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Heterogeneous anisotropic complex structure gradual model and constitutive relation*

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Four new gradually delaminate models of the three-dimensional macro-/mesoscopic structure and delamination of the heterogeneous anisotropic composite (HAC) are set up by conducting research into its structure and performance. A general theory, which demonstrates the three-dimensional constitutive relation of the macro-/mesoscopic performance of this structure is further developed. The macroscopic expression of HAC is presented in terms of a Tanigawa delaminate homogeneous equivalent approach, the mesoscopic problems are analysed utilizing Eshelby–Mori–Tanaka theory, with the introduction of the representative volume elements of monolayer single unit cell and interlaminar double unit cells. According to the gradual continuity of the structure as a whole, great attention is given to the modelling and research of the interlaminar macroscopic and mesoscopic problems of HAC structure. Comparison with the existing solutions is made through calculation of typical cases.

Keywords: HAC, constitutive relation, mesoscopic, Tanigawa approach
PACC: 0340D, 4630, 6220

1. Introduction

Heterogeneous anisotropic composite (HAC), a type of composite material, the components, structure and physical parameters of which are in gradual continuum variation with no distinct interfaces, is a new material designed in the late 1980s. Most of the intense research has adopted the particle period theory equivalent theory, and effective performance forecast, and focused on taking the volume percentage of the reinforcing phase as the parameter expressing the material structure. In this simple approach, the performance and structural essence of HAC are not unveiled. Efforts are made by some workers in different ways such as the gradual model of particle materials put forward in physical and chemical experiments by Zhigang Zou *et al*,[1] and the three-dimensional heterogeneous model suggested by Kitopornchai and coworkers.[2]

Focusing on HAC structure, we set up the three-dimensional HAC constitutive relation. To analyse HAC structure, the macroscopic and mesoscopic characteristics of HAC must be studied. We introduce in this paper the monolayer single unit cell and interlaminar double unit cell for the analysis of HAC structure and the gradual constitutive relation of HAC with ellipsoid reinforcing phase is set up using the Tanigawa approach.[3,4] The purpose of the research is to discover the intrinsic physical and mechanical mechanism of the HAC structure, with a view to choosing proper component materials and distribution functions to design an optimized HAC structure.

The analysis of the HAC interlaminar problem is essentially a complex three-dimensional problem, hence an effective calculation method of the interlaminar analysis of HAC multi-layer structure is of great significance in engineering. To obtain the effective solution of the interlaminar problem for the multi-layer HAC structure, we start from the three-dimensional stress state of laminate plates and suppose the interlaminar stress to be an exponential function according to the equilibrium of the total force and its moment and the principle of minimum residual energy. To acquire an accurate description of the interlaminar stress, we are careful in establishing the new model and the corresponding theory of interlaminar stress analysis. Microscopically, the Eshelby–Mori–Tanaka[3,4] approach and improved superposition method[5−7] are utilized to give the quantitative

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analysis of the interlaminar stress of HAC with ellipsoidal entrainment.

2. Fundamental theory

2.1. Macroscopic three-dimensional constitutive equation of HAC structure

Starting from the analysis of macroscopic elasticity properties of the laminate HAC structure, the three-dimensional constitutive equation of laminate thick HAC is established. In the research, two delamination models are set up, which make the distribution of materials in the structure more gradual, continuous, holistic and thus truly represents the HAC structure.

Taking such factors as preparation techniques, structure and calculation into consideration, HAC can be delaminated in two steps. The HAC is first delaminated into M ($M \to \infty$) orthotropic sublayers with the same thickness but different volume percentages f for each, namely f_i for sublayer i, say. Each sublayer is then delaminated in the same way into N orthotropic particle reinforcing HAC monolayers (with the same cross section area as the sublayer and the same thickness for each monolayer), having different volume percentages f and thereby different performance for each layer, i.e. $f_{(k)}$ for monolayer k, say.

However, with respect to one monolayer, the same volume percentage at each point in the layer makes it possible to view it as being homogeneous and therefore achieve to homogenized equivalent delamination,[8−11] as shown in Fig. 1.

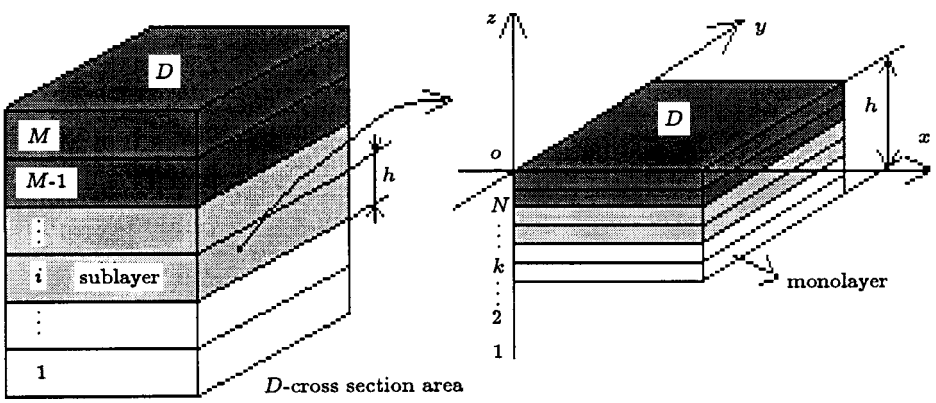


Fig.1. Model of HAC structure.

According to the definitions of the macroscopic effective stress and strain of three-dimensional HAC structure, both the stress σ_{mn} and the strain ε_{mn} of each sublayer can be viewed as in uniform distribution. The expression of the stress and strain of the holistic HAC structure can be obtained:

$$\bar{\sigma}_{mn} = \sum_{i=1}^{M} f_i \sigma_{mn}^i,$$

$$\bar{\varepsilon}_{mn} = \sum_{i=1}^{M} f_i \varepsilon_{mn}^i, \quad (i = 1, 2, \cdots, M),$$

$$f_i = \sum_{k=1}^{N} f_{(k)}/N, \tag{1}$$

in which f_i is the volume percentage of sublayer i. Suppose that the thickness of a monolayer is very small, the stress and strain of the monolayer within the plane can be viewed as in uniform distribution, the expression of the stress and strain of sublayer i is obtained:

$$\sigma_{mn}^i = \sum_{k=1}^{N} f_{(k)} \sigma_{mn}^{(k)},$$

$$\varepsilon_{mn}^i = \sum_{k=1}^{N} f_{(k)} \varepsilon_{mn}^{(k)}, \quad (k = 1, 2, \cdots, N), \tag{2}$$

in which $f_{(k)}$, the volume percentage of monolayer k, is determined by the formula

$$f_{(k)} = a_0 + a_1 x + a_2 x^2 + a_3 y + a_4 y^2 + a_5 z + a_6 z^2, \tag{3}$$

in which a_j is a changing parameter, the value of which is determined by the restraining conditions, preparation techniques and the relative position of the monolayer in a sublayer.

Therefore, the gradual constitutive equation of the three-dimensional macroscopic structure of heat-resistant HAC is obtained:

$$\begin{Bmatrix} \bar{\sigma}_{xx} \\ \bar{\sigma}_{yy} \\ \bar{\sigma}_{zz} \\ \bar{\sigma}_{yz} \\ \bar{\sigma}_{xz} \\ \bar{\sigma}_{xy} \end{Bmatrix} = \begin{Bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & 0 & 0 & \bar{C}_{16} \\ \bar{C}_{12} & \bar{C}_{22} & \bar{C}_{23} & 0 & 0 & \bar{C}_{26} \\ \bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & 0 & 0 & \bar{C}_{36} \\ 0 & 0 & 0 & \bar{C}_{44} & \bar{C}_{45} & 0 \\ 0 & 0 & 0 & \bar{C}_{45} & \bar{C}_{55} & 0 \\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{36} & 0 & 0 & \bar{C}_{66} \end{Bmatrix} \left\{ \begin{bmatrix} \bar{\varepsilon}_{xx} \\ \bar{\varepsilon}_{yy} \\ \bar{\varepsilon}_{zz} \\ \bar{\gamma}_{yz} \\ \bar{\gamma}_{xz} \\ \bar{\gamma}_{xy} \end{bmatrix} - \begin{bmatrix} \bar{\alpha}_{xx} \\ \bar{\alpha}_{yy} \\ \bar{\alpha}_{zz} \\ \bar{\alpha}_{yz} \\ \bar{\alpha}_{xz} \\ \bar{\alpha}_{xy} \end{bmatrix} \Delta T \right\}, \tag{4}$$

in which, related to the three-dimensional structure, $[\bar{C}]$ is the matrix of effective elasticity coefficients, $[\bar{\alpha}_{(mn)}]$ that of structural thermal expansion and ΔT the gradual temperature difference of the structure.

2.2. Mesoscopic analysis of HAC structure

The representative volume element (RVE) within an ellipsoidal entrainment in HAC monolayers is treated as the equivalent of HAC single cell which is the basic component of mesoscopic structure. The volume of the reinforcing material, which is closely connected with the matrix, is relatively small compared with that of the matrix, as shown in Fig. 2.

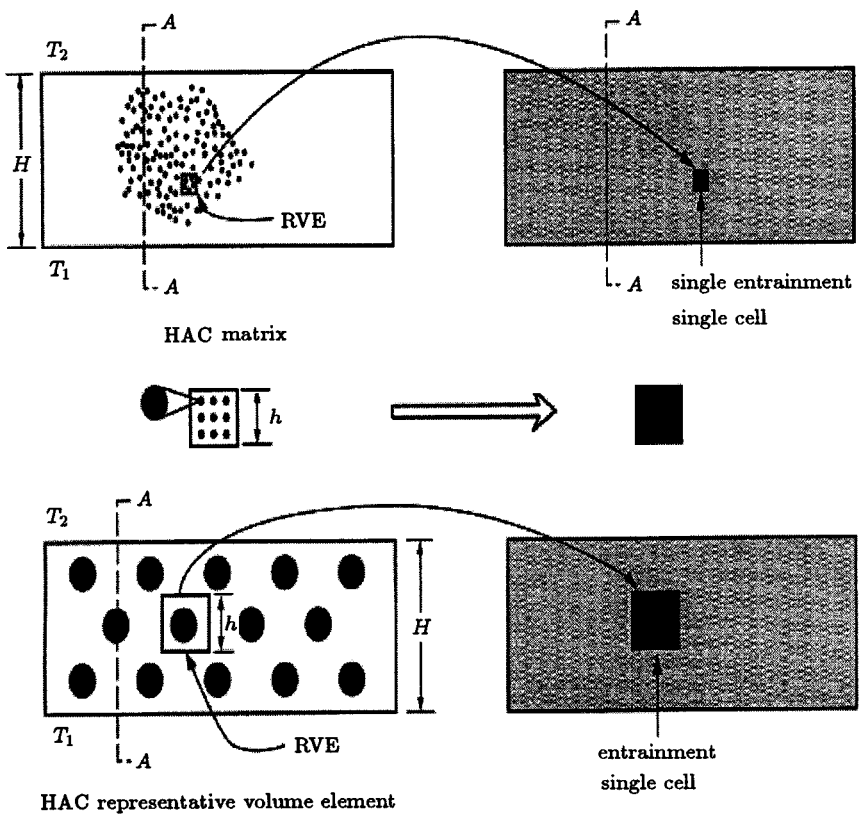


Fig.2. Mesoscopic model of HAC.

Now we study the stress and strain of the reinforcing phase $\Omega = \Omega_1 + \Omega_2 + \Omega_3 + \cdots$ located in single cell P of HAC monolayer. T_1 and T_2 stand for the temperatures of the upper and lower surfaces of cross section A-A, respectively. C_m is the elasticity coefficient matrix of HAC matrix $m(m = P - \Omega)$, C_r the elasticity coefficient matrix of the reinforcing phase and $f_{(k)}$ is its volume percentage. For a single cell of HAC with ellipsoidal entrainment, let σ_p be its uniform stress field, ε_p its uniform strain field, σ_m the uniform stress field of its matrix, σ_r the uniform stress field of the reinforcing phase, then

$$\sigma_m = \sigma_p - f_{(k)} C_m (S - E)\{C_m (C_m - C_r) \times [S - f_{(k)}(S - E)]\}^{-1} \times [(C_m - C_r) C_m^{-1} \sigma_p], \quad (5)$$

$$\sigma_r = \sigma_p + (1 - f_{(k)}) C_m (S - E)\{C_m (C_m - C_r) \times [S - f_{(k)}(S - E)]\}^{-1} \times [(C_m - C_r) C_m^{-1} \sigma_p], \quad (6)$$

$$\varepsilon_p = \{C_m - (C_m - C_r)[S - f_{(k)}(S - E)]\}^{-1} \times [C_m - (1 - f_{(k)})(C_m - C_r) S] C_m^{-1} \sigma_p, \quad (7)$$

in which S is the Eshelby tensor with the feature that at the same time solutions are found for the stress and strain of the complicated matrix, the stress and stain fields of the reinforcing phase are obtained with E as its unit matrix.

The mathematical expression of mesoscopic equivalent thermal expansion rate obtained through a further analysis of thermal stress is

$$\alpha_p = \alpha_m - f_{(k)}\{(C_m - C_r)[S - f_{(k)}(S - E)] - C_m\}^{-1} \times C_r (\alpha_r - \alpha_m). \quad (8)$$

Mesoscopically, the study of HAC heat conduction is of great significance. Considering the accuracy in engineering application, according to the principle of mesoscopic thermal balance, volume percentage $f(k)$ is substituted into formula (9) to obtain the equivalent temperature of ellipsoidal entrainment, which is

$$T_r = -\{(K_m - K_r)[S - f_{(k)}(S - E)] - K_m\}^{-1} \times (K_m - K_r) T_m + f_{(k)} E (T_2 - T_1) h / H. \quad (9)$$

The HAC mesoscopic equivalent heat conduction coefficient is obtained as

$$K_p = [|K_m^{-1} + f_{(k)}\{K_m - K_r)[S - f_{(k)}(S - E)] - K_m\}^{-1}(K_r - K_m) K_m^{-1}|]^{-1}. \quad (10)$$

The essential characteristic of HAC mesoscopic thermal stress alleviation can be foreseen through a thorough analysis of the basic mesoscopic thermal equivalent values given above.

2.3. The interlaminar constitutive relation of HAC macroscopic three-dimensional structure

Between two neighbouring sublayers in the HAC structure under research, there exists an ideal physical discontinuous interface. According to the equilibrium of holistic force and moment and the principle of the minimum residual energy, thermal loads are made the equivalent of mechanical loads. Interlaminar stress will be acting on the interface when the laminate plate is under the forces of thermal load, mechanical load and that of the thereby generated equivalent tensile stress $\bar{\sigma}^i_{xx}$ in the direction of x, the two side faces are cut-open free edges, as shown in Fig. 3.

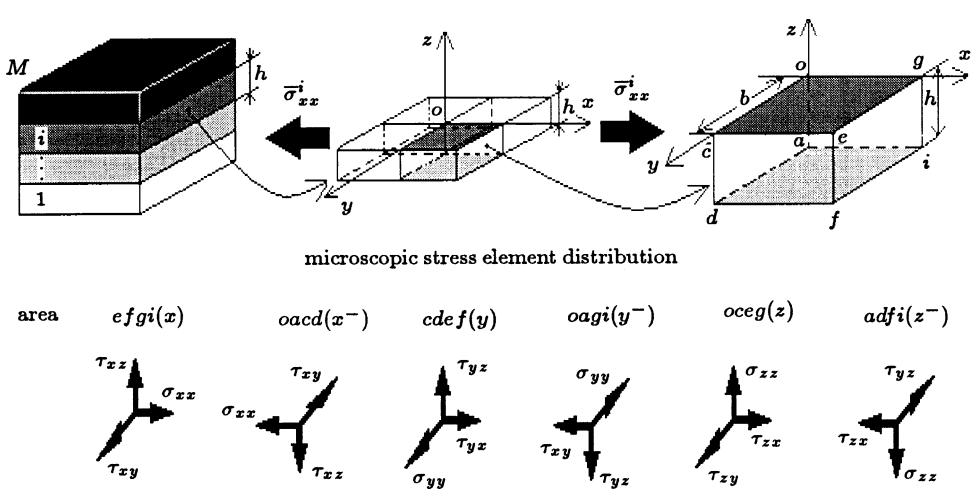


Fig.3. The interlaminar macroscopic analysis model of HAC 3-D structure.

In order to analyse the equilibrium state of the three-dimensional stress, the following hypotheses are made:

1. Away from the area which is under the effect of the tensile load, the stress is independent of the x-coordinate. 2. Away from the free edges area of the two side-faces, the solution of the classic laminate theory is adopted. 3. Being macroscopically orthotropic, the elasticity property of each sublayer is expressed by the three-dimensional effective elasticity coefficient.

In virtue of the symmetrical property of HAC structure and the load, a cuboid of 1/4 sublayer structure is chosen as the research object to establish the holistic equilibrium conditions. In the y-direction the free edge and the central symmetric plane are taken as the two opposite faces (where $y = 0, b$), while in the x-direction two opposite faces can be taken at arbitrary locations since the stress does not vary with x. In the z-direction, the top and bottom interfaces of the sublayer are adopted.

From the equilibrium conditions of the holistic force and its moment, six integral equations can be deduced:

$$\begin{aligned}
&\int_z \tau_{xz}\mathrm{d}y - \int_{z^-} \tau_{xz}\mathrm{d}y - \int_{y^-} \tau_{xy}\mathrm{d}z = 0,\\
&\int_z \tau_{yz}\mathrm{d}y - \int_{y^-} \sigma_{yy}\mathrm{d}z - \int_{z^-} \tau_{yz}\mathrm{d}y = 0,\\
&\int_z \sigma_{zz}\mathrm{d}y - \int_{z^-} \sigma_{zz}\mathrm{d}y = 0,\\
&\int_{y^-} \sigma_{yy} z\mathrm{d}z - \int_z \sigma_{zz} y\mathrm{d}y + \int_{z^-} \sigma_{zz} y\mathrm{d}y\\
&+ h\int_{z^-} \tau_{yz}\mathrm{d}y = 0,\\
&\int\int_x \tau_{xz}\mathrm{d}x\mathrm{d}z - \int_{y^-} \tau_{xy} z\mathrm{d}z - h\int_{z^-} \tau_{xz}\mathrm{d}y = 0,\\
&\int\int_x \tau_{xy}\mathrm{d}y\mathrm{d}z - \int_z \tau_{zx}(b-y)\mathrm{d}y = 0.
\end{aligned} \tag{11}$$

According to hypothesis 1, the stress field satisfying the integral equations above is independent of x. Further supposing that it is a function of y and z and the variables can be separated, the interlaminar stress of sublayer i in HAC structure can be expressed as

$$\sigma^i_{mn} = p^i_{mn}(y) g^i_{mn}(z), \tag{12}$$

in which parameters with subscripts m, n are not summed up, and

$$g^i_{mn}(z) = f_i L^i_k, \tag{13}$$

in which f_i is the volume percentage of sublayer i in HAC laminate, L^i_k its structural stress coefficient and for a given sublayer the coefficient is definite. We have

$$p^i_{mn}(y) = A^i_a \mathrm{e}^{-\theta y} + A^i_b \mathrm{e}^{-\chi\theta y} + A^i_c. \tag{14}$$

According to the principle of minimum residual energy only two exponential terms are chosen because the first-order cross terms must be in the state of minimum energy. Due to the boundary conditions, stress on the free edge $y = b$ is zero and coefficient A can be determined by applying the stress expression of the classic laminate theory. χ, θ are coefficients to be determined yet. At the interface between sublayers i and $i+1$, interlaminar stress τ_{yz}, τ_{xz} must be continuous,[7,10,12] and the interlaminar stresses on the top and bottom of the three-dimensional structure are zero, so L^i_k can be determined.

From the above results the general interlaminar stress expression of sublayer i in HAC macroscopic three-dimensional structure is obtained as:

$$\begin{aligned}
\sigma^i_{yy} =& \bar{\sigma}^i_{yy}\left[1 - \frac{\chi}{\chi-1}\left(\mathrm{e}^{-\theta y} - \frac{1}{\chi}\mathrm{e}^{-\chi\theta y}\right)\right],\\
\sigma^i_{zz} =& \theta^2 \frac{\chi}{\chi-1}(\chi \mathrm{e}^{-\chi\theta y} - \mathrm{e}^{-\theta y})\\
&\times \left(\bar{\sigma}^i_{yy}\frac{z^2}{2} + f_i L^i_4 z + f_i L^i_5\right),\\
\tau^i_{yz} =& \theta \frac{\chi}{\chi-1}(\mathrm{e}^{-\theta y} - \mathrm{e}^{-\chi\theta y})(\bar{\sigma}^i_{yy} z + f_i L^i_4),\\
\tau^i_{xz} =& \theta \mathrm{e}^{-\theta y}(\bar{\sigma}^i_{yy} z + f_i L^i_2),\\
\tau^i_{xy} =& \bar{\tau}^i_{xy}(1 - \mathrm{e}^{-\theta y}).
\end{aligned} \tag{15}$$

2.4. The interlaminar mesoscopic analysis of HAC structure

Now consider the case that between the two sublayers $i-1$ and i in the HAC structure there exists an interlaminar double cell with an ellipsoidal entrainment included. The former sublayer includes a semi-space interlaminar single cell with half a prolate ellipsoidal reinforcing phase entrainment, the three axes (a_x, a_y, a_z) of which run parallel with those of the single cell (x_d, y_d, z_d) and those of the sublayer (x_d, y_d, z_d). We proceed to study the stress and strain of the half prolate ellipsoidal reinforcing phase interlaminar entrainment Ω located in single cell P of HAC sublayers, the volume percentage of the reinforcing phase entrainment being f_i and the elasticity coefficient matrix of the matrix substance $M (M = P - \Omega)$ being C_m, as shown in Fig. 4.

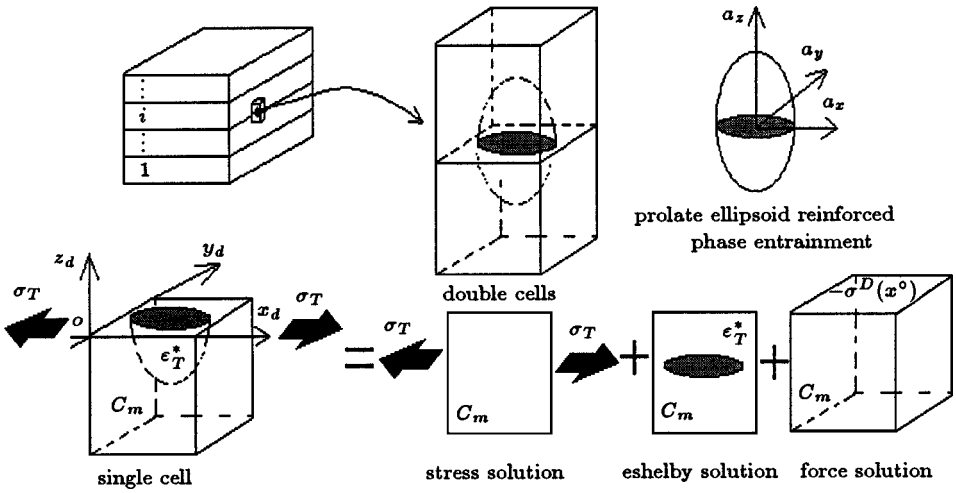


Fig.4. HAC interlaminar mesoscopic structure analysis model.

Due to the interlaminar entrainment, the stress and strain in the entrainment are different from those in the matrix around. The stress in the ellipsoidal entrainment is

$$\sigma_{\text{in}} = \sigma_T + C_m(\varepsilon_p - \varepsilon_T^*), \tag{16}$$

in which ε_p denotes the difference of the stress in the ellipsoidal entrainment compared with that of the matrix. From Eshelby–Mori–Tanaka theory,[4,7,9] the following relations are obtained:

$$\sigma_{\text{in}} = C_m[\varepsilon^0 + (S - E)\varepsilon_T^*], \tag{17}$$

in which S is the Eshelby tensor which is dependent on the entrainment shape and properties of the matrix material. E is a four-order unit tensor. Owing to the existence the ellipsoid, the stress outside the ellipsoid (inside the matrix) is

$$\sigma_{\text{out}} = C_m[\varepsilon^0 + f_i(E - S)\varepsilon_T^*]. \tag{18}$$

Hence, the accurate expressions of the interior and exterior stresses of HAC ellipsoidal entrainment are obtained.

If an ellipsoidal entrainment is included in between HAC sublayers, the interlaminar section[7,10,11] can be treated as a free section on which the antiforce $-\sigma^D(x^\circ)$ is imposed:

$$\sigma^D(x^\circ) = f_i\sigma_{\text{in}} + (1 - f_i)\sigma_{\text{out}}. \tag{19}$$

The problem can de reduced to a plane stress problem, an Eshelby–Mori–Tanaka problem and that of the semi-space[13,14] under the surface force. The mesoscopic stress expression of HAC interlaminar problem can be obtained through superposition:

$$\begin{aligned}\sigma(x^*) =& \sigma_T + \sigma^D(x^*) - \int_A \sigma_{33}^D B(x^*, x^\circ)\mathrm{d}x^\circ \\ &- \int_A \sigma_{13}^D C(x^*, x^\circ)\mathrm{d}x^\circ \\ &- \int_A \sigma_{23}^D C(x^*, x^\circ)\mathrm{d}x^\circ,\end{aligned} \tag{20}$$

where x^* is a random point of the semi-space entity, x° is the point on the free surface, $B(x^*, x^\circ)$ is the Boussinesq stress tensor,[8] $C(x^*, x^\circ)$ is the Cerruti stress tensor and A is the free surface.

3. Cases of calculation

Being limited by space, we only provide the calculation of HAC interlaminar mesoscopic structure in this paper. Take HAC semi-infinite-entity[15,16] with an interlaminar ellipsoidal entrainment which is under the tensile force as the example. The initial eigenstress of HAC interlaminar single cell ε_T^*=0.017 and the interlaminar interface traverses the ellipsoidal entrainment from the middle.

We obtained the effect of macro-/mesoscopic interlaminar interface on HAC thermal stress via the calculation using the macro and mesoscopic models, and compared the different effects when the entrainment is located at different positions relative to the interlaminar interface. Our results are compared with the calculated values using the analytical method[3] and finite-element method[9]of the thermal stress, as shown in Fig. 5. Discussion is made for the case when the distance between the ellipsoid reinforcing particle and the interlaminar interface is $2a$ (a being the longer semidiameter). In the figure σ_1 is the absolute value of σ_{zz} in an infinite-sized entrainment.

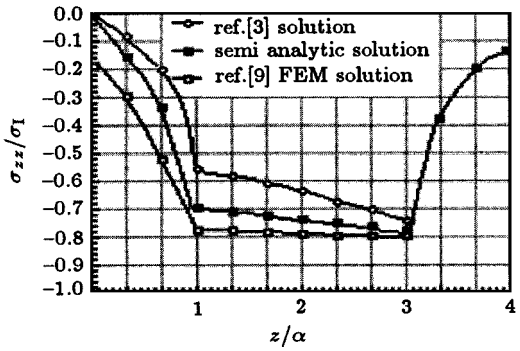


Fig.5. Stress distribution along the direction of HAC thickness, $D = 2a$.

Figure 5 shows that the stress in the entrainment remains non-uniform when the distance D between the interlaminar interface and the core of the entrainment is $2a$. The curve in the figure shows that our solution, which is based on the macro-/mesoscopic gradual interlaminar model, is more efficient though all the solutions are well in accordance with each other. Consequently, with its universality, it provides a better solution for complicated problems. It can be seen that the HAC mesoscopic structure bears the property of the sawtooth effect of stress between the sublayers.With increasing the distance between the entrainment and the interlaminar interface, the extent of its effect decreases. It is found through calculation that when $D \to 3a$ the effect is quite small. It is hence believed that with respect to such factors as the interlaminar interface, thermal load, material difference which influence HAC properties are only related to the entrainment located within $3a$ from the interlaminar interface. So $3a$ is the effective extent of influence on HAC single cell, beyond which the influence of the presence of entrainment and the interlaminar interface, etc. can be ignored. Theoretical support can thereby be provided for the formation of HAC interlaminar crack in technical application through the above-mentioned quantitative calculation of HAC interlaminar stress.

4. Conclusion

The theoretical method of the paper is based on four points of consideration: model solution efficiency, the three macroscopic fields (stress field, strain field and temperature field) and three mesoscopic fields are obtained at the same time, readiness of adapting the Eshelby tensor theory and Mori–Manaka approach to the semi-analytical calculation method and corresponding algorithm, and mesoscopic scale having gradual continuity as the basis. With its unique structure and its characteristics, HAC distinguishes itself from the usual three-dimensional intertexture, fibre ply structure and ceramic-metal complex structure. The paper combines the macroscopic constitutive theory and the mesoscopic expressions to acquire the mesoscopic expressions that are suited to HAC material and its structural characteristics for each HAC macroscopic three-dimensional elasticity coefficient. By utilizing the research results, all the elasticity coefficients can be clearly expressed in solving HAC stress and strain and the nature of HAC structure can be expressed in a thorough and quantitative way. It brings not only the correct solutions to complicated problems but also convenience for later thermal stress calculation. The optimizing method which can alleviate the thermal stress of HAC structure and the results of the numerical analysis, which can be applied in practice, are to be studied in later work.

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