A THERMAL CONDUCTIVITY ANALYSIS AFFECTING THERMOELASTIC STRESS MEASUREMENT OF LAMINATE COMPOSITES

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SUMMARY: Thermoelastic stress measurement is a useful nondestructive evaluation technique that can be in-situ applied. In order to apply it quantitatively to composite laminates, thermal conduction from inner layer and in-plane conduction of surface layer affecting thermoelastic stress measurement was examined in this paper. The reason of this heat conduction can be ascribed to the fact that each layer generates different levels of heat by the thermoelastic effect. Two-dimensional finite element analysis was conducted here to evaluate this heat conduction effect. Consequently, it was clarified that thermoelastic stress measurement could be quantitatively applied to conventional stacking sequences of laminate composites. It was also obtained that thermoelastic stress measurement data must be carefully dealt with if the surface layer generates relatively low heat thermoelastically.

KEYWORDS: thermoelastic stress measurement, thermal conduction, FEA, stress concentration

INTRODUCTION

A solid body shows thermoelastic temperature change caused by load under adiabatic condition, similarly in mechanism but to much less extent than gaseous body. By utilizing this phenomenon, thermoelastic stress measurement technique was established. This technique provides the sum of principle stress changes in the surface of isotropic solid body through a temperature measurement corresponding to a load change by using infrared thermo-camera. A cyclic load is required for an accumulation of data to improve S/N ratio in temperature change data. The thermoelastic stress measurement takes only reversible stress amplitude in principle. So, effect of viscoelasticity and internal friction are not taken into account in measuring temperature data.
In the case of CFRP laminates, however, thermal conduction from inner layer (out-of-plane) and in-plane conduction occur, affecting thermoelastic stress measurement because each layer shows different generated heat by thermoelastic effect or because stress concentration generates more heat. So, this thermal conduction should be examined to make sure the meaning of measured data. Two-dimensional finite element analysis was conducted here to evaluate this heat conduction effect and numerical results were compared with experimental results.

**BASIS OF THERMOELASTIC STRESS MEASUREMENT APPLIED TO LAMINATE COMPOSITES**

Thermoelastic constant of unidirectional CFRP

In the case of unidirectional CFRP (UD-CFRP), thermoelastic stress analysis must be examined with consideration to its orthotropic properties. A theoretical basis of thermoelastic stress measurement applied to unidirectional CFRP is reviewed in this section.

A temperature change caused by thermoelasticity can be described in the following equation as demonstrated by Kageyama 1).

\[ dT = -\frac{T}{\rho \cdot C_\sigma} \left( \alpha_L \cdot d\sigma_L + \alpha_T \cdot d\sigma_T \right) \]  

(1)

where \(dT\) is a temperature amplitude, \(T\) is an environmental temperature (the absolute in Kelvin), \(\rho\) is a density, \(C_\sigma\) is a specific heat at constant stress, \(\alpha\) is a thermal expansion and \(d\sigma\) is a stress amplitude. In this paper, subscripts, \(L\) and \(T\), indicate the fiber and transverse directions respectively. By substituting the following equations into Equation (1), we have

\[ K_L = \frac{\alpha_L}{\rho \cdot C_\sigma} \]  

(2)

\[ K_T = \frac{\alpha_T}{\rho \cdot C_\sigma} \]  

(3)

It can be rewritten as follows:

\[ dT = -T \left( K_L \cdot d\sigma_L + K_T \cdot d\sigma_T \right) \]  

(4)

These \(K\)'s (in Equations (2) and (3)) are referred to as the thermoelastic constants.

In the case of CFRP, a thermoelastic constant in the fiber direction is, however, much smaller than the transverse constant, that is \(|K_L| < \ll |K_T|\), and so a temperature amplitude caused by load in the fiber direction is also much smaller than the transverse temperature amplitude. Therefore measured temperature amplitude can be ruled by stress amplitude in the transverse direction, if the fiber angle is enough away from 0. In this situation, Equation (4) can be approximated by the next equation.

\[ dT \cong -K_T \cdot T \cdot d\sigma_T \]  

(5)
The stresses on orthotropic elastic axes, \( d\sigma_T \) and \( d\sigma_L \), are respectively zero in 0 and 90 UD-CFRP under uniaxial loads to 0 and 90. So, the thermoelastic constants of UD-CFRP, \( K_L \) and \( K_T \), are easily obtained from experimental data and Equation (1) without any approximation. The following thermoelastic constants\(^2\) are obtained in this procedure with UD-CF/Epoxy laminates.

\[
K_L = -1.16 \times 10^{-13} \text{[Pa]}
\]

\[
K_T = 2.21 \times 10^{-11} \text{[Pa]}
\]

These values are used in finite element analysis (FEA) in this paper.

**Thermoelastic stress measurement applied to multi-directional CFRP laminates**

From Equation (6) and (7), it is very clear that a generated heat amplitude caused by the transverse stress is much higher than the amplitude in the fiber direction. So, the generated heat amplitudes are different in each layer of multi-directional laminates. On the other hand, it is very difficult to maintain adiabatic conditions between layers due to upper frequency limit in the present tests of 30 Hz. Therefore, thermal conduction between layers may occur and the heat flux from inner layers to the surface has the same frequency as generated heat. This thermal conduction between layers will be examined in the following.

**FINITE ELEMENT MODELS**

Finite element code ANSYS was used in this paper to examine a heat conduction effect from inner layer to the surface of CFRP laminates. Heat convection on the surface was also calculated in some cases. Two dimensional 8-node heat transfer element was used. Two types of the problems are assumed: One case is a no-hole model shown in Figure 1. This figure shows a normal section to the loading direction in the smooth specimen without a hole. The other case is a model with a circular hole, shown in Figure 2. The smooth model was a half of an actual section and the hole model was taken to a quarter of the whole section due to the symmetry derived from adiabatic conditions.
Calculation procedures for smooth laminate models

Two stacking sequences A: (45/-45/0/90) s and B: (0/90/45/-45) s, were considered and compared with experimental results 3). The calculation procedure is as follows:

1. Nominal stresses were calculated with a uniform strain in the lamina and elastic constants of the whole laminates.
2. A stress in each layer was calculated from nominal stresses using the classical lamination theory.
3. Stresses in each layer were converted to stresses in fiber and transverse directions.
4. A generated heat amplitude in each layer was obtained.
5. These amplitudes were used as thermal input settings in FEA and the shape of generated heat in each layer was assumed as a sinusoidal function.
6. A temperature distribution in a surface node was obtained after enough time to achieve periodically stable state.

Material properties used in this calculation are shown in Table 1. Three boundary conditions were assumed as follows:

(a) With no conduction between layers and no convection on the surface (boundary condition #2 in Figure 3).
(b) With conduction between layers and no convection on the surface (boundary condition #3).
(c) With conduction between layers and convection on the surface (boundary condition #4).

<table>
<thead>
<tr>
<th>Table 1 Input material property</th>
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<tbody>
<tr>
<td>Thickness of 1 ply</td>
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<tr>
<td>Thermal conductivity</td>
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<tr>
<td>Specific heat</td>
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<tr>
<td>Density</td>
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Calculation procedures for circular hole models

In order to focus in-plane heat conduction under some stress concentration, laminate composite model with a circular hole was considered. The FEA results were compared with a theoretical result. The calculation procedure is as follows:

1. Nominal stresses in the far field point from the circle were calculated with a uniform strain and elastic constants of the whole laminates.
2. A stress distribution shape of a homogeneous isotropic plate with a hole was assumed and multiplied by the nominal remote stress for determining specific stress levels.
3. Stresses at each node were calculated from the above stress distribution and by using the classical lamination theory.
(4) Stresses in each layer were converted to stresses in the fiber and transverse directions.
(5) A generated heat amplitude in each layer at each node was obtained.
(6) These amplitudes were used as thermal input settings in FEA and the shape of generated
heat in each layer was assumed as a sinusoidal function.
(7) A temperature distribution in a surface node was obtained after enough time to achieve
periodically stable state.

Input material properties were the same as Table 1 and also boundary conditions.

RESULTS OF FINITE ELEMENT ANALYSIS

Smooth laminate models

Temperature histories at surface nodes were obtained by the procedure mentioned above. The
experimental and FEA results with three boundary conditions are shown in Figure 3 for
laminates A and B. In the results of laminate A with a 45 surface layer, boundary condition #2
(no heat conduction and convection considered) provides a little higher temperature amplitude
than the experimental value. Conditions #3 and #4 provide very similar results to the
experiment. In the laminate B with 0 surface layer, condition #2 gives, however, almost null
amplitude and quite different from the experimental value. Conditions #3 and #4 lead to
similar results to the experiment. The later case (laminate B) shows a typical example of an
effect of heat conduction between layers. The reason of this effect is considered that a 0
surface layer generates much less heat than inner layers of 90, 45 and –45 directions. In the
case of a 45 surface layer, the generated heat there is close to the average of generated heat in
all layers. Hence, even no heat conduction condition provides a reasonable result in the case
of laminate A. The heat convection at the laminate surface was also examined with a
boundary condition #4 and the result is shown in Figure 3. There was no significant difference
between #3 and #4. So, heat convection on the surface can be negligible in the present
thermoelastic stress analysis.

If we check time histories in temperature change, there is no phase shift between histories of
the surface temperature and load for condition #2. However, a phase shift can be observed for
conditions #3 and #4 as shown in Figure 4. Heat conduction can be ascribed to one of the
main source of the phase shift appearing in actual measurements.
Figure 3 Comparison of temperature amplitudes in the surface of laminate composites, A: (45/-45/0/90)s and B: (0/90/45/-45)s, with FEA and experimental results.

1: experiment
2: with no heat conduction between layers and no convection on the surface
3: with heat conduction between layers and no convection on the surface
4: with heat conduction between layers and convection on the surface

Figure 4 Temperature histories in one cycle after reached periodically steady state.
Circular hole models

In the same way of smooth laminate model, calculations for circular hole models were conducted in laminate A case. Two loading frequencies, 5 and 20 Hz, were assumed. The temperature amplitude distributions at the surface along the center line perpendicular to the load are shown in Figure 5. Position 0.0 denotes the hole center where two square and one cross legends correspond to two FEA results of 5 and 20 Hz and the no heat conduction solutions neither in-plane nor out-of-plane. Figure 5 indicates that the in-plane heat conduction affects very little to temperature amplitude distribution at remote points from the hole edge. The temperature amplitude in FEA, however, leads to slightly lower amplitude than the theoretical result at a hole edge. This fact is considered as an effect of in-plane heat conduction. The temperature amplitudes by FEA for 5 and 20 Hz and the theoretical results are detailedly compared in Figure 6. This reduction of stress concentration depends on the frequency and higher frequency makes it closer to theoretical value. The temperature amplitude with 5 and 20 Hz are 83 and 90 % of theoretical, respectively. A thermoelastic stress measurement result must be carefully examined at a stress concentration region.

Figure 5 Temperature amplitude distributions on the surface along to center line perpendicular to the load, laminate (45/-45/0/90)s.
CONCLUSIONS

The thermoelastic stress measurement can be applied to quantitative stress measurement for composite laminates with a 45 layer surface of common stacking sequence in the aerospace composite structures. In such a laminate, heat conduction from inner layers can be almost neglected. The heat convection effect on the surface is found to be negligibly small. On the other hand, it was uncovered that thermal conduction must be considered for 0 surface laminates where very low heat is generated thermoelastically. Another important finding is that the phase shift between load and temperature histories is mainly caused by the heat conduction.

It is also clarified that in-plane heat conduction effect is not significant in the remote region from stress concentration for laminates with a circular hole. It should be noted that FEA data at the hole edge is less than the no heat conduction solutions where as adiabatic condition is considered. If a sharp stress concentration exists, it is suggested that the calculated stress amplitude at the highest concentration will be relaxed by considering heat conduction. These conclusions suggest a possible application of thermoelastic stress analysis to quantitative measurement for multi-directional laminate composites.

REFERENCES