused by the flash lamps, the reduced energy input at the bottom may also be attributed to the way the sample was secured. A 3D-printed sample holder was used to support the sample, and a metallic screw was employed to fasten it in place to prevent movement. The contact between the sample, the holder, and the screw likely facilitated lateral heat conduction away from the sample, contributing to the lower energy input in that region. Nevertheless, the close agreement with FEM results highlights its accuracy and demonstrates its potential as a reliable alternative for evaluating material behaviour in cases where defects cannot be readily created experimentally.

Fig. 14 shows the residual plots similar to the ones generated for the FEM. Similar to the FEM results, an initial oscillatory behaviour is observed during the heating phase, which Equation (2) does not capture accurately. However, once the temperature profile at the back wall begins to stabilise, the residuals become centred around zero, indicating a bias-free fit.

Regarding the closeness of fit to the experimental data, all R^2 values once again exceed 0.99, with some plots reaching as high as 0.9994. The RMSE values are also consistently low, with the highest recorded value being 0.0186, suggesting that the NLSF captures the underlying thermal behaviour with a high degree of accuracy. Compared to the FEM results, which yield a single smooth profile, the experimental data exhibit greater dispersion due to higher noise levels. Despite this, the NLSF demonstrates strong robustness, successfully providing accurate fits even in the presence of such variability.

4.2.1. Dual-mode analysis for the laboratory experiments

Finally, similar to Figs. 10 and 15 presents the first derivative plots from the laboratory experiments. These graphs were generated by averaging temperature values across five runs in both reflection and transmission modes. Analysis of the first derivative curves reveals trends consistent with those observed in the FEM results.

Firstly, as with the FEM, the 5 mm depth defects do not produce distinguishable peaks in the reflection mode but do so in the transmission mode. Secondly, as the defect depth increases, the first derivative peaks in reflection mode shift closer to their transmission mode counterparts. A third observation, which also aligns with the FEM, is the sharp drop preceding the transmission mode peaks. This drop is attributed to limitations in the NLSF fitting algorithm, which struggles to accurately model the back wall's thermal response during the initial seconds following the flash event (also indicated by the residual plots in Fig. 14). As for differences, the timing and magnitude of the peaks differ, likely due to uneven heating and the sample's inherent non-uniform material properties, as well as external variations due to the use of plugs. A comprehensive breakdown discussing the variation between the FEM and experiments can be found in a previous work by the authors [20]. However, once again, the similarity between Figs. 10 and 15 further strengthens the FEM's capability to accurately model the

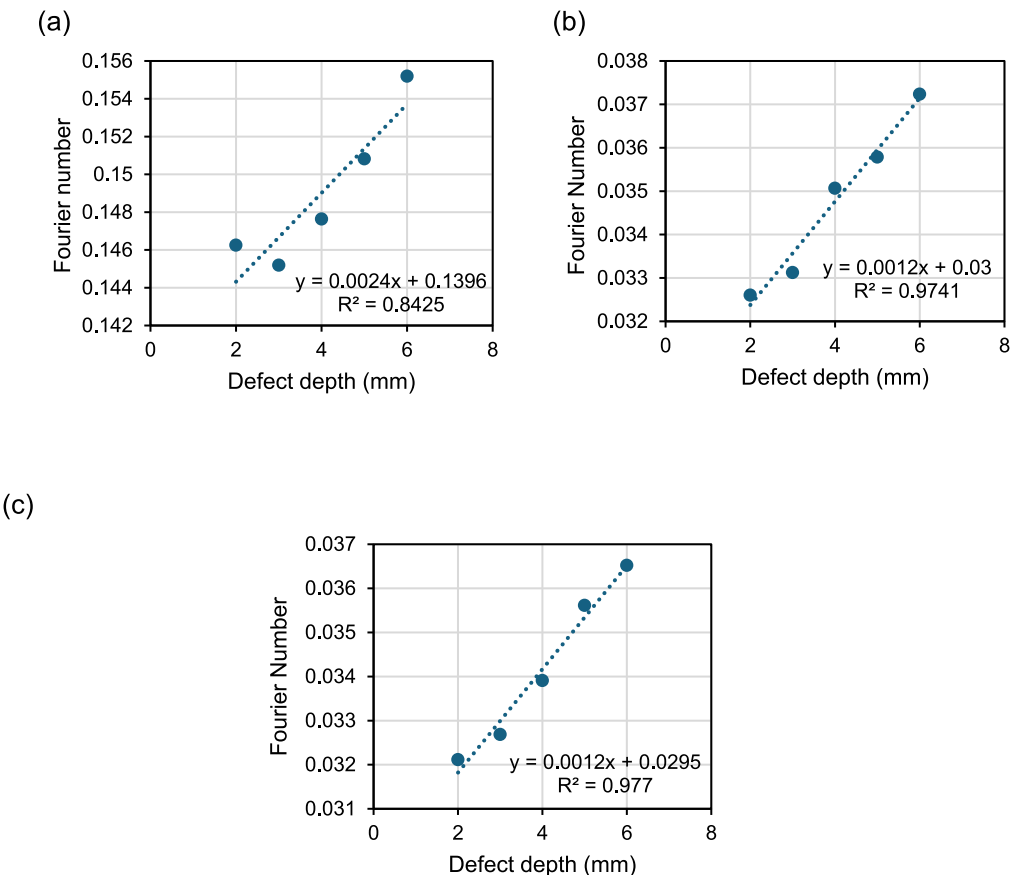


Fig. 16. Defect depths with their corresponding Fourier number for a) 8 mm circle b) 16 mm circle and c) 16 mm square defects.

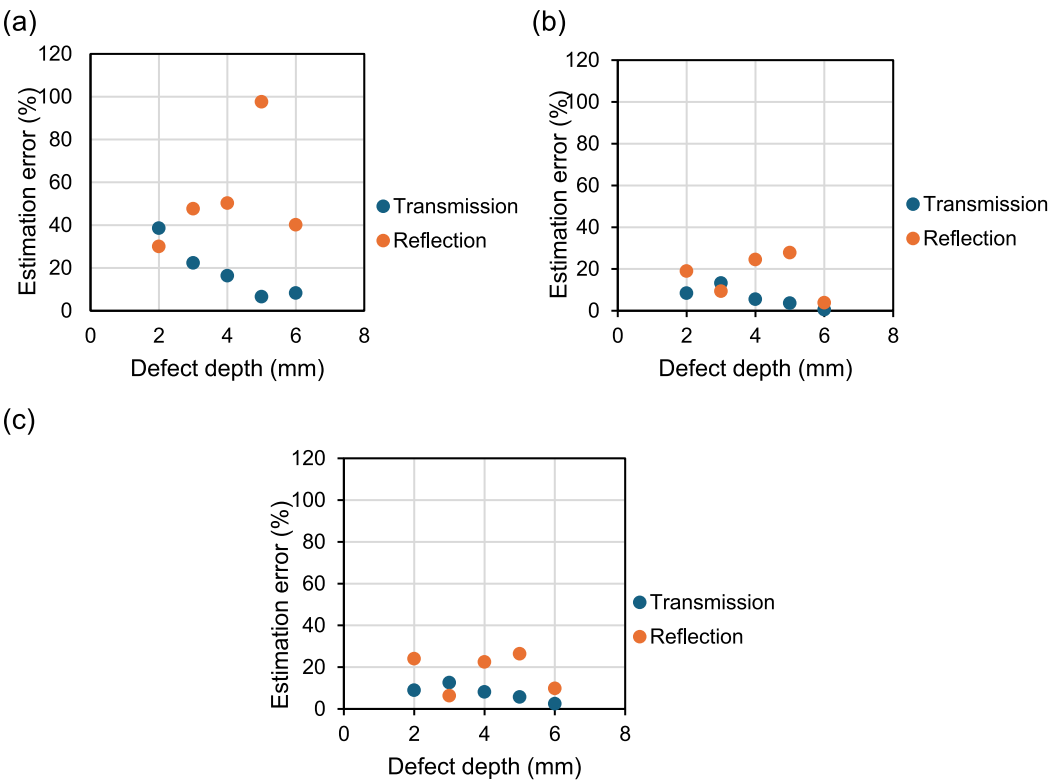


Fig. 17. Defect depth estimation error using the reflection and transmission modes for a) 8 mm circle b) 16 mm circle and c) 16 mm square.

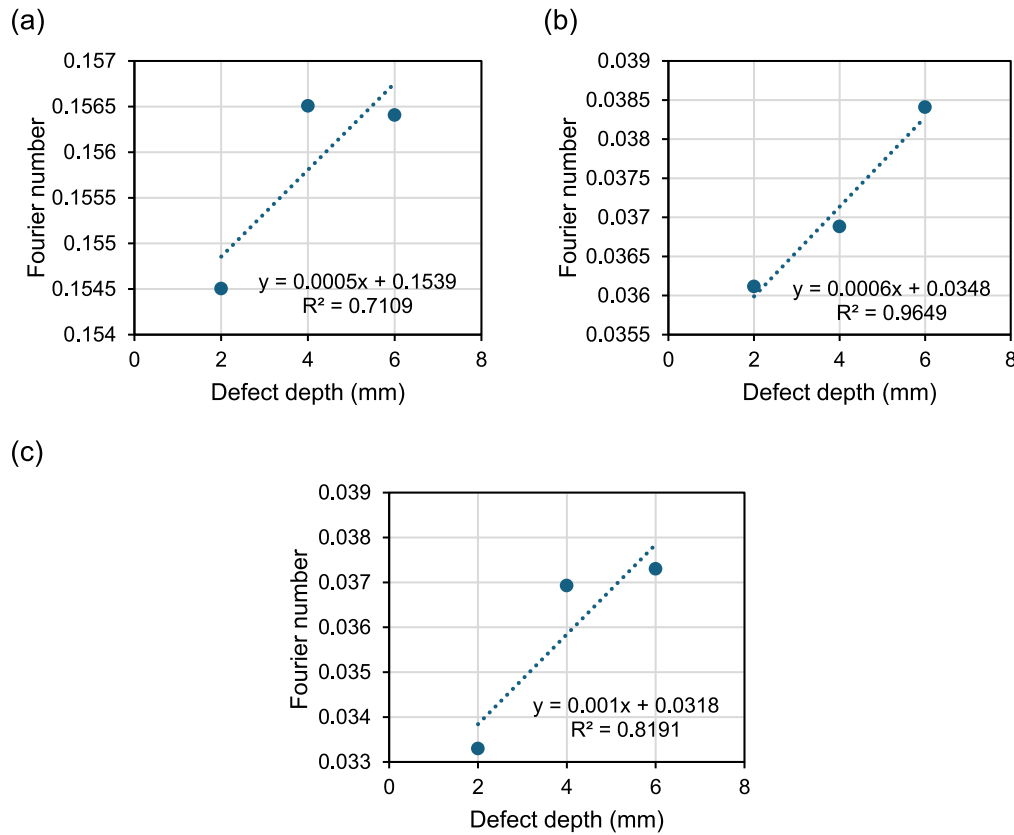


Fig. 18. Defect depths with their corresponding Fourier number for a) 8 mm circle b) 16 mm circle and c) 16 mm square defects for the laboratory experiments.

temperature behaviour of a defected sample subjected to flash heating.

4.3. Depth estimation

4.3.1. FEM

With the closeness of the FEM and laboratory experiments established in Section 4.2, the procedure outlined in Fig. 7 was first applied to the FEM model. Additionally, the convention used to indicate the depth of the defect was modified. Previously, depth was measured from the rear side of the specimen due to plugs on the front side of the physical sample hindering reflection mode measurements. Now, all depth measurements are taken from the front side of the sample i.e., the side exposed to flash heating during through-transmission measurements. As a result, depths of 1 mm, 3 mm, and 5 mm (previously measured from the rear side) now correspond to 6 mm, 4 mm, and 2 mm respectively, when measured from the front surface. Furthermore, the simulation was repeated with the 2 mm and 4 mm depths adjusted to 3 mm and 5 mm, respectively, to obtain additional data points and develop a more comprehensive understanding of the relationship between defect depth and the Fourier number. Fig. 16 shows the defect depths and their corresponding Fourier numbers calculated using Equation (8) for all the three different defect types.

Each defect type exhibits a positive linear correlation between its depth and the Fourier number. Since the characteristic length defined here as the defect diameter remains constant, the observed increase in the Fourier number with depth is governed entirely by the interaction between effective thermal diffusivity α and half-rise time $t_{1/2}$. From a physics perspective, this implies that for deeper defects, the heat has more time to diffuse across the defect region before the thermal response is detected at the rear surface. A higher Fourier number therefore reflects a more developed thermal diffusion process, indicating that the thermal wave has travelled a longer path and interacted more exten-

sively with the sound material before reaching the airgap. This behaviour highlights the potential depth-sensitive nature of the thermal response in transmission mode, where deeper defects lead to an increased diffusion, possibly due to the thermal disparity between the sound and defect regions.

The linear equation for each plot was obtained using the in-built linear trendline function available in Microsoft Excel. The R^2 value indicates that using a linear equation is sufficient to describe the relationship between the depth and Fourier number.

While a polynomial regression mode using a higher order polynomial can be used e.g. a polynomial of order $n = 2$, it results in an R^2 value of 1 which might indicate a stronger fit but could lead to over fitting. It must be noted that further work is required to develop a deeper understanding of this relationship using different material types, material thicknesses, defect depths and shapes in order to standardise the regression model. However, for the purpose of this study adopting linear regression has shown to be sufficient for depth estimation.

Fig. 16 also shows that the larger defects i.e., the 16 mm diameter circular and 16 mm length square defects exhibit a stronger correlation between depth and Fourier number compared to the 8 mm circular defect. This observation aligns with our current understanding of defect behaviour, where smaller defects are more difficult to characterise due to their lower thermal contrast relative to the surrounding sound material. Moreover, from a practical standpoint, the weaker correlation between the Fourier number and the 8 mm defect depth can also be attributed to the lower SNR in this region, as well as the camera's minimum resolvable temperature difference. Enhancing these two factors could potentially improve the correlation and thus increase the accuracy of defect depth estimation.

To further demonstrate the strength of the newly developed method's strength in quantifying defect depth, Fig. 17 shows the defect depth estimation error for the reflection and transmission modes. For the

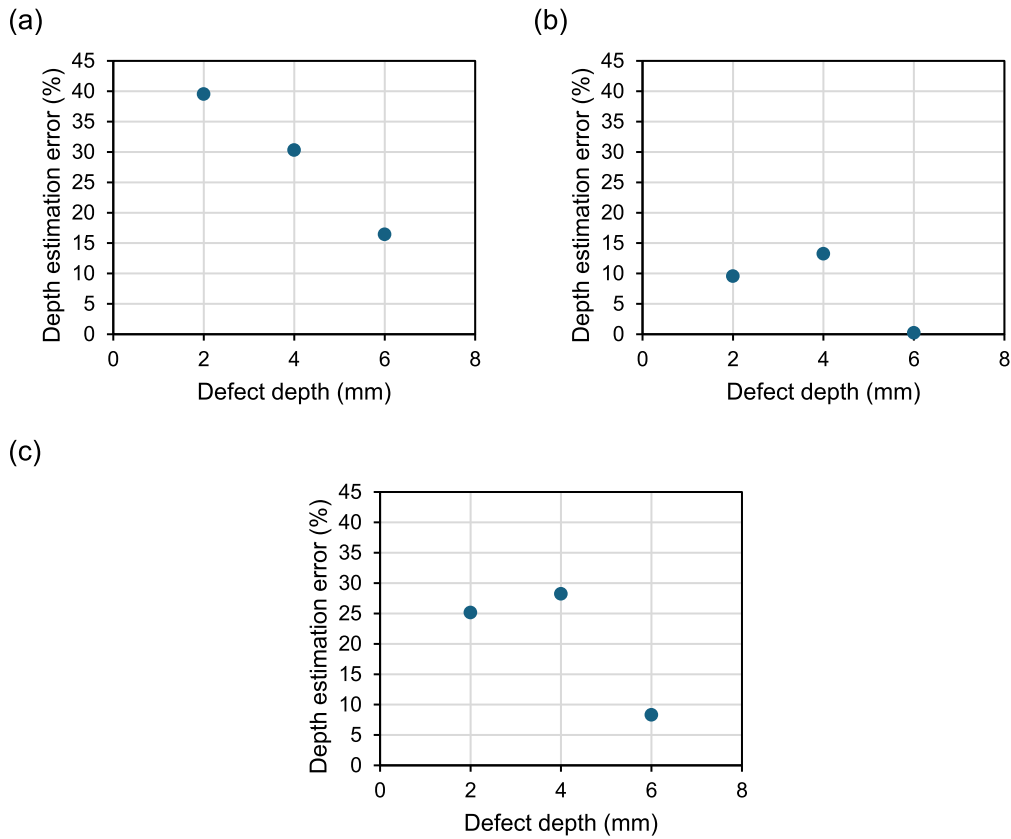


Fig. 19. Defect depth estimation error for the laboratory experiments using the transmission mode for a) 8 mm circle b) 16 mm circle and c) 16 mm square.

reflection mode the Log Second Derivative method (LSD) first proposed by Shepard et al. [31] was used for the depth calculation. Knowing the thermal diffusivity of a material, the depth of the defect can be calculated using:

$$L = \sqrt{t_{LSD} \cdot \pi \cdot \alpha} \quad (9)$$

where t_{LSD} is the peak time of the second derivative and α is the thermal diffusivity of the sound material. For every defect type the proposed depth quantification technique exhibits a greater estimation accuracy to the established LSD method (an average error of 10.75 % across all defect sizes and depths compared to LSD's 29.3 %) especially at depths closer to the back surface. This is line with our current understanding of deeper sub-surface defects which are detected more clearly in the through-transmission configuration. Moreover, the average estimation error of the 8 mm defect (≈ 18.48 %) is much higher than the 16 mm defect (≈ 6.26 %), once again aligning with our current understanding of the effect of lateral defect size on the thermal response. It is important to note however, that the LSD method used here is a basic one computed in MATLAB. Industrial systems that implement LSD based on Thermographic Signal Reconstruction (TSR) utilise patent proprietary technology that has been optimised specifically for performance with other components with the system. Therefore, the performance of our computed TSR does not represent the performance that actual industrial systems would exhibit. By comparison, most recent works on depth retrieval focus on reflection-mode pulsed thermography, such as Wang et al., who report depth estimation errors of up to approximately 20 % prior to nonlinear correction and below approximately 5 % following correction for flat-bottom-hole defects with depths in the range of 0.5–2.5 mm and maximum defect size of 20 mm in diameter, with accuracy strongly dependent on defect size and depth [6].

In contrast, the present work considers fully enclosed defects with

circular and square geometries, defect sizes up to 16 mm in diameter or length, and a substantially larger depth range of 2–6 mm, further emphasising the distinct thermal response characteristics and improved depth sensitivity enabled by through-transmission pulsed thermography.

4.3.2. Laboratory experiments (steel sample)

Following the FEM model, the same procedure shown in Fig. 7 was applied to the physical sample. Unlike the FEM study, only 2 mm, 4 mm, and 6 mm depths were used due to physical limitations preventing inclusion of 3 mm and 5 mm on the same sample. Fig. 18 illustrates the relationship between Fourier number and defect depth. For the 8 mm circular defect, the Fourier number exhibited low variability across repeated measurements, with mean values of 0.1545 ± 0.0033 , 0.1565 ± 0.0040 , and 0.1564 ± 0.0015 for defect depths of 5 mm, 3 mm, and 1 mm, respectively. For the 16 mm circular defect, the corresponding Fourier numbers were 0.0361 ± 0.0012 , 0.0369 ± 0.0008 , and 0.0384 ± 0.0006 . Similarly, for the 16 mm square defect, Fourier numbers of 0.0333 ± 0.0007 , 0.0369 ± 0.0010 , and 0.0373 ± 0.0009 were obtained for depths of 5 mm, 3 mm, and 1 mm, respectively. Across all defect sizes, geometries, and depths, the Fourier number exhibited low variability, with CV values in the range of approximately 1.0–3.3 %. In all cases, the low standard deviations indicate good experimental repeatability and confirm the expected scaling of the Fourier number with defect size.

Except for the 16 mm circular defect, the 6 mm depths show weaker linearity, possibly due to factors such as lower signal-to-noise ratio, non-uniform heating, material inhomogeneity, heat interference from surface plugs, and manufacturing uncertainties. Still, the R^2 values indicate a reasonably strong positive correlation across all defect types, supporting the feasibility of depth estimation via a linear model.

Fig. 19 presents the depth estimation errors. Reflection mode could

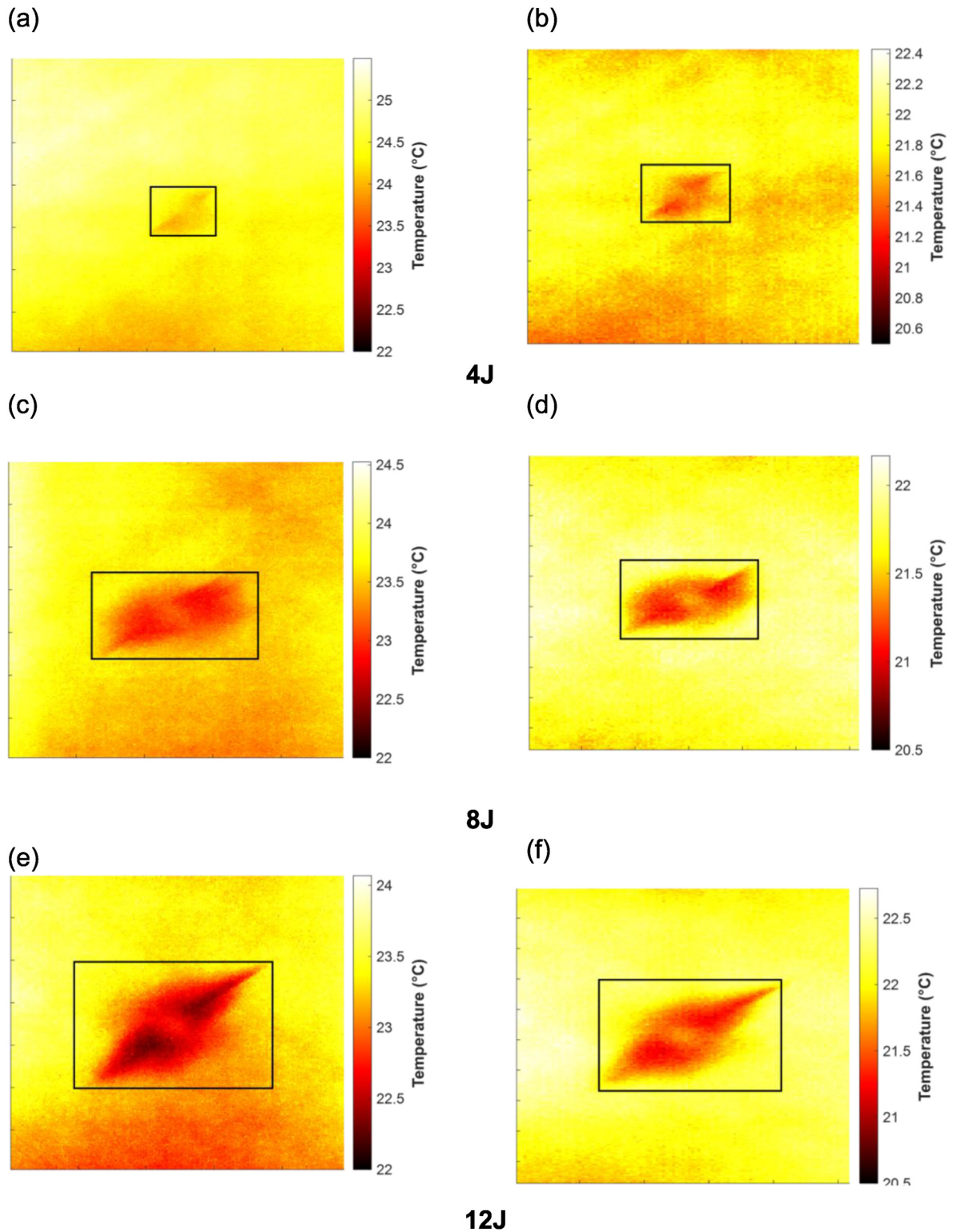


Fig. 20. Raw thermograms for the impact samples at 4J, 8J and 12J using the longwave (a, c, e) and mid-wave (b, d, f) cameras in the TB configurations (image taken 3.76 s or 188 frames after flash).

not be evaluated experimentally due to front-surface plugs. Future work may involve more precise machining or symmetrical sample designs to enable dual-side measurements. Notably, the 16 mm circular defect showed the least estimation error, aligning with its strong linear fit.

Additionally, the experimental error trends closely match FEM results, reinforcing FEM's value for analysing complex scenarios beyond practical experimental reach. It is important to note that the 16 mm

square defect's error is double the 16 mm circle's indicating that manufacturing uncertainties as well as geometrical features also have a role in determining the measurement accuracy and this sensitivity will be the subject of a future study.

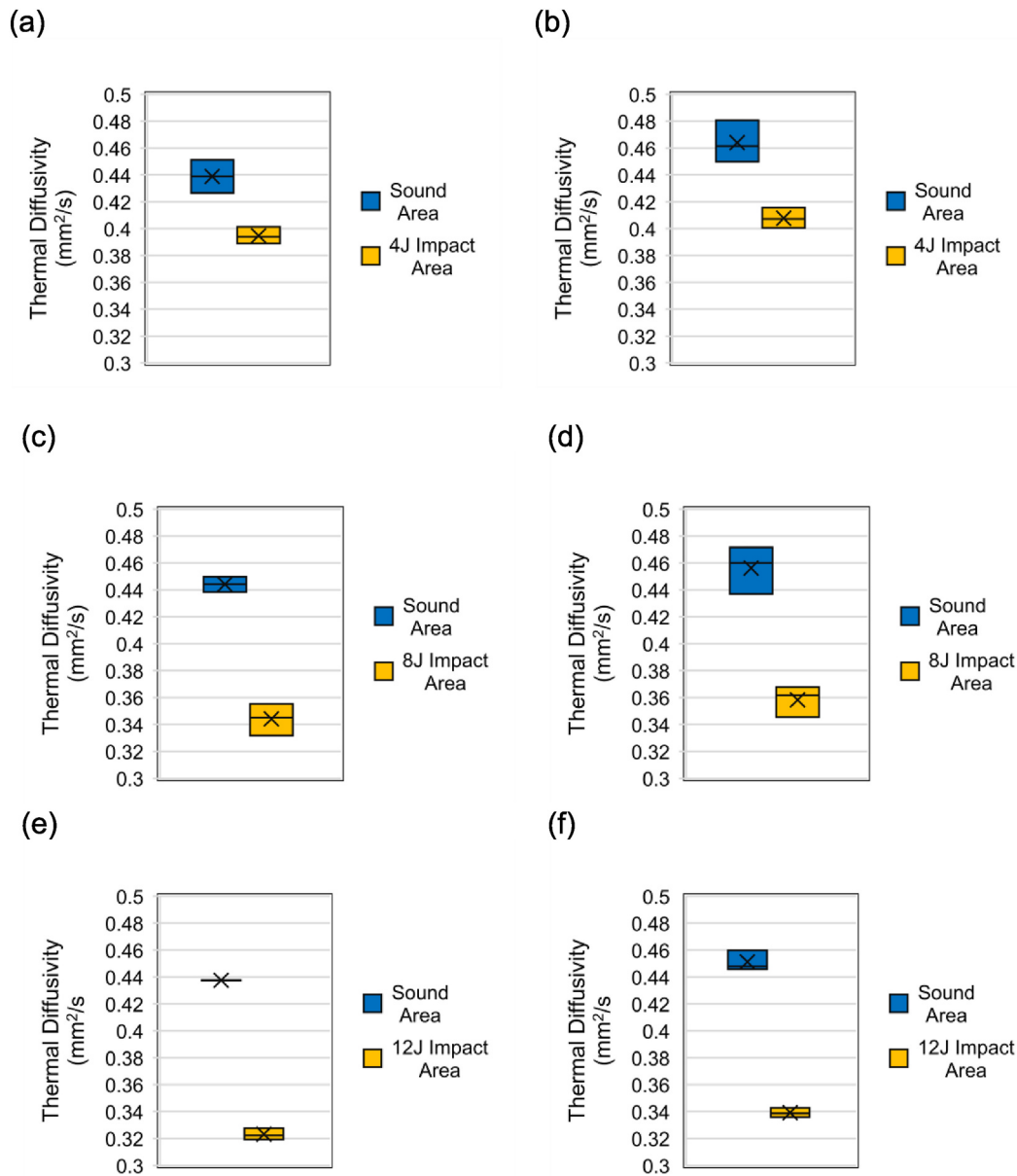


Fig. 21. Thermal diffusivity estimation in TB configuration using the long-wave (a, c, e) and mid-wave (b, d, f) cameras.

4.4. Impact damage estimation for CFRP samples

Fig. 20 displays representative raw thermograms of the CFRP samples impacted at varying energy levels, captured using both longwave and mid-wave infrared cameras in the TB configuration. The thermograms were taken at 3.76 s or 188 frames after flash. As shown in Fig. 11, black rectangles denote the defect regions. Both cameras successfully detect defects resulting from all impact levels. However, the mid-wave camera demonstrates slightly superior spatial resolution, providing clearer defect characterisation compared to the longwave camera. As mentioned previously, the resolution of defects is not the main objective of this study which is why no image enhancement algorithms were applied to improve visual clarity. The focus is on the accurate estimation of effective thermal diffusivity, for which the raw thermograms provide sufficient temporal information.

The box plots in Figs. 21 and 22 show the thermal diffusivity and input energies for both cameras respectively in the TB configuration. For the LWIR measurements, the thermal diffusivity exhibits standard deviations of approximately ± 0.001 – 0.018 mm^2/s with corresponding CV

values in the range of about 0.3–4.1 % across sound and impact regions. The MWIR measurements show comparable repeatability, with standard deviations of approximately ± 0.003 – 0.018 mm^2/s and CV values of about 1.0–3.9 %. In terms of input energy, both camera systems demonstrate high stability, with LWIR and MWIR standard deviations on the order of ± 1 – 4 J and CV values generally below 1.1 %, indicating consistent thermal excitation conditions. It is observed that the variation between repeats is less for the longwave camera compared to the mid-wave camera. This is consistent with the theory of peak spectral emission, which establishes a direct relationship between temperature and the wavelength at which peak emission occurs. As the temperature increase is relatively small, the long-wave camera captures the backwall's temporal behaviour with greater precision than the mid-wave camera as indicated by the reduced variation in the boxplots shown in Figs. 21 and 22.

It can be inferred from Fig. 21 that the effective thermal diffusivity decreases as the impact energy increases. This is in line with the understanding that a higher impact energy would cause a larger damage (in this case a delamination) thereby reducing the rate at which heat can

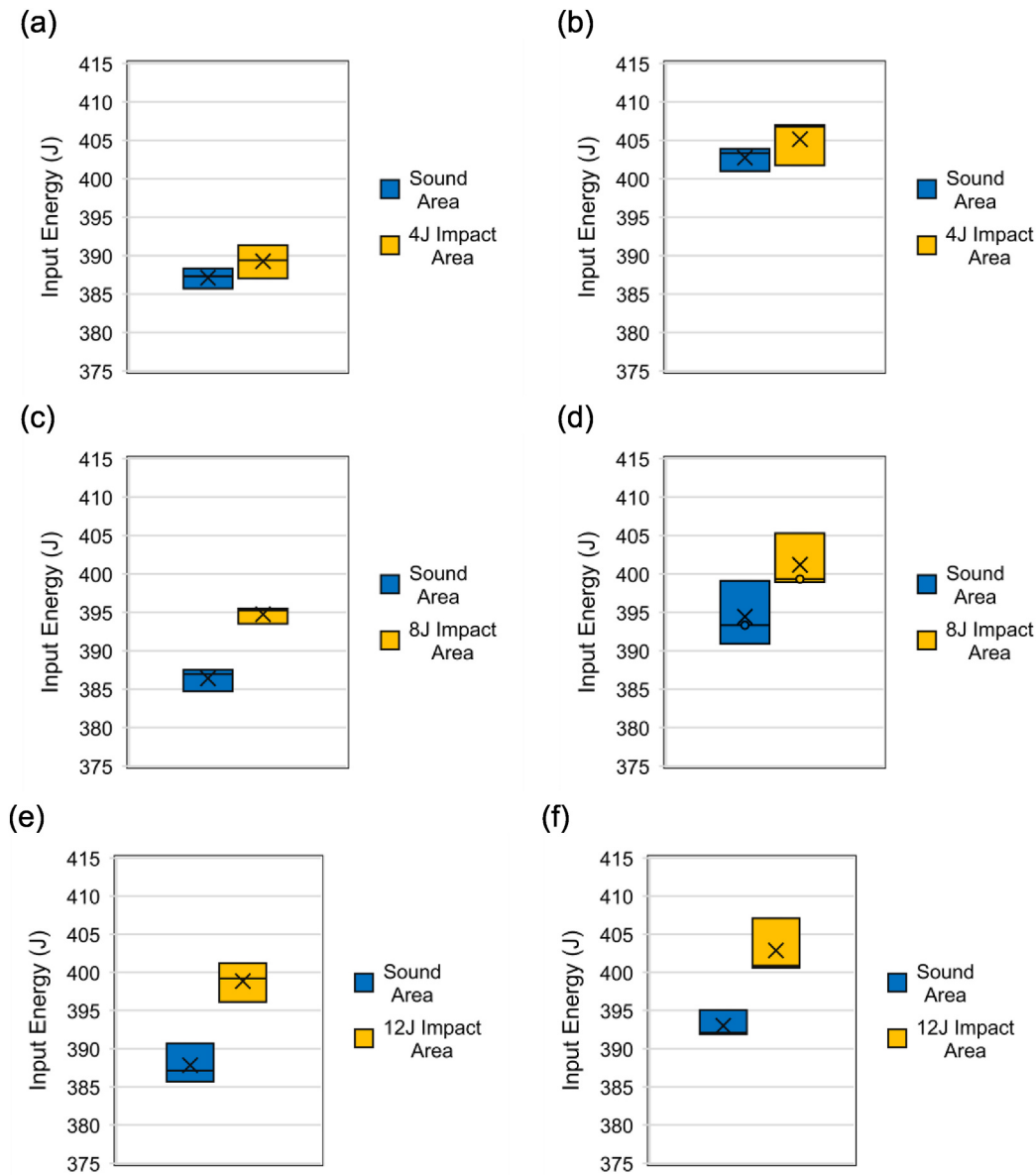


Fig. 22. Fig. 3 Input energy estimation in TB configuration using the long-wave (a, c, e) and mid-wave (b, d, f) cameras.

travel through the thickness of the sample. A close examination of the effective thermal diffusivity values reveals that the change is more pronounced when the impact energy increases from 4J to 8J than from 8J to 12J. This trend is consistent across both the long-wave and mid-wave infrared camera data, suggesting that the extent of the damage is greater in the CFRP samples when the impact energy is increased from 4 J to 8 J compared to 8J–12J. While the increase in impact energy is uniform, the corresponding increase in damage is not, indicating a non-linear relationship between impact energy and thermal damage severity. The results have not been shown for the TF configuration however, the relative precision of the estimated values is once again found to be greater in the longwave camera.

Since the depth of the damage in the CFRP samples is unknown a relationship between the Fourier number and impact energy is established instead of the depth. Fig. 23 shows the sensitivity of the Fourier number to the defect depth. Across both TB and TF configurations, the Fourier number exhibits a systematic dependence on defect depth for both camera systems, with mean values typically on the order of 0.13–0.14 and associated standard deviations ranging from approximately ± 0.0002 to ± 0.0042 across repeated measurements. This

corresponds to CV values generally below about 3.5 %, indicating that the observed depth-dependent trends are not dominated by measurement uncertainty. Analysis of the plot slopes indicates that Fourier number calculations based on temperature data from the longwave camera exhibit greater sensitivity compared to the mid-wave camera, with a 200 % increase in the TF configuration and a 50 % increase in the TB configuration. This sensitivity is translated into more accurate assessments of impact energy in Fig. 24. In terms of correlation, all plots exhibit a strong negative correlation which is attributed to the fact that a larger defect would result in a lower effective thermal diffusivity and a larger value for the half-rise time as the backwall temperature increases at a slower rate. Based on the current analysis it could be concluded that the longwave camera is better suited for this type of analysis. The use of the longwave camera for impact energy assessment is further strengthened in Fig. 24 where the TF configuration using the longwave camera produces the most accurate estimates of the impact energy. Moreover, the accuracy increases with increasing impact energy for the longwave camera as opposed to the mid-wave camera where no such trend between impact energy and estimation error is observed.

Finally, as demonstrated using the steel sample, it is important to

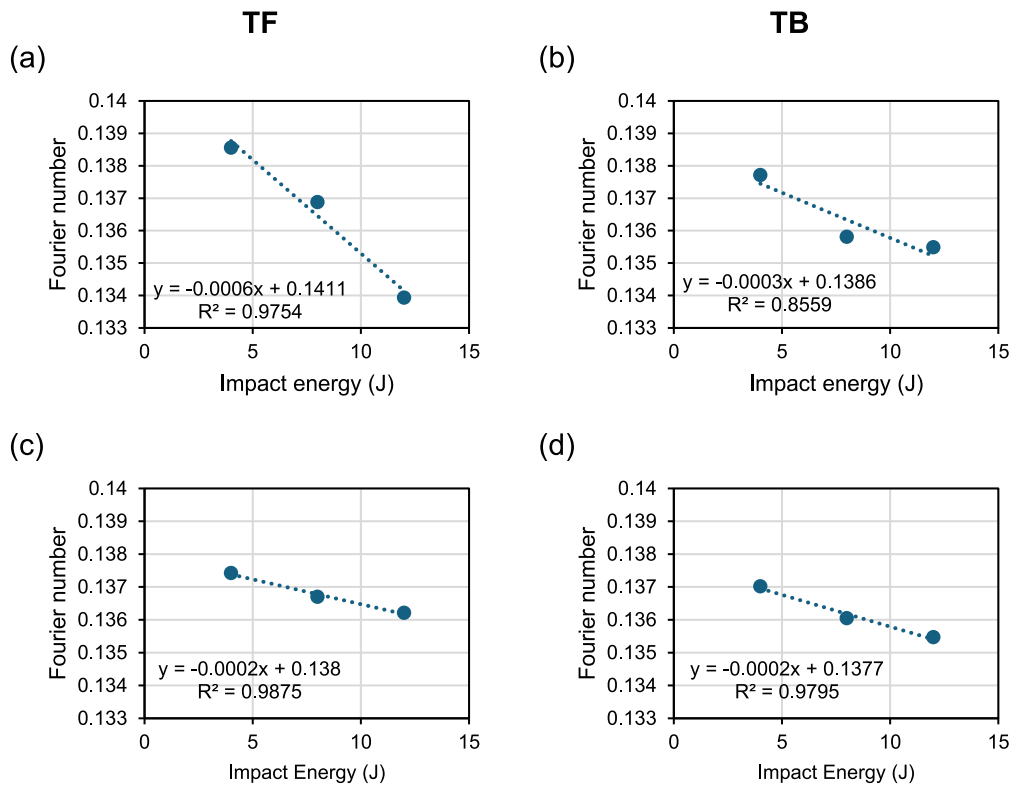


Fig. 23. Fourier number sensitivity to impact energy using the longwave camera (a & b) and mid-wave camera (c & d) in both the TF and TB configurations.

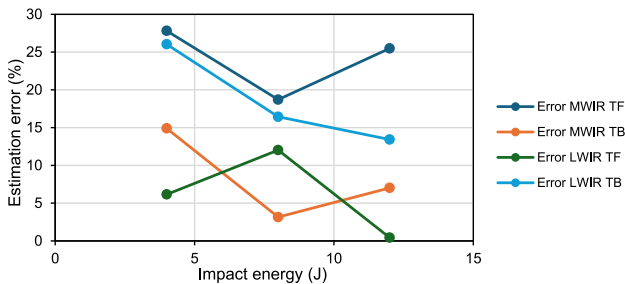


Fig. 24. Impact energy estimation error for both TF and TB configurations using the longwave and mid-wave cameras.

evaluate how accurately the NLSF algorithm captures the backwall temperature rise. To this end, residual analysis will be performed for both cameras in the TF and TB configurations.

4.4.1. Mid-wave camera

Figs. 25 and 26 show the residual plots for the TF and TB configurations respectively and their corresponding autocorrelation function plots (ACF). The ACF quantifies the correlation of a signal with itself over different time lags, providing a measure of how residuals are temporally related and allowing detection of systematic patterns not captured by the model. It is evident from both Figs. 25 and 26 that while statistically the NLSF algorithm captures the backwall temperature with reasonable levels of accuracy (as indicated by the R^2 and RMSE values), a visual inspection of the residual plot reveals a sinusoidal pattern indicative of a systematic error.

To explore this further, a sinusoidal function was fitted to the residuals, and autocorrelation analysis was performed. The ACF plots were

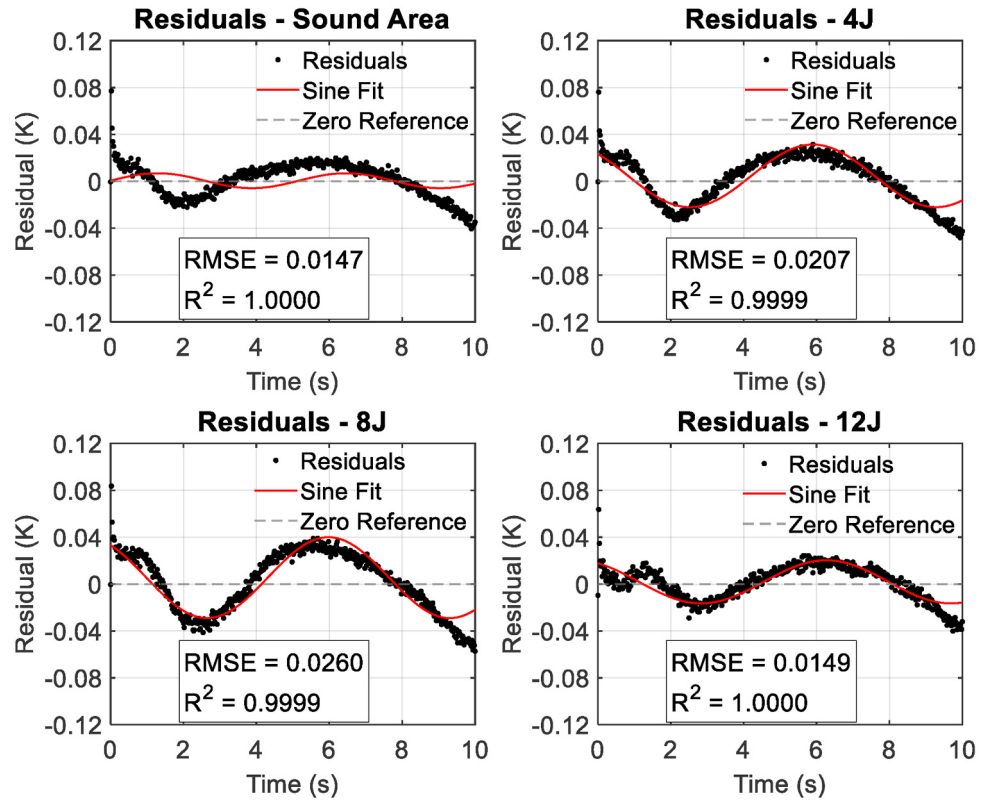
computed up to 150 lags, corresponding to approximately 3 s of the signal, which covers the most dynamic part of the thermal response i.e., the temperature rise. These plots revealed a gradual, smooth decay across increasing lags, with autocorrelation coefficients remaining significantly above the 95 % confidence bounds for a considerable portion of this range. This behaviour suggests that the residuals exhibit weak but persistent temporal structure, rather than behaving as random noise. The presence of such correlated residuals, alongside the fitted sinusoidal trend, points to minor systematic effects in the thermal signal. These could arise from boundary interactions, IR sensor dynamics, or from the simplifications in the 1D heat conduction model used. Despite these observations, the overall residuals remain small, and the model fits the measured data very well. This suggests the model remains practical and reliable for interpreting transient thermal behaviour. Future work could consider refining the model to include multidimensional effects or correction terms to better reflect the actual thermal behaviour.

4.4.2. Longwave camera

Figs. 27 and 28 show the residual and ACF plots for the long-wave camera in the TF and TB configurations, respectively. Although a small sinusoidal pattern is present, it is much weaker compared to their mid-wave counterparts.

Furthermore, analysis of the ACF initially shows a gradual decay, indicating some short-term correlation, but quickly falls within the confidence bounds, suggesting limited longer-term autocorrelation, particularly with the Sound and 4J data in the TF configuration. This also explains why the TF configuration produced the most accurate estimates for impact energy, as shown in Fig. 24. Analysing the residual and ACF plots further strengthen the case for using the longwave camera for through-transmission analysis.

(a)



(b)

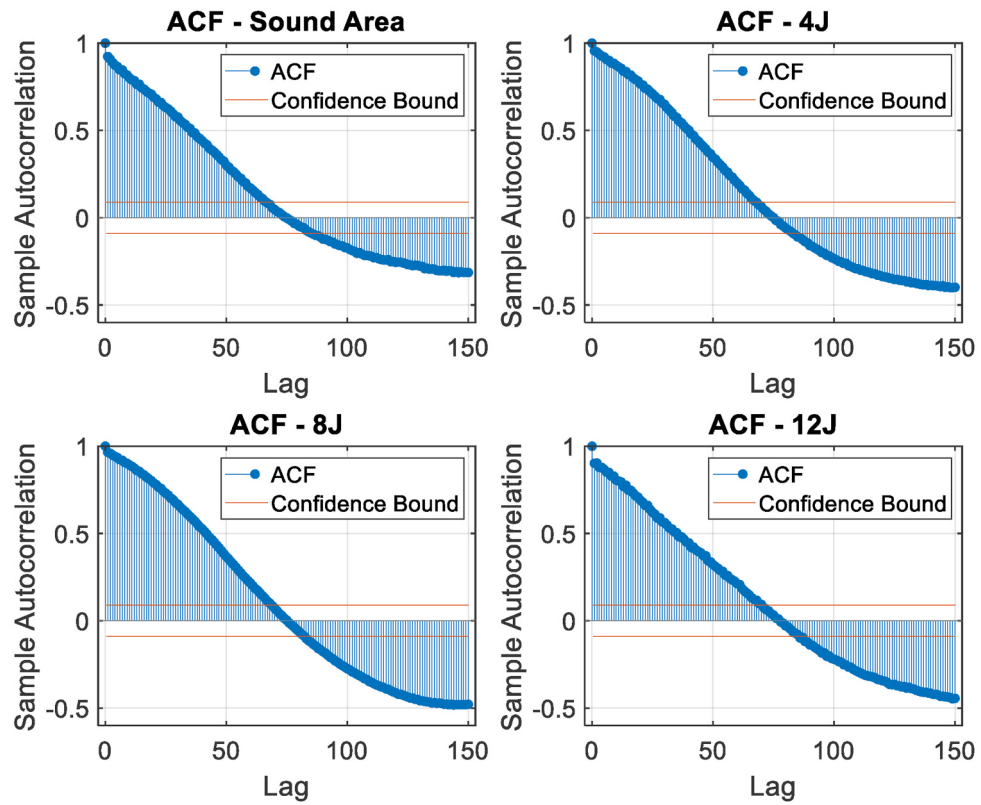
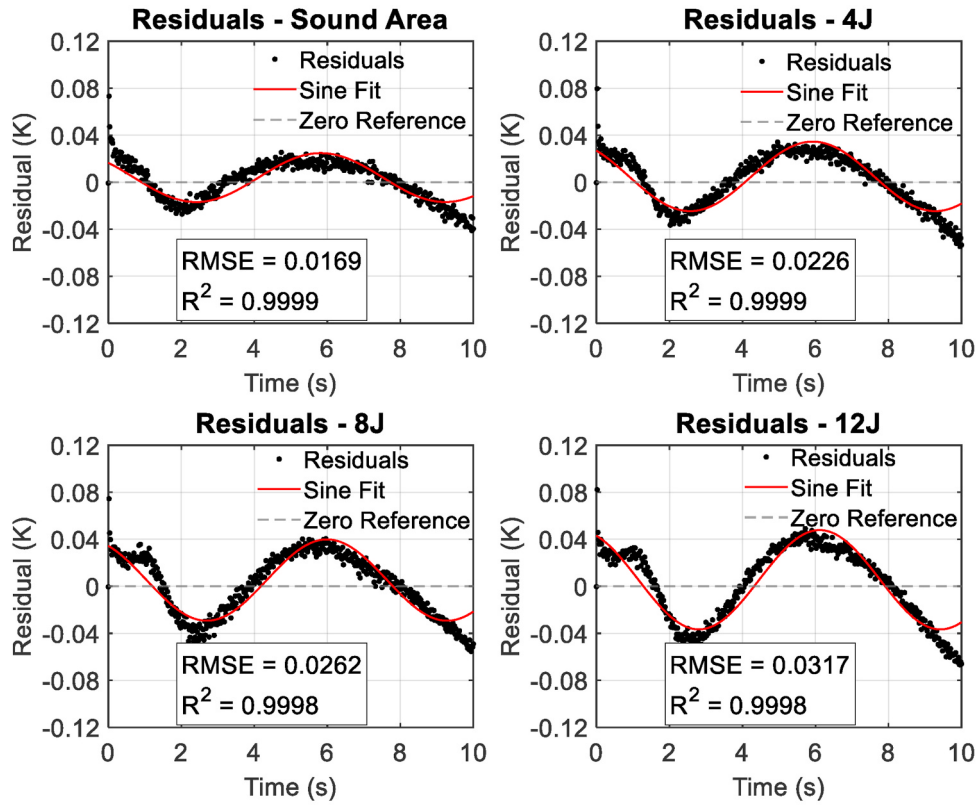


Fig. 25. a) Residual analysis of the TF configuration and its b) autocorrelation analysis for the mid-wave camera.

(a)



(b)

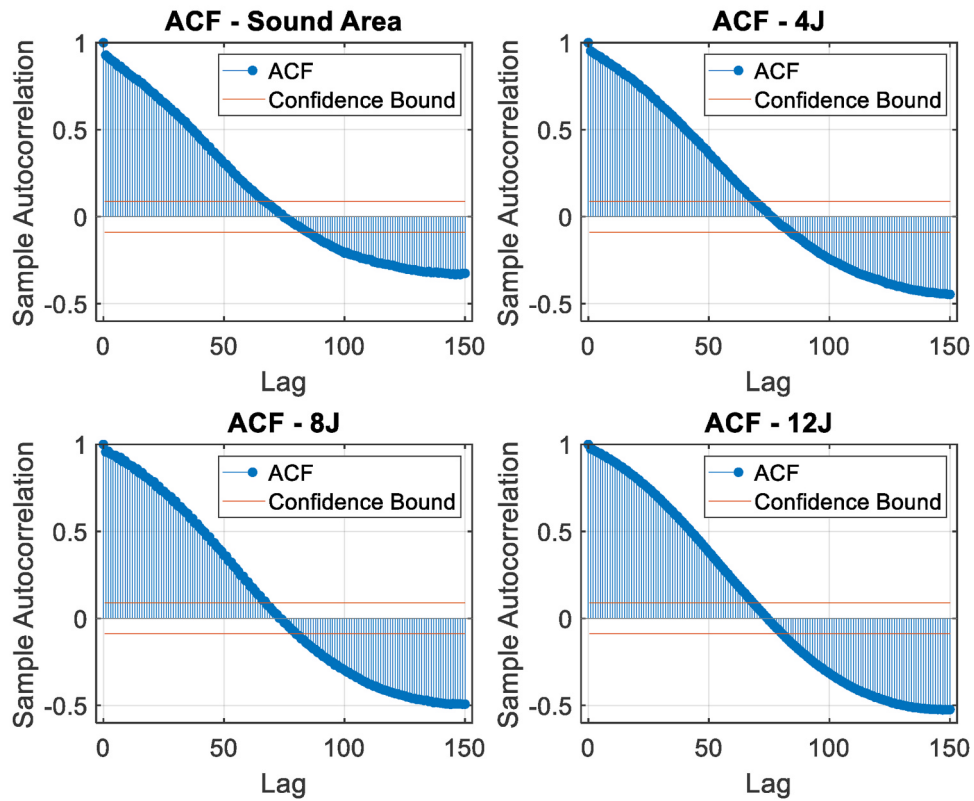
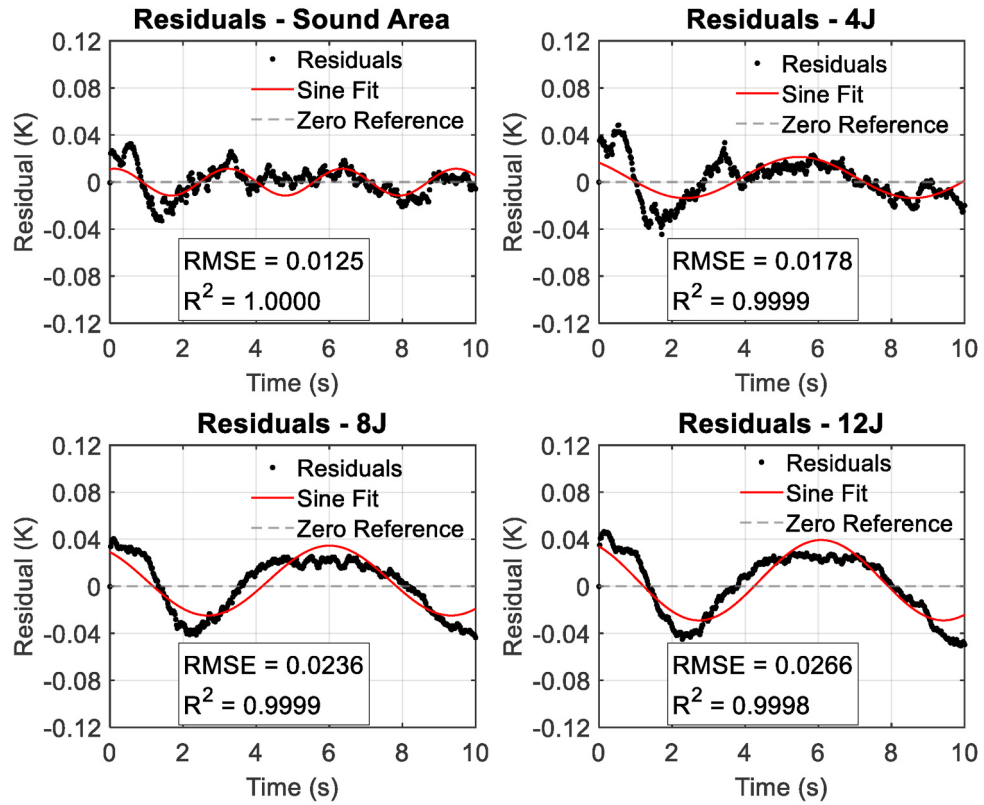


Fig. 26. a) Residual analysis of the TB configuration and its b) autocorrelation analysis for the mid-wave camera.

(a)



(b)

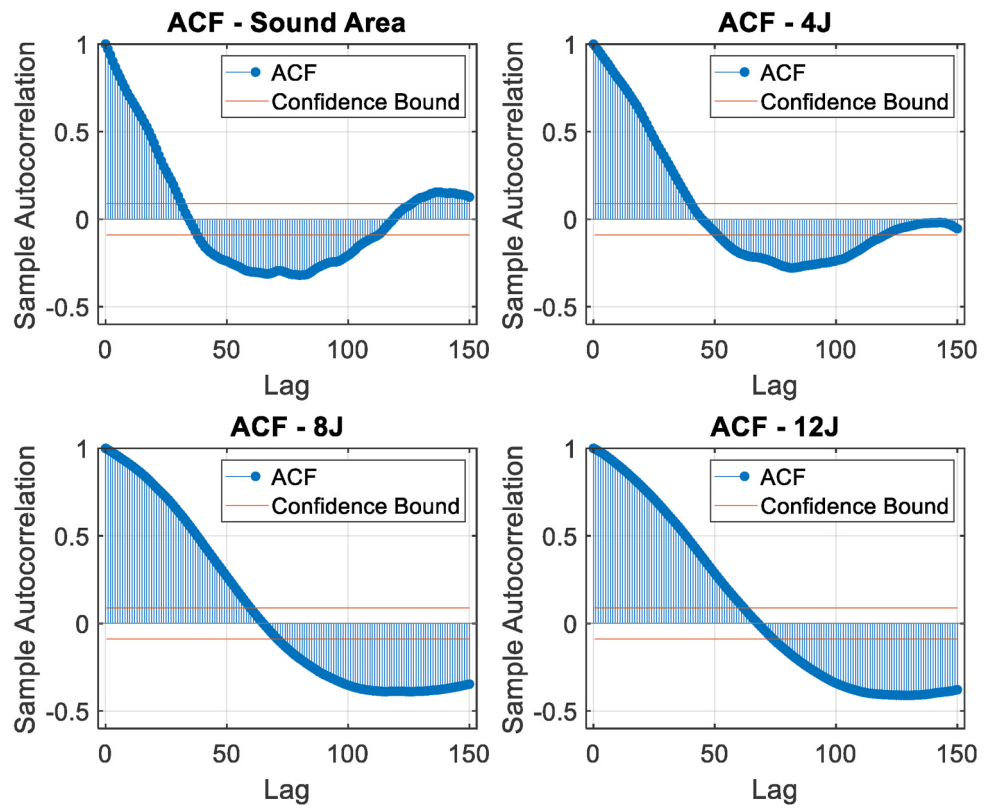
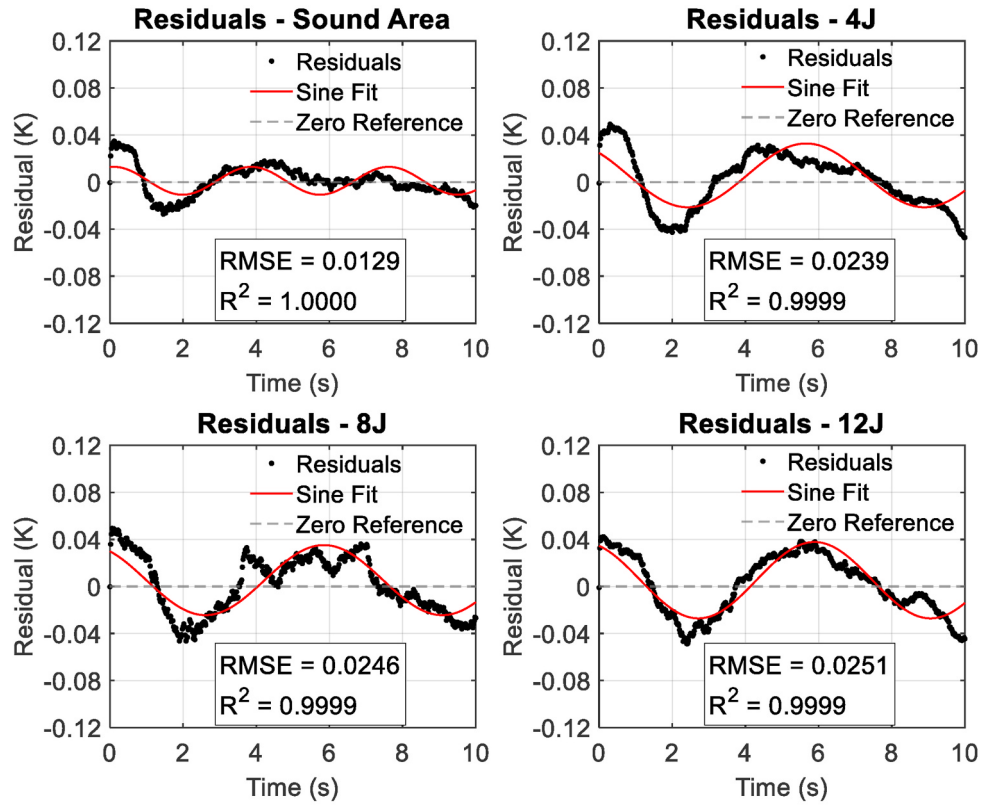


Fig. 27. a) Residual analysis of the TF configuration and its b) autocorrelation analysis for the longwave camera.

(a)



(b)

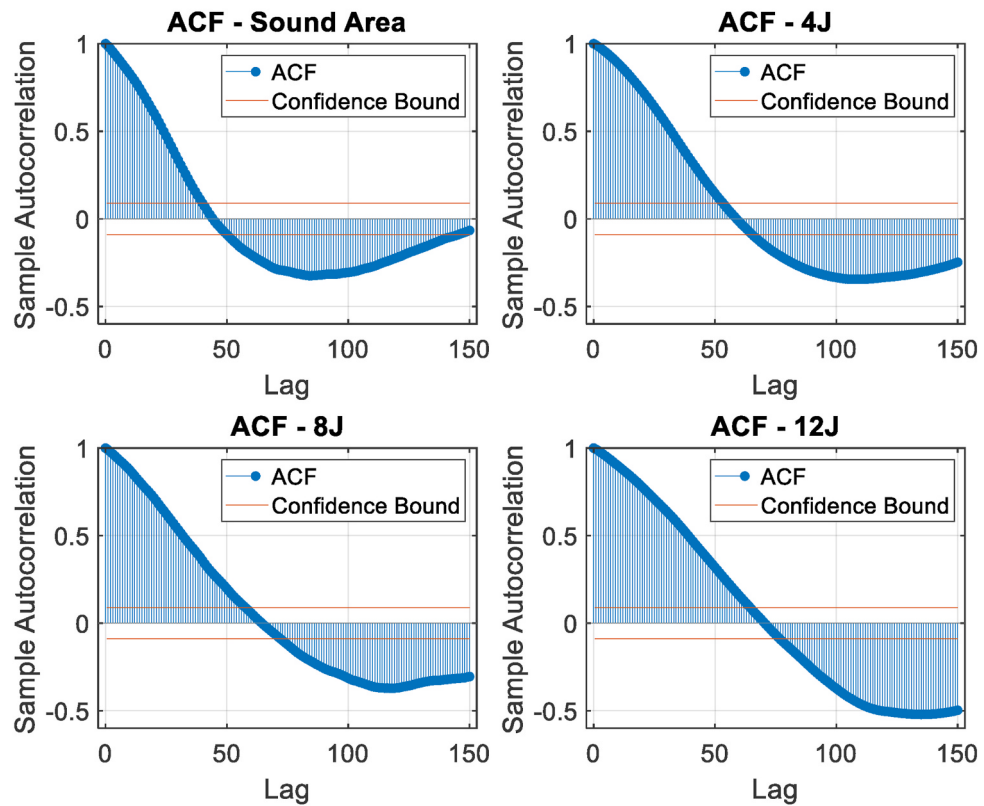


Fig. 28. a) Residual analysis of the TB configuration and its b) autocorrelation analysis for the longwave camera.

5. Summary and conclusion

This study performs a detailed analysis of the thermal response of a sample with embedded defects subjected to pulsed heating. Analysis is conducted in both simulation and laboratory environment. The key takeaways from this work are listed below.

5.1. Summary

- Finite element analysis was conducted where a steel sample was created with sub-surface air gaps and subjected to pulsed heating with the temperature information being captured in both the reflection and transmission modes. Due to the addition of plugs in the physical samples, the rear side of the sample in both the FEM and physical experiments was the one exposed to flash heating and data capture in the reflection mode (See section 3.2).
- A sample with embedded air gaps at known defects was manufactured to address the lack of calibration samples for through-transmission pulsed thermography (See section 3.3).
- A proposed solution is presented to quantify defect depth by establishing a relationship with the Fourier number. This approach is further extended to quantify impact damage, using the same relationship, but applied between impact damage and the Fourier number.

5.2. Conclusions

- For through-transmission pulsed thermography, the depth quantification has been a challenge due to the distance travelled by the thermal wave being the same for the defect and defect free regions. Moreover, a calibration sample with actual sub-surface air gap defects (an equivalent to flat bottom holes for the reflection mode) did not exist further complicating the problem (See section 1.2).
- Performing a dual-mode analysis by analysing the first derivative curves for both the reflection and transmission mode revealed that the peaks of the transmission mode occurred at similar times regardless of defect depth whereas the reflection mode peaks shifted closer to their through-transmission counterparts as the defect depth from the surface increased. This indicated that an approximate location of the defect depth can be estimated by observing both the first derivative peaks however it still cannot be used to quantify the defect depth (See section 4.1.1 & 4.2.1).
- A potential solution to quantify defect depth is developed by establishing a relationship between the Fourier number and defect depth. The estimation error is compared with the reflection mode using basic TSR/LSD method in the FEM. The results from both FEM and laboratory experiments indicate that the accuracy of the proposed solution is greater at defects closer to the backwall (See section 4.3.2).
- The newly proposed method is extended to quantify impact damage in CFRP samples. The results show that the TF configuration using the longwave IR camera is best suited for this type of analysis. Moreover, the ACF plots reveal minor systematic deviations which would need to be corrected for in order to develop a more representative mathematical model to describe the backwall temporal behaviour (See section 4.4).

While this study offers a promising solution for depth quantification in through-transmission pulsed thermography, it has several limitations. First, the laboratory experiments lack a comparative analysis with reflection mode techniques such as PPT, beyond TSR, to fully assess accuracy. Second, all defects used a fixed height of 1 mm, which is why future work should explore varying defect heights, depths, and geometries. Third, only two material types were investigated; studies on materials with different thermal diffusivities or heterogeneous properties are needed. Finally, the ACF plots revealed systematic deviations arising

from the use of the current 1D model to describe the backwall temperature evolution. These deviations indicate that the present formulation does not fully capture the lateral heat-diffusion effects associated with finite defects. Future work will therefore focus on refining the mathematical model to incorporate lateral heat flow, with the aim of reducing or potentially eliminating these deviations and improving the overall accuracy of the depth-estimation framework. Despite these limitations, this study's primary contribution is its clear repeatable and reliable methodology for evaluating depth quantification in through-transmission mode. The results lay the groundwork for advancing both analytical and experimental approaches in defect depth characterisation.

CRedit authorship contribution statement

Zain Ali: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Sri Addepalli:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Yifan Zhao:** Writing – review & editing, Supervision, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The raw data supporting the findings of this study can be found at <https://doi.org/10.57996/cran.ceres-2764>.

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Defect depth estimation using through-transmission pulsed thermography: a numerical and experimental investigation

Ali, Zain; Addepalli, Sri; Zhao, Yifan

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