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Examination on heat conduction modeling for thermoplastic CFRP prepreg layup by the PGD

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Introduction

CFRP (Carbon Fiber Reinforced Plastics)
- Due to its superior specific strength and specific rigidity, the use is expanding as a lightweight material for airplanes.
- Sheet-type intermediate substrate (prepreg) is laminated and used.

CFRTP (Carbon Fiber Reinforced ThermoPlastics)
- Short molding time
- High-speed press molding
- Easy to store

Mass production is expected.
It is necessary to develop a simple, non-destructive evaluation method to detect defects (delamination, wrinkles and misalignments) during manufacturing and molding.

Infrared thermography
- Detection of internal defects by measuring surface temperature
- Large areas can be inspected in a single inspection
- Non-contact, short time

Boeing 787 [1]

[1] https://www.mhi.com/jp/products/air/boeing_787.html

Purpose of research

Press forming of CFRTP

Laminating → Preforming → Forming

Abnormality (e.g., fiber misalignment) should be detected before molding in various configurations.

→ In order to detect defects, it is necessary to know the thermal conduction characteristics at the intact state.

A computationally efficient method is required for defect detection in the molding line

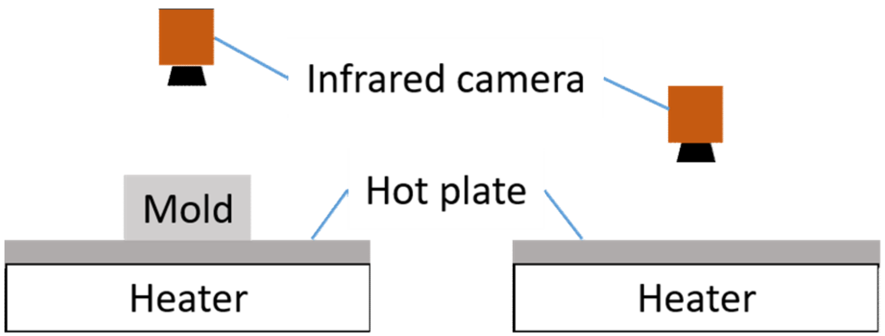
→ Considering application of the Proper Generalized Decomposition (PGD) method

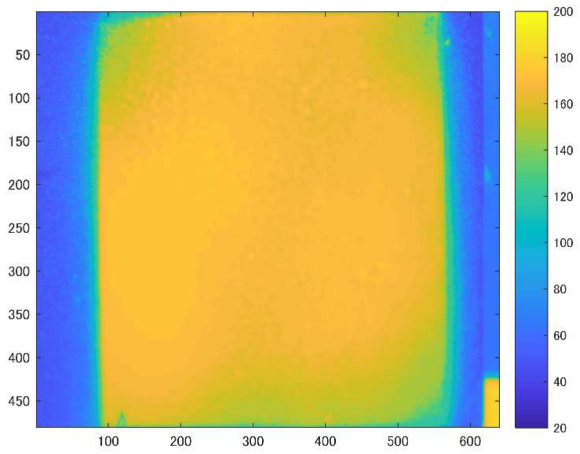
Solving the diffusion equation and studying a simple method to evaluate the internal temperature distribution from the surface temperature

- The temperature distribution is evaluated using the PGD and its validity is discussed.

Surface temperature measurement

- Measuring the surface temperature of the aluminum mold (20mm thickness) and the hot plate connected to the heater
- Black (matte) painted surface to reduce reflection
- Set heater temperature to 473K
- Record the temperature change from 1 minute to 20 seconds after the heater is turned off
- Using the average temperature data of a 200 × 200 pixel (display area is about 60mm × 60mm) near the center.





PGD method

PGD (Proper Generalized Decomposition)

- One of the dimensionality reduction methods of the model
- More computationally efficient than FEM and suitable for image processing

$$u(x,t) \approx u^n(x,t) = \sum_{i=1}^{N} X_i(x) \cdot T_i\ (t)$$

N: The number of bases

We can express the solution in the separated form

When the number of data in u is $m \times n$, the number of data is reduced to $N \times (m + n)$ by the PGD

Solving the diffusion equation in 1D (thickness direction) using the PGD

$$\frac{\partial u}{\partial t} - k\frac{\partial^2 u}{\partial x^2} = f$$

k: Thermal diffusivity
f: Source term (we assume zero here)

（参考）Francisco Chinesta, Roland Keunings, Adrien Leygue, "The Proper Generalized Decomposition for Advanced Numerical Simulations" (2014)

Computational steps of the PGD (1)

Diffusion equation in 1D (thickness direction)

$$\frac{\partial u}{\partial t} - k\frac{\partial^2 u}{\partial x^2} = f$$

k: Thermal diffusivity
f: Source term (we assume zero here)

- Find u by using the weighted residual method

$$\int_{\Omega_x \times \Omega_t} u^* \cdot \left(\frac{\partial u}{\partial t} - k\frac{\partial^2 u}{\partial x^2} - f\right) dx \cdot dt = 0$$

- The enrichment step of $n - 1 \rightarrow n$

$$u^{n-1}(x,t) = \sum_{i=1}^{n-1} X_i(x) \cdot T_i(t)$$

Computing $X_n(x),\ T_n(t)$

$$u^n(x,t) = u^{n-1}(x,t) + X_n(x) \cdot T_n(t) = \sum_{i=1}^{n-1} X_i(x) \cdot T_i(t) + X_n(x) \cdot T_n(t)$$

Computational steps of the PGD (2)

Iteration number p

$$u^{n,p}(x,t) = n^{n-1}(x,t) + X_n^p(x) \cdot T_n^p(t)$$

$X_n^1(x)$ and $T_n^1(t)$ when $p = 1$ are random values

1. Approximation function

$$u^{n,p}(x,t) = \sum_{i=1}^{n-1} X_i(x) \cdot T_i(t) + X_n^p(x) \cdot T_n^{p-1}(t)$$

Weight function

$$u^*(x,t) = X_n^*(x) \cdot T_n^{p-1}(t)$$

Calculating $X_n^p(x)$ from $T_n^{p-1}(t)$

2. Approximation function

$$u^{n,p}(x,t) = \sum_{i=1}^{n-1} X_i(x) \cdot T_i(t) + X_n^p(x) \cdot T_n^p(t)$$

Weight function

$$u^*(x,t) = X_n^p(x) \cdot T_n^*(t)$$

Calculating $T_n^p(t)$ from $X_n^p(x)$

Iteration proceeds until reaching a point within tolerance ϵ,

$$\left\| X_n^p(x) \cdot T_n^p(t) - X_n^{p-1}(x) \cdot T_n^{p-1}(t) \right\| < \epsilon$$

Calculation condition

The temperature of the mold surface is calculated from the temperature of the hot plate surface by the PGD

Boundary conditions

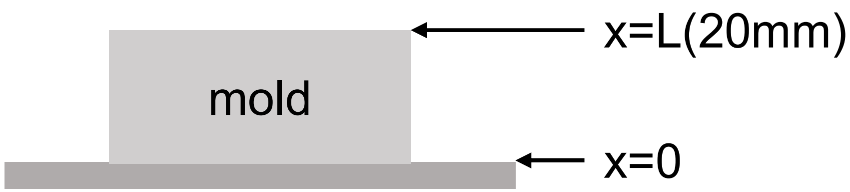
$$\begin{cases} u(x=0,t) = T_{plate}(t) & \text{The temperature of the mold surface} \\ \left.\dfrac{\partial u}{\partial x}\right|_{x=L,t} = q(t) = \text{const} & \text{Time distribution of heat flux is constant} \end{cases}$$

➡ Used in calculation as

$$\begin{cases} T_1(t) = T_{plate}(t) \\ X_1(x) = \begin{cases} 1 & (x=0) \\ 0 & (\text{else}) \end{cases} \\ \left.\dfrac{\partial X}{\partial x}\right|_{x=L} = q(t) \end{cases}$$

Divide into 100 points in x direction,
1000 points in t direction

Thermal diffusivity of aluminum : 98.8 mm²/s



Calculation results (1)

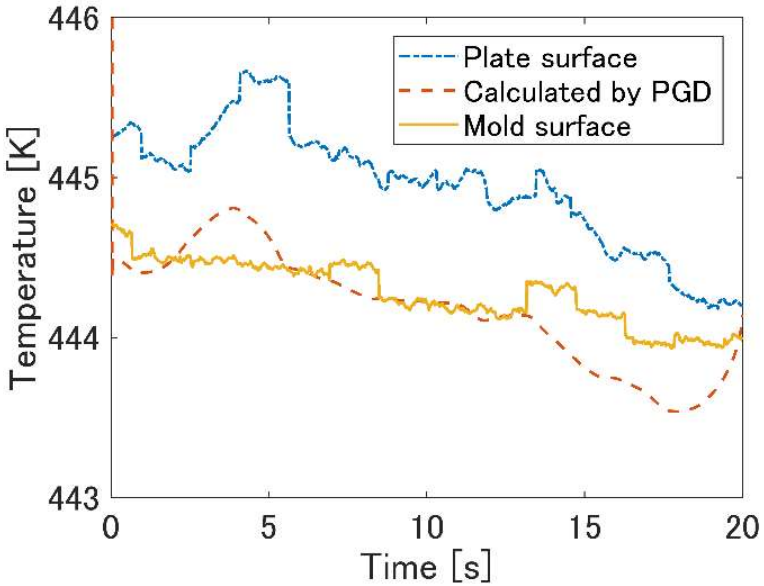
Comparing

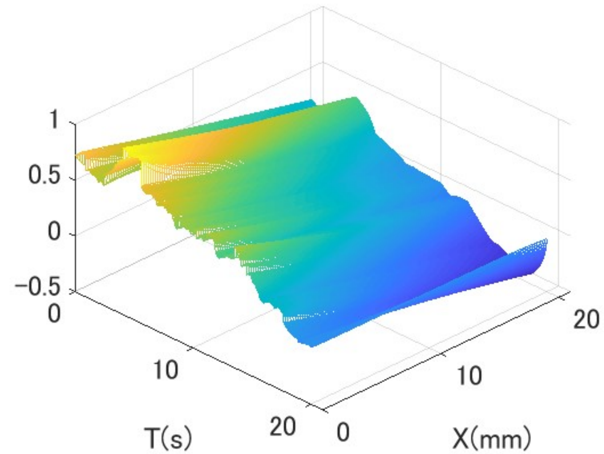
- Hot plate surface temperature
- Temperature of the mold surface calculated by the PGD
- Measured mold surface temperature

Assuming $q = -0.025$ W/mm^2, the temperature calculated by the PGD and the surface temperature of the mold are almost identical.

The temperature distribution across the entire thickness direction was determined

The validity of the PGD has been verified



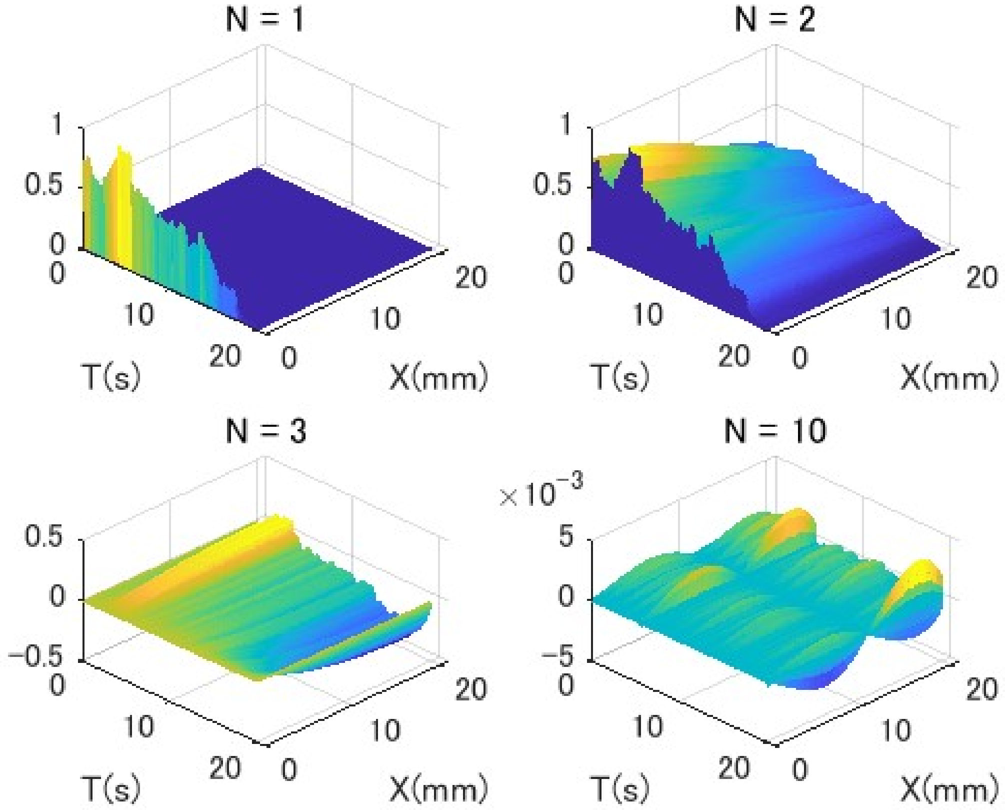


Calculation results (2)

Comparison of $X_N(x) \cdot T_N(t)$ for $N = 1, 2, 3, 10$

The order at $N = 10$ is small enough to be 10^{-3}

- Up to N=10, most of the information in the original data is represented
- Dimensionality can be significantly reduced by the PGD



Conclusion

1. The validity of the PGD for unsteady heat conduction with a boundary condition of heat flux has been verified
2. Calculated and measured values of the PGD method are close to each other.
3. It was confirmed that the PGD method reduces the dimensionality significantly.

Future issues

To apply to CFRP prepreg laminated body, we have to consider

- Examination of the thickness and degree of contact between layers
- Anisotropy of thermal diffusivity in the plane direction

→ Predicting the overlap and contact strength between layers from the surface temperature