

A COMPARISON BETWEEN 3D AND 1D NUMERICAL SIMULATION MODELS FOR INFRARED THERMOGRAPHIC NDT

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Abstract

Numerical simulation is an important tool to study the thermal response of test specimen in infrared thermography. For simplicity in theoretical analysis and quantitative calculation, 3D model is often simplified to 1D model. 3D and 1D models for 2 samples, one is a CFRP panel and another is an aluminum one, are built and calculated by FEM method. The results show that influence of lateral heat diffusion is more serious in materials with greater thermal diffusivity. An experiment was carried out on a GFRP/NOMEX honeycomb panel. It was seen that lateral heat diffusion become obvious in materials with low thermal diffusivity as time goes by. In conclusion, error should be estimated before using 1D model instead of 3D model for simulation and analysis in infrared thermographic NDT.

Keywords: infrared thermographic nondestructive testing, numerical simulation, error, finite element method

1. Introduction

Infrared thermographic nondestructive testing (IT NDT) is increasingly used in the inspection of materials and structures due to its full field, rapid and noncontact testing capabilities. Modeling of IT NDT problems was used for: 1) exploring relations between surface temperature signals and various parameters such as heating parameters, defect size, sample size, thermal properties of host material and defect, surface convection and radiation, etc. 2) finding out the optimized inspection parameters and procedure for a given sample, 3) developing new testing methods and data processing techniques.

Studies on modeling and analysis of IT NDT based on 1D, 2D and 3D models were made using finite difference method (FDM) and FEM^[1~2]. Modeling of complex IT NDT problems were investigated, such as detection of overlapped defects^[3], cracks^[4-5], buried landmines^[6], inner holes in concrete^[7], and modeling of effect of heating intensity^[8], effect of natural convection on inspection^[9], *etc.* For simplicity in theoretical analysis and quantitative calculation, 3D model is often simplified to 1D model. Lateral heat diffusion is ignored and error of the simplification needs to be evaluated. This paper gives the comparison between 3D model and 1D model by numerically simulating.

2. 3D models and 1D models simplified from 3D models

IT NDT of carbon fiber reinforced plastics (CFRP) and aluminum are described by 3D models and 1D models respectively, and analyzed using FEM in this paper.

The cylindrical model of the IT NDT of CFRP shown in Fig.1 is used to simulate a delamination in a CFRP sample. The 1D model simplified from the 3D model is shown in Fig.2.

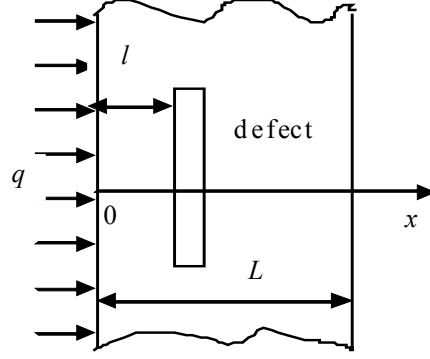
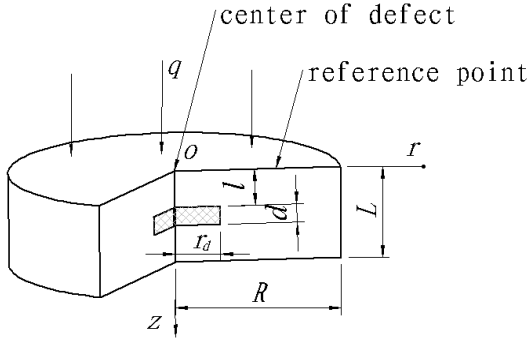


Fig.1 3D cylindrical model of IT NDT of CFRP

Fig.2 1D model simplified from 3D cylindrical model

A delamination defect is represented by a disc located at the depth l . The defect radius is r_d and defect thickness is d . Here R and L are the radius and thickness of the sample respectively, and q is the heat flux density. The sound area is simplified to a slab with the thickness L in 1D model in Fig.2. The defect area is a three-layer slab and the middle layer is the defect with thickness d , depth l .

3D model shown in Fig.3 is used to analyze corrosion problems of aluminum. The sample's size is $B \times B$ and thickness L . The corrosion area's size is $b \times b$ and depth l . Heat is infused into the sample from the surface $Z = L$. This 3D model is simplified to such a 1D model as the sound area is a slab with thickness L and the defect area is a slab with thickness l .

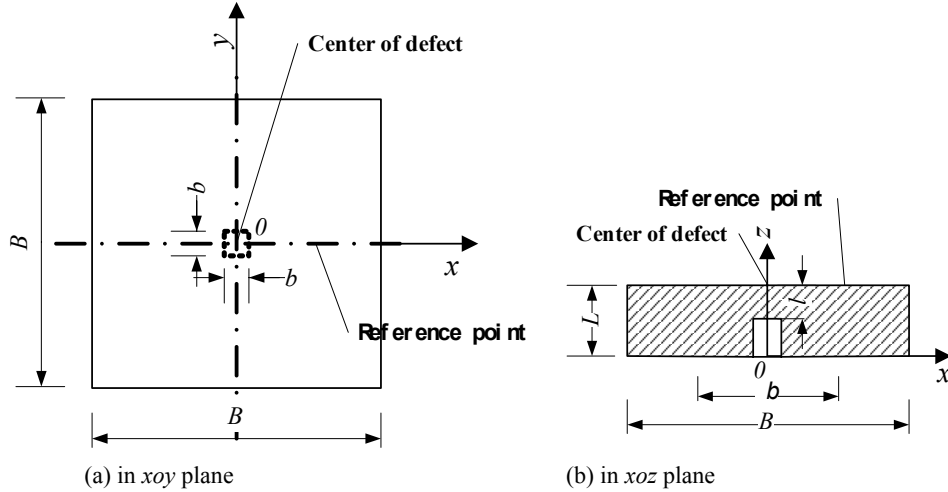


Fig.3 3D model to analyze corrosion problems in metal

3. Numerical Simulation Comparison

Firstly, temperature distribution on heating surface is given in the following simulation example as:

The model is 3D model shown in Fig.1. Surfaces of the sample are supposed to be adiabatic during heating process except heating surface. After heating, all of those surfaces are assumed to be adiabatic. The initial temperature of sample is supposed to be same as ambient temperature. The material of sample is CFRP and the defect is a delamination. Thermal properties of materials are shown in Table 1 and other parameters for numerical simulation are shown in Table 2.

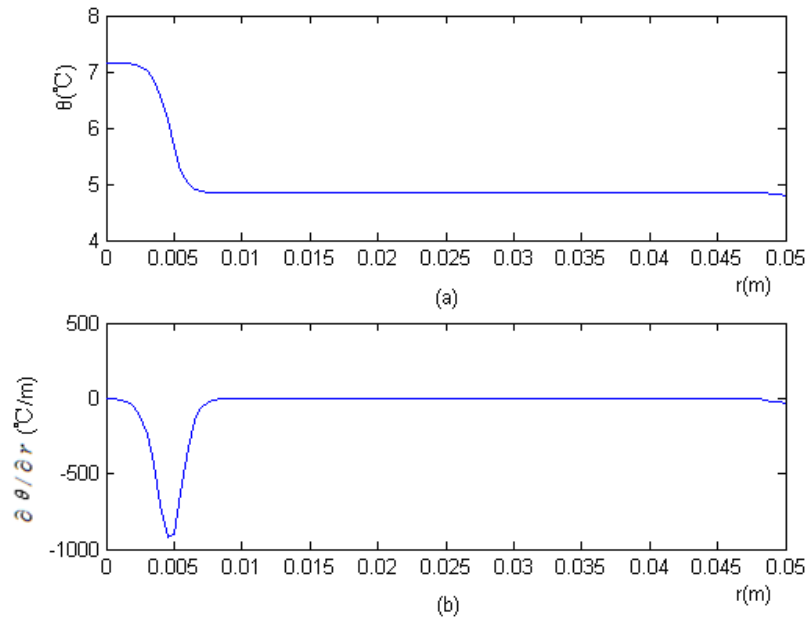
Table 1 Thermal properties of materials

material	Density ρ kg/m ³	Heat capacity c J/(kg·K)	Conductivity λ W/(m·K)	Diffusivity a m ² /s
CFRP ^[10,11]	1620	760	0.64	5.2×10^{-7}
air(20□) ^[12]	1.205	1005	0.0259	2.14×10^{-5}
aluminum(20□) ^[12]	2710	902	236	9.65×10^{-5}

Table 2 Parameters for numerical simulation to investigate temperature distribution in 3D cylindrical model

Sample thickness L (m)	Defect thickness d (m)	Defect depth l (m)	Sample radius R (m)	Defect radius r_d (m)	Heating flux density q_0 (W/ m ²)	Heating pulse duration τ_h (s)	End time τ_{stop} (s)	Finite element size Siz (m)
0.002	0.0001	0.0009	0.05	0.005	1.0×10^6	0.01	5	0.00002

Temperature distribution on heating surface at time $\tau = 1.8728$ s is shown as curve (a) in Fig.4. The curve (b) is $\partial\theta/\partial r$ vs. r curve. In this paper, θ is the temperature with initial temperature subtracted.

Fig.4 (a) temperature distribution on heating surface at time $\tau = 1.8728$ s (b) $\partial\theta/\partial r$ vs. radius r curve

The surface temperature of defect area was much higher than that of sound area because delamination is a heat resistance defect. The maximum of $\partial\theta/\partial r$ was appeared at the edge of defect. Because of transverse heat flux density q_r increased with $\partial\theta/\partial r$, lateral heat diffusion appeared which is ignored in 1D model.

Then 3D model shown in Fig.1 and 1D model shown in Fig.2 were numerically simulated. Heat pulse is supposed to be a rectangle pulse with duration τ_h . The material of sample is CFRP and the defect is a delamination. Parameters for numerical simulation are shown in Table 3. Sample radius R is 0.05m and defect radius r_d is 0.005m. Surfaces of the sample are supposed to be adiabatic during heating process except heating surface. After heating, all of those surfaces are assumed to be adiabatic.

Table 3 Parameters for comparison between 3D cylindrical model and 1D model

Sample thickness	Defect thickness	Defect depth	Heating flux density	Heating pulse duration	End time τ_{stop} (s)	Finite element size
L (m)	d (m)	l (m)	q_0 (W/ m ²)	τ_h (s)		Siz (m)
0.002	0.0001	0.0009	1.0×10^6	0.01	5	0.00002

Surface temperature of center point in defect area (named as center of defect shown in Fig.1) and surface temperature of center point in sound area (named as reference point shown in Fig.1) are used to be contrasted.

Some error parameters are defined as follows:

1. Absolute error e_a ,

$$e_a = |\theta_1 - \theta_2| \quad (1)$$

Here θ_1 is the temperature from 1D model θ_2 is the temperature from 3D model.

2. Relative error e_r ,

$$e_r = \frac{|\theta_1 - \theta_2|}{\theta_1} \times 100\% \quad (2)$$

The comparison results of those temperatures are shown in Table 4.

Table 4 Comparison results of 3D cylindrical model and 1D model

	Maximum of absolute error ($\square$)	Time of Maximum of absolute error (s)	Maximum of relative error (%)	Time of Maximum of relative error (s)
Reference point	0.0010	0.21761	0.0071	0.21761
Center of defect	0.0896	0.44541	1.5508	5

The maximum of relative error of center of defect was 1.5508%, however, the maximum of relative error of reference point was 0.0071%. The reason why the difference was clear is that defect area was so small that the center of defect was close to the edge of defect where the influence of lateral heat diffusion was obvious. However, the reference point was much farther than the center of defect to the edge of defect, so it's less affected by lateral heat diffusion.

3D model to analyze corrosion problems in metal shown in Fig.3 and 1D simplified from the 3D model were numerically simulated with conditions as follows:

The material of sample is aluminum. Thermal properties of materials are shown in Table 1 and parameters for numerical simulation are shown in Table 5. Surfaces of the sample are supposed to be adiabatic during heating process except heating surface. After heating, all of those surfaces are assumed to be adiabatic. The comparison results of temperatures of center of defect and reference point are shown in Table 6.

Table 5 Parameters for comparison between 3D model to analyze corrosion problems in metal and 1D model

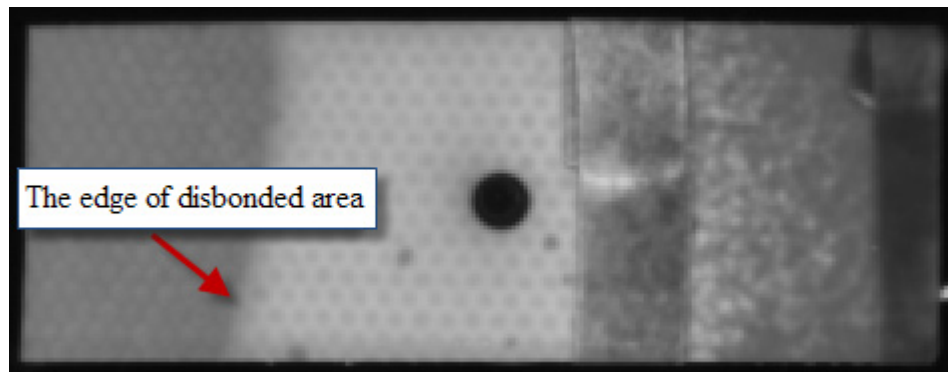
Sample size	Sample thickness	Defect size	Defect depth	Heating flux density	Heating pulse duration	End time	Finite element size
B (m)	L (m)	b (m)	l (m)	q_0 (W/ m ²)	τ_h (s)	τ_{stop} (s)	Siz (m)
0.02	0.002	0.002	0.0006	1.0×10^6	0.01	0.5	0.0002

Table 6 Comparison results of 3D model to analyze corrosion problems in metal and 1D model

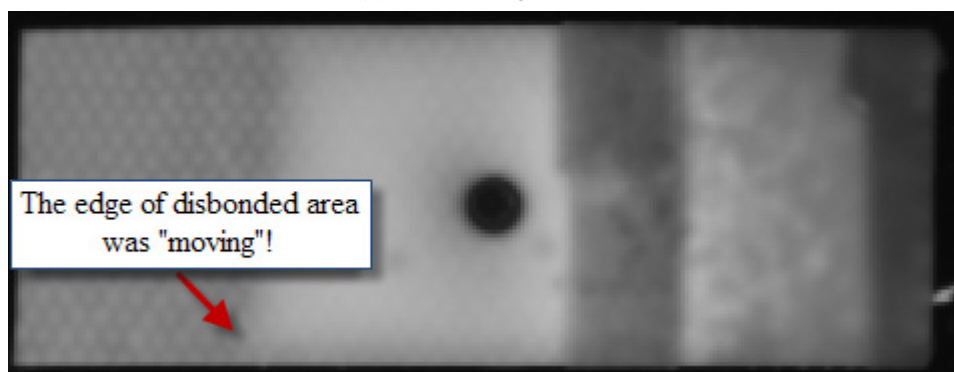
Model	Maximum temperature of center of defect (□)	temperature of center of defect at $\tau=0.5s$ (□)	Maximum temperature of reference point (□)	Temperature of reference point at $\tau=0.5s$ (□)
1D	7.64214	6.81825	4.63135	2.04548
3D	6.05680	2.06055	4.63152	2.06017
Difference	1.58534	4.75770	-0.00017	-0.01469

In Table 6, temperatures of reference point in 3D model and 1D model were almost similar, but temperatures of center point in defect area in those models were quite different because the influence of lateral heat diffusion which is ignored in 1D model was great in the 3D model. From results shown in Table 4 and Table 6, it was found that the effect of lateral heat diffusion in aluminum 3D model was greater than that in CFRP 3D model because thermal diffusivity of aluminum is much larger than that of CFRP. That is to say, the influence of lateral heat diffusion becomes more obvious in materials with greater thermal diffusivity, regardless of anisotropism of materials. Consequently the accuracy of simulation and analysis on those materials becomes worse because of the simplification from 3D model to 1D model.

Even in CFRP samples, the influence of lateral heat diffusion got greater with time going on. An experiment was made on a GFRP/NOMEX honeycomb panel of which the right part was disbonded and IT NDT results are shown in Fig.5. First image was the thermal image at time $\tau=0.5s$ in Fig.5 and last one was the thermal image at time $\tau=4s$. The edge of disbonded area was obviously seen in both images, but locations of the edge were different. It seemed that the edge of disbonded area was “moving” with time, which was caused by lateral heat diffusion.



(a) Thermal image at $\tau=0.5s$



(b) Thermal image at $\tau=4s$

Fig.5 IT NDT results of honeycomb core sandwich

4. Conclusion

From the numerical simulation results of 1D and 3D models, conclusions are made as follows:

- 1) Influence of lateral heat diffusion becomes more obvious in materials with greater thermal diffusivity. Consequently the accuracy of simulation and analysis on those materials becomes worse with the simplification from 3D to 1D.
- 2) Influence of lateral heat diffusion becomes more obvious even in materials with low thermal diffusivity as time goes by.
- 3) The error should be estimated when using 1D model instead of 3D model to simulate and analyze infrared NDT problems.

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