MULTISCALE ANALYSIS OF MATERIAL DAMPING PROPERTIES FOR TEXTILE COMPOSITES

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ABSTRACT

In this paper, we have proposed a numerical method that the damping properties of textile composites are obtained by mesh superposition method based on finite element method. To obtain the material damping properties of textile composites, finite element is formulated with strain energy method. The proposed method has been applied to the plain woven fabric composites. Experiments have been conducted to evaluate the validity of the proposed method. It is recognized that the computational results have agreed with the experimental ones.

1. INTRODUCTION

Material damping represents the cumulative contributions of the viscoelastic response of the constituents, cyclic heat flow and the friction at the fiber/matrix interface. Recent work on the material damping of FRP has shown that the composite damping depends on an array of micromechanics and laminate parameters, including constituent material properties, fiber volume fraction, stacking sequence and so on [1][2]. These studies, however, are mostly limited to unidirectional composites.

On the other hand, textile composites are applied to many fields such as the space structures, sports items. Recently, many researchers have studied the identification of mechanical properties of textile composites by finite element modeling to predict mechanical properties of textile composites. Though many researchers have reported the static characteristics of woven composites, the material damping of those materials have not been investigated [3-5]. And, the practical modeling technique and its systematization considering the complicated non-homogeneity of textile composites have not been developed completely. Furthermore, it is very difficult to evaluate the mechanical behavior of composites because of the complicated geometrical shape.

Fish and Wagiman used another microscopic model that directly expressed the microscopic heterogeneity of the microscopic region to be analyzed [6]. They superimposed the microscopic model onto the homogenized model. This finite element mesh superposition method was originally presented by Fish under the name of s-version FEM, in a series of studies on the adaptive FEM [7]. This application is limited to stress analysis, such as the damage analysis.

This paper presents the application of the mesh superposition method for calculation of material damping properties of textile composites.

2. MULTISCALE ANALYSIS OF MATERIAL DAMPING

The finite element mesh superposition method uses two independent meshes. One of them is macroscopic mesh that uses the homogenized material model reflecting microscopic heterogeneity. The other one is the microscopic mesh that is arbitrarily superimposed onto the macroscopic mesh, without taking care of matching nodes. The microscopic heterogeneity is modeled directly on the microscopic mesh and local heterogeneity such as void, inclusion, crack, interface, etc.

As shown in Figure 1, Ω is the overall region and Γ is its boundary. the local region, onto which the microscopic mesh is superimposed, is Ω^L. Ω^G is defined as $\Omega \setminus \Omega^L$. Γ^{GL} is the boundary between Ω^G and Ω^L. Hereafter, the suffix G denotes the global quantity and the suffix L denotes the local quantity.

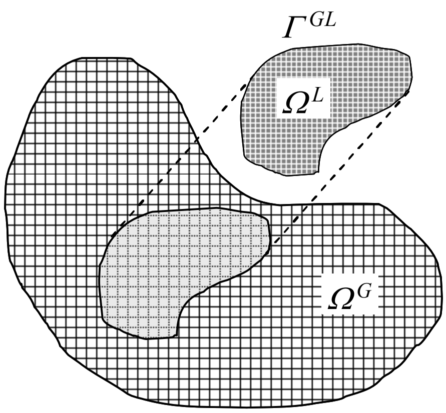

Figure 1: Macro- and microscopic domain

The displacement is written as follows:

$$\boldsymbol{u} = \begin{cases} \boldsymbol{u}^G & \text{on } \Omega^G, \Gamma^{GL} \\ \boldsymbol{u}^G + \boldsymbol{u}^L & \text{on } \Omega^L \end{cases} \tag{1}$$

It should be noted that the displacement is interpolated in the finite element by the shape function $\boldsymbol{N}$. The mesh superposition method is one of the techniques that allow two meshes with different element sizes. The shape functions of the two meshes connect the macroscopic and microscopic displacement fields. To retain continuity at the boundary Γ^{GL}, we assume that the following equation holds true.

$$\boldsymbol{u}^L = 0 \quad \text{on } \Gamma^{GL} \tag{2}$$

The constitutive equations in each region are written as follows:

$$\boldsymbol{\sigma} = \begin{cases} \boldsymbol{D}^G \boldsymbol{B}^G \boldsymbol{u}^G & \text{on } \Omega^G \\ \boldsymbol{D}^G (\boldsymbol{B}^G \boldsymbol{u}^G + \boldsymbol{B}^L \boldsymbol{u}^L) & \text{on } \Omega^L \end{cases} \tag{3}$$

where $\boldsymbol{D}$ and $\boldsymbol{B}$ denote the elastic stress-strain matrix and strain-displacement matrix. To assure the consistency between the macroscopic and microscopic governing equations, the homogenized constitutive equation should be predicted by the asymptotic homogenization method accurately for arbitrary complex 3D microstructure architecture. The strain and stress are discontinuous at the boundary Γ^{GL}. The microscopic region Ω^L can be arbitrary only if the homogenized constitutive model can be predicted accurately for Ω^L in this paper's setting.

Above relations are substituted into the following governing equation.

$$\int_V \bar{\boldsymbol{u}}^T \rho \ddot{\boldsymbol{u}} dV + \int_V \bar{\boldsymbol{\varepsilon}}^T \boldsymbol{D} \boldsymbol{\varepsilon}\, dV = \int_V \bar{\boldsymbol{u}}^T \bar{\boldsymbol{F}} dV + \int_V \bar{\boldsymbol{u}}^T \bar{\boldsymbol{T}} d\Gamma \tag{4}$$

where $\bar{\boldsymbol{u}}$ and $\bar{\varepsilon}$ are the virtual displacement and strain, respectively. However, it is not the limitation of the mesh superposition method, and the external force, body force, and thermal stress can be considered if needed.

In the present work, the general vibration equations of motion can then be written in the form of relation Eqs.5 and 6.

$$\begin{bmatrix} \boldsymbol{M}^G & \boldsymbol{M}^{GL} \\ \boldsymbol{M}^{LG} & \boldsymbol{M}^L \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{d}}^G \\ \ddot{\boldsymbol{d}}^L \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}^G & \boldsymbol{K}^{GL} \\ \boldsymbol{K}^{LG} & \boldsymbol{K}^L \end{bmatrix} \begin{Bmatrix} \boldsymbol{d}^G \\ \boldsymbol{d}^L \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{5}$$

$$\left(\begin{bmatrix} \boldsymbol{K}^G & \boldsymbol{K}^{GL} \\ \boldsymbol{K}^{LG} & \boldsymbol{K}^L \end{bmatrix} - \omega^2 \begin{bmatrix} \boldsymbol{M}^G & \boldsymbol{M}^{GL} \\ \boldsymbol{M}^{LG} & \boldsymbol{M}^L \end{bmatrix} \right) \begin{Bmatrix} \boldsymbol{u}^G \\ \boldsymbol{u}^L \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{6}$$

where

$$\left.\begin{aligned}
\boldsymbol{M}^G &= \int_{\Omega^G} (\boldsymbol{N}^G)^{\mathrm{T}} \rho^G \boldsymbol{N}^G d\Omega^G + \int_{\Omega^L} (\boldsymbol{N}^G)^{\mathrm{T}} \rho^L \boldsymbol{N}^G d\Omega^L \\
\boldsymbol{M}^{GL} &= \int_{\Omega^L} (\boldsymbol{N}^G)^{\mathrm{T}} \rho^L \boldsymbol{N}^L d\Omega^L \\
\boldsymbol{M}^L &= \int_{\Omega^L} (\boldsymbol{N}^L)^{\mathrm{T}} \rho^L \boldsymbol{N}^L d\Omega^L \\
\boldsymbol{K}^G &= \int_{\Omega^G} (\boldsymbol{B}^G)^{\mathrm{T}} \boldsymbol{D}^G \boldsymbol{B}^G d\Omega^G + \int_{\Omega^L} (\boldsymbol{B}^G)^{\mathrm{T}} \boldsymbol{D}^L \boldsymbol{B}^G d\Omega^L \\
\boldsymbol{K}^{GL} &= \int_{\Omega^L} (\boldsymbol{B}^G)^{\mathrm{T}} \boldsymbol{D}^L \boldsymbol{B}^L d\Omega^L \\
\boldsymbol{K}^L &= \int_{\Omega^L} (\boldsymbol{B}^L)^{\mathrm{T}} \boldsymbol{D}^L \boldsymbol{B}^L d\Omega^L \\
\boldsymbol{P}^G &= \int_{\Omega^G} (\boldsymbol{N}^G)^{\mathrm{T}} \bar{\boldsymbol{F}}^G d\Omega^G + \int_{\Omega^L} (\boldsymbol{N}^G)^{\mathrm{T}} \bar{\boldsymbol{T}}^L d\Gamma^{GL} \\
\boldsymbol{P}^L &= \int_{\Omega^L} (\boldsymbol{N}^L)^{\mathrm{T}} \bar{\boldsymbol{F}}^L d\Omega^L
\end{aligned}\right\} \tag{7}$$

A modal damping ratio, the ratio of the dissipated energy during one complete cycle to the maximum stored energy from the beginning of the loading to the maximum, is expressed as

$$\zeta_n = \frac{1}{4\pi} \cdot \frac{\Delta U_n}{U_n} \tag{8}$$

where ΔU_n is the total damping energy per cycle of vibration, U_n is the maximum strain energy and n is the modal number. In terms of the present method, each energy are given by following equations

$$U = \frac{1}{2}\begin{Bmatrix} \boldsymbol{u}^G \\ \boldsymbol{u}^L \end{Bmatrix}^T \begin{bmatrix} \boldsymbol{K}^G & \boldsymbol{K}^{GL} \\ \boldsymbol{K}^{LG} & \boldsymbol{K}^L \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}^G \\ \boldsymbol{u}^L \end{Bmatrix} \tag{9}$$

$$\Delta U = \frac{1}{2}\begin{Bmatrix} \boldsymbol{u}^G \\ \boldsymbol{u}^L \end{Bmatrix}^T \begin{bmatrix} \boldsymbol{\Psi}^G & \boldsymbol{\Psi}^{GL} \\ \boldsymbol{\Psi}^{LG} & \boldsymbol{\Psi}^L \end{bmatrix} \begin{Bmatrix} \boldsymbol{u}^G \\ \boldsymbol{u}^L \end{Bmatrix} \tag{10}$$

where $\boldsymbol{\Psi}$ is damped stiffness matrix.

3. MULTISCALE ANALYSIS OF PLAIN WOVEN COMPOSITES

3.1 Material

Test specimens have been fabricated by the hand-lay up method, using vinylester resin (supplied from Showa polymer Co. LTD.: R-806) reinforced by E-glass woven cloth fabric with 3 bundles (supplied from Asahi fiber glass Co. LTD.: WR570B). Figure 2 shows a part of cross section of the fiber bundles by a laser microscope. From this image, the volume fraction for a fiber bundle can be measured with a digital image processing technique. In case of the plain woven fabric composites, as shown in Figures 3 and 4, there is the distribution of volume fraction in a fiber bundle. The center parts have higher volume fraction 69.0% and edge parts have lower value of 58.7%.

Figure 2: Laser microscope image of the test specimen

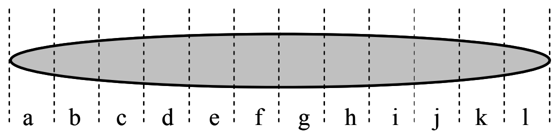

Figure 3: Schematic of division of fiber bundle

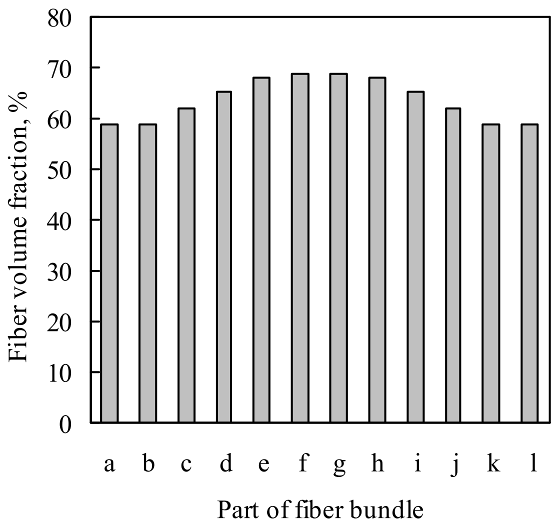

Figure 4: Fiber volume fraction of fiber bundle

3.3 Numerical example

The dimensions of global model are shown in the Figure 5. The mechanical properties were calculated by the homogenization method. The number of total nodes and elements of global mesh are 12,663 and 8,000, respectively.

To analyze the mesoscopic energy dissipation at the woven architecture, the mesoscopic mesh shown in Figure 6 is generated. The number of solid elements and nodes are 3,360 and 4179, respectively. Fiber bundles were treated as unidirectional FRP, and the mechanical properties were calculated by the rule of mixture based on the obtained fiber volume fractions.

To estimate the material damping, finite element analysis has been carried out. Computational results of plain woven composite are shown in Figure 7. As shown in Figure 7, it is recognized that the damping ratio does not depend on frequency.
To confirm the validity of the numerical results, vibration tests have been carried out in the low-pressure condition (40Pa) in order to consider effect of aerodynamic force. The numerical results both natural frequency and damping ratio have a good agreement with the experimental ones as shown in Figure 7.

From this results, it can be recognized that the material damping of plain woven composites can be estimated with the proposed numerical method.

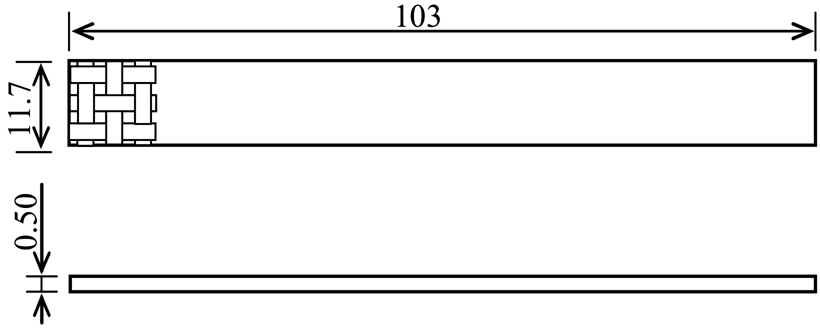

Figure 5: Dimensions of test specimen.

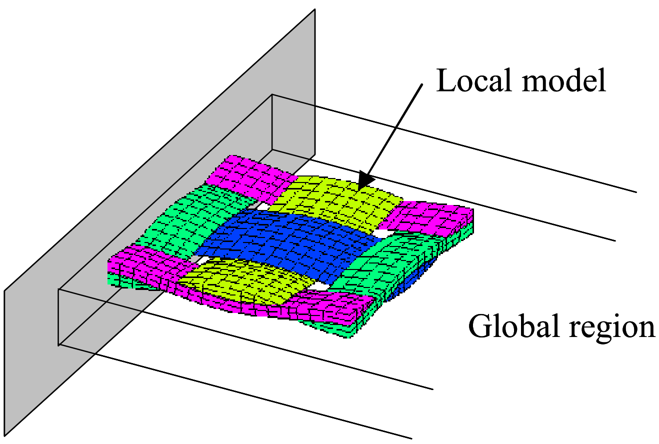

Figure 6: Finite element mesh model.

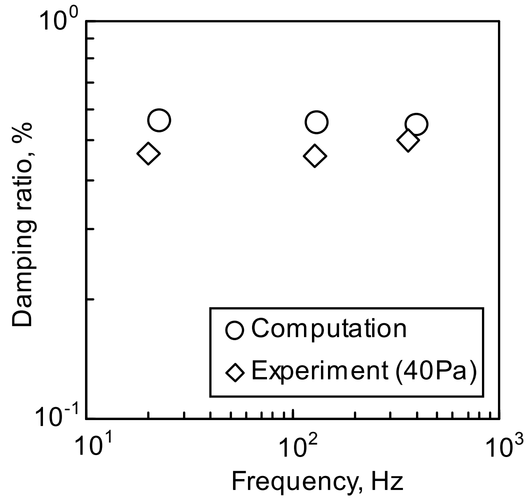

Figure 7: Comparison of experimental and numerical results

4. CONCLUSIONS

The numerical method of material damping for textile composites by mesh superposition method has proposed. Comparing the numerical results with the experimental ones, it is recognized that the proposed method is capable to estimate the material damping of woven composites.

REFERENCES

1- Saravanos, D.A. and Chamis, C.C., "Unified micromechanics of damping for unidirectional and off-axis fiber composites", *Journal of Composite Technology Research*, 1990; 12(1): 31-40.
2- Adams, R.D. and Bacon, D.G.C., "Effect fiber-orientation and laminate geometry on properties of CFRP", *Journal of Composites Materials*, 1973; 7: 402-428.
3- Carvelli, V. and Poggi, C.A., "A homogenisation procedure for the numerical analysis of woven fabric composites", *Composites Part A*, 2001; 32: 1425-1432.
4- Whitcomb, J. and Sriengan, K., "Effect of various approximations on predicted progressive failure in plain weave composites", *Composite structures*, 1996; 34: 13-20.
5- Verpoest, I. and Lomov, S.V., "Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis", Composites Science and Technology, 2005; 65: 2563-2574.
6- Fish, J., "The s-version of the finite element method" *Computers and Structures*, 1992; 35-4: 539-547.
7- Fish, J. and Wagiman, A., "Multiscale finite element method for heterogeneous medium" *Computational Mechanics*, 1993; 12: 1-17.