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Homogenization of fin layers in tube-fin structures subjected to compression and bending: Analyses and experiments

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ABSTRACT

This paper verifies fin-homogenization for finite element analysis of heat exchanger cores with stacking of flat tubes and thin wavy fins. A first-order homogenization method is proposed on the assumption that uniform deformation prevails a short distance away from each fin layer in the stacking direction while the wavy fins have periodicity in the in-layer directions. Using this homogenization method, the homogenized elastic stiffness values of outer and inner fin layers in an intercooler are evaluated by considering real and sinusoidal shapes of the wavy fins. The homogenized elastic stiffness values attained are examined by performing fin-homogenization-based (fin-h-based) analyses, full-scale analyses, and experiments of tube-fin layered specimens subjected to compression and bending. It is shown that the fin-h-based and full-scale analyses give good agreements to each other even in the presence of macro-strain gradients in the outer and inner fin layers though the homogenization method is of first-order. Moreover, it is shown that the fin-h-based analyses reproduce well the experiments if the homogenized elastic stiffness values obtained for the real shapes of outer and inner fins are used in the analyses. It is also shown that the Bernoulli-Euler assumption is not satisfied in the homogenized outer fin layers under longitudinal bending because the homogenized elastic shear stiffness responsible for the bending is very low.

1. Introduction

Tube-fin structures with stacking of flat tubes and wavy fins have been in heavy usage as heat exchanger cores in radiators, intercoolers, and so on. A heat exchanger of this type is schematically illustrated in Fig. 1. The flat tubes in the figure can be inserted by wavy fins, called inner fins, to enhance heat transfer, as depicted in Fig. 1(b). Temperature generally distributes non-uniformly in this type of heat exchangers because a fluid flows in the tubes from a high to a low temperature tank. Due to the start/stop of engines and generators, the temperature profiles cyclically vary to cause cyclic thermal stresses. Consequently, fatigue cracks may occur at the joint of a tube and a tank if heavy endurance tests are performed.

Finite element analysis is effective for predicting the fatigue failure mentioned above. If heat exchangers as illustrated in Fig. 1 are fully divided into finite elements, the number of finite elements must be enormously large to cause very high computational loads. This problem can be overcome by applying homogenized material models to heat exchanger cores [1–5]. For the type of heat exchangers illustrated in Fig. 1, however, it is difficult to homogenize all parts of tube-fin structures, because each tube has no periodicity in the end portions in the width-direction, as indicated in Fig. 1(b). Moreover, fatigue failure may occur at the junction of a tube and a tank, as already stated. This means that it is not appropriate to homogenize the tubes. It is therefore suggested to homogenize only the fin layers for leaving the tubes unchanged [6,7].

Homogenized mechanical properties of inhomogeneous materials can be evaluated by averaging micro-stress and micro-strain in periodic unit cells (PUCs), or more generally representative volume elements (RVEs), in which macro-strain is assumed to be uniform [8–12]. This kind of homogenization methods is classified as first-order. However, first-order homogenization methods cannot be suitable if macro-strain has non-negligible gradients in PUCs, or RVEs, in boundary-value problems [13]. A typical example is bending of a beam which consists of a relatively small number of

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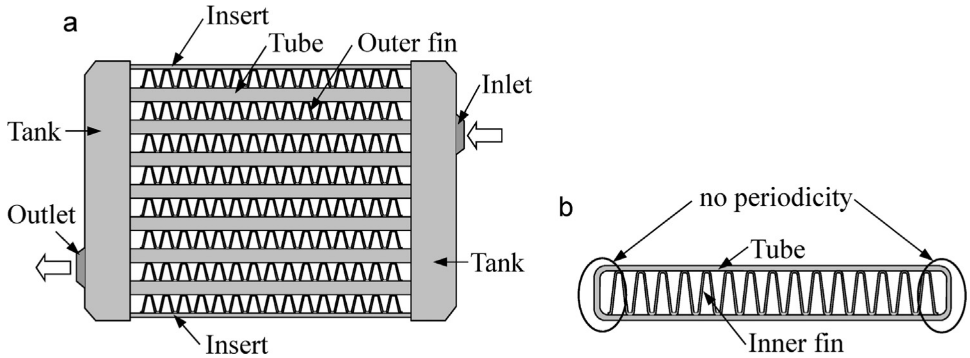

Fig. 1. Heat exchanger with core composed of flat tubes and wavy fins; (a) schematic view of heat exchanger and (b) cross-section of flat tubes.

PUCs in the height direction, because the PUCs in such beams normally have macro-strain gradients in the height direction [13,14]. Macro-strain gradients have been taken into account by developing second-order homogenization methods [13,15].

Tubes and fin layers in the type of tube-fin structures illustrated in Fig. 1 can be subjected to bending, in addition to tension/compression, due to non-uniform temperature profiles and outer constraints. It is noted that, because the stacking distance of tubes and outer fin layers may not be sufficiently small, first-order homogenization methods may not be suitable for fin-homogenization in the presence of bending. It is, therefore, worthwhile to examine first-order homogenization methods for fin-homogenization in tube-fin structures subjected to bending. If a first-order homogenization method is verified for fin-homogenization, the resulting homogenized elastic stiffness can be immediately used in commercial finite element software in contrast to second-order homogenization methods.

A notice is provided for the fin-homogenization stated above. The outer and inner fins have periodicity in the in-layer directions, while no periodicity can be imposed on the fin layer boundaries in the stacking direction, as described in Section 2.1. In other words, the homogenization methods developed for three-dimensional (3D) periodic composites are not directly applicable to the outer and inner fins. Hence, it is necessary to assume an appropriate boundary condition in the stacking direction for evaluating the homogenized properties of the outer and inner fin layers.

This paper describes the validity of fin-homogenization for finite element analysis of tube-fin structures with stacking of flat tubes and thin wavy fins. First, a first-order homogenization method is proposed on the assumption that uniform deformation prevails a short distance away from each fin layer in the stacking direction while the wavy fins have periodicity in the in-layer directions. The bilayer model developed by Tsuda and Ohno [16] is then used to attain the homogenized elastic stiffness of a fin layer. Second, the proposed homogenization method is applied to real and sinusoidal shapes of outer and inner fins in an intercooler. Third, the obtained homogenized elastic stiffness values of the outer and inner fin layers are examined by performing fin-homogenization-based (fin-h-based) and full-scale analyses of a tube-fin layered board subjected to uniaxial compression and cantilever bending. Finally, fin-homogenization is verified by performing experiments and fin-h-based analyses of tube-fin specimens subjected to uniaxial compression and four-point longitudinal bending. It is shown that the experiments are predicted well by the fin-h-based analyses using the homogenized elastic stiffness values obtained for the real fin shapes although the homogenization method is of first order. It is also shown that the Bernoulli-Euler assumption is not satisfied in the homogenized outer fin layers under longitudinal bending because the homogenized elastic shear stiffness responsible for the bending is very low.

2. Homogenization method for fin layers

In this section, a first-order homogenization method is proposed to evaluate the homogenized elastic stiffness of a fin layer. Vectors and tensors are expressed using components with respect to the Cartesian coordinates x_i $(i = 1, 2, 3)$, and differentiation with respect to x_i is indicated as $(\ )_{,i}$. The summation convention is used. The Cartesian coordinates x, y, and z are also used in Section 2.2.

2.1. Basic assumptions and equations

Let us consider a thin wavy fin, of height $\tilde{h}$, sandwiched by plates. The fin and the plates are made of a base solid. We assume that the wavy fin is periodic in the in-layer directions. We further assume that uniform deformation prevails in the plates at a distance $\bar{h}$ away from the fin layer, because mechanical interactions necessarily occur on the boundaries between the fin and plates. These assumptions allow us to consider the unit cell Y illustrated in Fig. 2. This unit cell is referred to as the plate-fin unit cell hereafter. The displacement u_i in the solid part Y^s in the plate-fin unit cell Y can then be written as

$$u_i = E_{ij}x_j + u_i^* \tag{1}$$

where E_{ij} indicates the macro-strain, x_i denotes the position in Y^s, and u_i^* signifies the perturbed part of u_i satisfying

$$u_i^*(\boldsymbol{x}^+) = u_i^*(\boldsymbol{x}^-) \text{ on } \partial Y^s_{\text{in}}, \tag{2}$$

$$u_i^* = 0 \text{ on } \partial Y^s_{\text{out}}. \tag{3}$$

Here, ∂Y^s_{in} and $\partial Y^s_{\text{out}}$ denote the in-layer and out-of-layer boundaries of Y^s, and $\boldsymbol{x}^+$ and $\boldsymbol{x}^-$ are a pair of points on ∂Y^s_{in} (Fig. 2). Eq. (2) is the Y-periodic condition on ∂Y^s_{in}, whereas Eq. (3) is the uniform deformation condition on $\partial Y^s_{\text{out}}$.

When u_i is written as Eq. (1), the stress in Y^s is expressed as[1]

$$\sigma_{ij} = D^s_{ijkl}(E_{kl} + \varepsilon^*_{kl}), \tag{4}$$

where D^s_{ijkl} is the elastic stiffness of the base solid, and ε^*_{kl} indicates the perturbed strain defined as

$$\varepsilon^*_{kl} = \frac{1}{2}(u^*_{k,l} + u^*_{l,k}). \tag{5}$$

The stress balance in Y^s is represented in the following form in the

[1] Since the plate-fin unit cell shown in Fig. 2 is made of a single base solid, the homogenized thermal expansion coefficient of the unit cell is trivially the same as that of the base solid. Hence, the present study focuses on the mechanical homogenized behavior, and accordingly, thermal stress and thermal strain are not considered in Eq. (4).