

This book presents original mathematical models of thermal-stress-field interactions in two-component materials, which result from the superposition method, along with mathematical models of thermal-stress induced micro-/macro-strengthening and thermal-stress induced intercrystalline or transcrystalline crack formation. The mathematical determination results from mechanics of an isotropic elastic continuum. The materials consist of an isotropic matrix with isotropic ellipsoidal inclusions. The thermal stresses are a consequence of different thermal expansion coefficients of the matrix and ellipsoidal inclusions. The mathematical models of the thermal-stress-field interactions include microstructural parameters of a real matrix-inclusion composite. In case of a real matrix-inclusion composite, such numerical values of the microstructural parameters can be determined, which result in maximum values of the micro- and macro-strengthening, and which define limit states with respect to the intercrystalline or transcrystalline crack formation in the matrix and the ellipsoidal inclusion. This numerical determination is performed by a programming language.



Ladislav Ceniga

Thermal-Stress-Field Interactions in Composite Materials I

Superposition Method

Dr. Ladislav Ceniga, DSc. (Institute of Materials Research, Slovak Academy of Sciences, Kosice, Slovak Republic) works on mathematical models of stresses in composites.



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Thermal-Stress-Field Interactions in Composite Materials I

Superposition Method

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Táto kniha je venovaná s láskou mojim najdrahším
rodičom a starým rodičom.

This book is dedicated with love to my dearest
parents and grandparents.

Contents

Introduction	1
1 Matrix-Inclusion Composite	3
2 Mechanics of Elastic Solid Continuum	9
2.1 Fundamental Equations	9
2.2 Elastic Energy	12
2.3 Boundary Conditions	12
2.3.1 Inclusion	12
2.3.2 Matrix	13
2.3.3 Stress-Field Interactions	13
3 Mathematical Model 1	17
3.1 Mathematical Procedure	17
3.2 Matrix	18
3.3 Inclusion	20
4 Mathematical Model 2	23
4.1 Mathematical Procedure	23
4.2 Matrix	26
5 Mathematical Model 3	37
5.1 Mathematical Procedure	37
5.2 Matrix	40
6 Mathematical Model 4	53
6.1 Mathematical Procedure	53
6.2 Matrix	54
6.3 Inclusion	62
7 Mathematical Model 5	65
7.1 Mathematical Procedure	65
7.2 Matrix	67

8	Strengthening	77
9	Crack Formation	81
10	Appendix	87
	Bibliography	93
	Index	96

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Introduction

This book¹ presents original mathematical models of thermal-stress-field interactions in composite materials, along with mathematical models of thermal-stress induced micro-/macro-strengthening and thermal-stress induced intercrystalline or transcrystalline crack formation. The materials consist of an isotropic matrix with isotropic ellipsoidal inclusions. These stresses originate during a cooling process, and are a consequence of different thermal expansion coefficients of the matrix and ellipsoidal inclusions.

The mathematical models are determined for a suitable model system. The model system is required to correspond to real isotropic matrix-inclusion composites. The thermal stresses are derived within a suitable coordinate system. The coordinate system is required to correspond to a shape of the ellipsoidal inclusions.

The mathematical determination results from mechanics of an isotropic elastic continuum, and result in different mathematical solutions for the thermal stresses. Due to these different mathematical solutions, the principle of minimum elastic energy is considered.

The mathematical models of the thermal-stress-field interactions, which result from the superposition method, along with the mathematical models of the thermal-stress induced micro-/macro-strengthening and crack formation, include microstructural parameters of a real matrix-inclusion composite, i.e., the inclusion dimensions a_1, a_2, a_3 , the inclusion volume fraction v_{IN} , as well as the inter-inclusion distance $d = d(a_1, a_2, a_3, v_{IN})$.

Consequently, the mathematical models are applicable to composites with ellipsoidal inclusions of different morphology, i.e., $a_1 \approx a_2 \approx a_3$ (dual-phase steel), $a_1 \gg a_2 \approx a_3$ (martensitic steel).

In case of a real matrix-inclusion composite, such numerical values of the microstructural parameters can be determined, which result in maximum values of the micro- and macro-strengthening, and which define limit states with respect to the

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intercrystalline or transcrystalline crack formation in the matrix and the ellipsoidal inclusion. This numerical determination is performed by a programming language. The mathematical procedures in this book are analysed in Appendix.

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Matrix-Inclusion Composite

Figure 1.1 shows a model system, corresponding to real matrix-inclusion composites, which is considered within the mathematical models of the thermal stresses. This model system consists of an infinite isotropic matrix and isotropic ellipsoidal inclusions with the dimensions a_1, a_2, a_3 and the inter-inclusion distance d along the axes x_1, x_2, x_3 of the Cartesian system ($Ox_1x_2x_3$), respectively, where O represents a centre of the ellipsoidal inclusion.

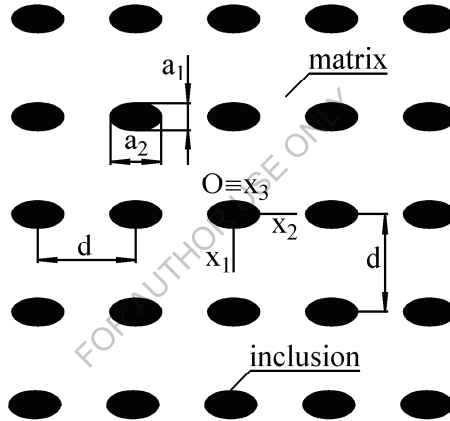


Figure 1.1: The matrix-inclusion system with an infinite isotropic matrix and isotropic ellipsoidal inclusions with the dimensions a_1, a_2, a_3 and the inter-inclusion distance d along the axes x_1, x_2, x_3 of the Cartesian system ($Ox_1x_2x_3$), respectively, where O represents a centre of the ellipsoidal inclusion.

As presented in [1]–[22], the thermal stresses are determined in the cubic cells with the dimension d along the axes x_1, x_2, x_3 and with central ellipsoidal inclusions (see Figure 1.2). Due to the infinite matrix, the thermal stresses, which are determined for one of the cubic cells, are identical with those, which are determined for any of the cubic cells [1]–[22]. With regard to the volume $V_{IN} = 4\pi a_1 a_2 a_3$ [23] and $V_C = d^3$ of the ellipsoidal inclusion and the cubic cell, the inter-inclusion distance d as a function of the inclusion volume fraction v_{IN} is derived as

$$v_{IN} = \frac{V_{IN}}{V_C} = \frac{4\pi a_1 a_2 a_3}{3d^3} \in \left(0, \frac{\pi}{6}\right), \quad d = \left(\frac{4\pi a_1 a_2 a_3}{3v_{IN}}\right)^{1/3}, \quad (1.1)$$

where the value $v_{INmax} = \pi/6$ results from the condition $a_i \rightarrow d/2$ ($i=1,2,3$). Accordingly, the thermal stresses are functions of the material parameters a_1, a_2, a_3, v_{IN}, d .

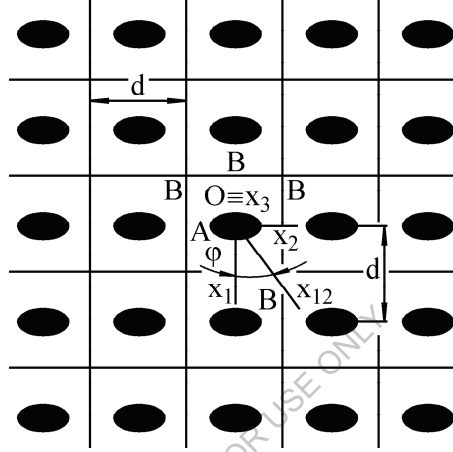


Figure 1.2: The cubic cells with the dimension d along the axes x_1, x_2, x_3 of the Cartesian system $(Ox_1x_2x_3)$ and with the plane $x_{12}x_3$, where O represents a centre of the ellipsoidal inclusion, and $(x_{12} \subset x_1x_2, x_{12}x_3 \perp x_1x_2)$. The thermal stresses in the cell A and the neighbouring cells B are mutually affected.

Additionally, the thermal stresses in the cell A and the neighbouring cells B are mutually affected. In contrast to [1]–[13], [15]–[22], this effect is explicitly determined [14].

Figure 1.3 shows the ellipse E with the dimensions a, b along the axes x, y , respectively. The ellipse E is described by the function

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1. \quad (1.2)$$

Any point P of the ellipse E is described by the coordinates [23]

$$x = a \cos \alpha, \quad y = b \sin \alpha, \quad \alpha \in \langle 0, 2\pi \rangle, \quad (1.3)$$

where the normal n of the ellipse E at the point P is derived [23]

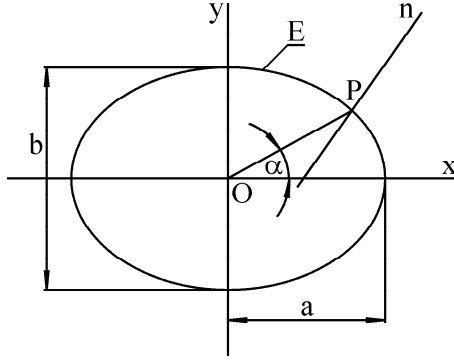


Figure 1.3: The ellipse E with the dimensions a, b along the axes x, y of the Cartesian system (Oxy) , respectively, and the point P related to the angle α .

$$y = \frac{xa \tan \alpha}{b} - \frac{(a^2 - b^2) \sin \alpha}{b}. \quad (1.4)$$

The thermal stresses are determined by the spherical coordinates (r, φ, ν) (see Figure 1.4). The model system in Figures (1.1), (1.2) is symmetric, and then the thermal stresses are determined within the intervals $\varphi \in \langle 0, \pi/2 \rangle$, $\nu \in \langle 0, \pi/2 \rangle$ [1]–[22].

Figure 1.4 shows the ellipsoidal inclusion for $\varphi, \nu \in \langle 0, \pi/2 \rangle$ with the centre O and with the dimensions $a_1 = O1$, $a_2 = O2$, $a_3 = O3$ along the axes x_1, x_2, x_3 of the Cartesian system (O, x_1, x_2, x_3) (see Figures (1.1), (1.2)), respectively. Finally, $(P, x_n, x_\varphi, x_\nu)$ is a Cartesian system at the point P , where the axes x_n and x_ν represents a normal and a tangent of the ellipse E_{123} at the point P , respectively, $x_{12}x_3 \perp x_1x_2$, $x_{12} \subset x_1x_2$, $x_\varphi \perp x_{12}$. Figure 1.5 shows the cross section $O567$ of the cubic cell in the plane $x_{12}x_3$ (see Figures 1.2, 1.4). The angle $\nu \in \langle 0, \pi/2 \rangle$ defines a position of the point P with the Cartesian system $(P, x_n, x_\varphi, x_\nu)$ (see Figure 1.4) for $\nu = \nu_0$ (see Figure 1.5a), $\nu \in \langle 0, \nu_0 \rangle$ (see Figure 1.5b), $\nu \in \langle \nu_0, \pi/2 \rangle$ (see Figure 1.5c). The points P_1, P_2 represent intersections of the normal x_n with $O567$.

With regard to Equations (1.2)–(1.4), the angle ν_0 represents a root of the following equation [24]

$$\frac{\cos \nu_0}{a_3} \left[\frac{d \sqrt{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi}}{2 f(\varphi) \sin \nu_0} + a_3^2 - (a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi) \right] - \frac{d}{2} = 0, \\ f(\varphi) = \cos \varphi, \quad \varphi \in \left\langle 0, \frac{\pi}{4} \right\rangle; \quad f(\varphi) = \sin \varphi, \quad \varphi \in \left\langle \frac{\pi}{4}, \frac{\pi}{2} \right\rangle, \quad (1.5)$$

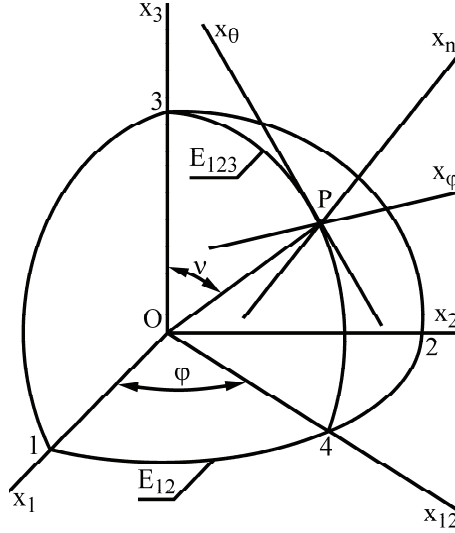


Figure 1.4: The inclusion with the centre O and with the dimensions $a_1 = O1$, $a_2 = O2$, $a_3 = O3$ along the axes x_1 , x_2 , x_3 of the Cartesian system (O, x_1, x_2, x_3) , respectively, where E_{12} , E_{123} represent ellipses in the planes x_1x_2 , $x_1x_2x_3$, respectively, and $x_{12}x_3 \perp x_1x_2$, $(x_{12} \subset x_1x_2, x_\phi \perp x_{12})$. The point P on the inclusion surface is defined by $\varphi, v \in \langle 0, \pi/2 \rangle$, $v \in \langle 0, \pi/2 \rangle$, and (P, x_n, x_ϕ, x_v) is a Cartesian system at the point P , where $P \subset E_{123}$. The axes x_n and x_v represents a normal and a tangent of the ellipse E_{123} at the point P , respectively.

and this root is determined by a numerical method. The angle $\theta = \angle(x_n, x_3)$ is derived as [24]

$$\begin{aligned} \cos \theta &= \frac{\sqrt{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi}}{\sqrt{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi + (a_3 \tan v)^2}}, \\ \sin \theta &= \frac{a_3}{\sqrt{(a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi) \cot^2 v + a_3^2}}. \end{aligned} \quad (1.6)$$

Consequently, we get [23]

$$\frac{\partial}{\partial \theta} = \left(\frac{\partial \theta}{\partial v} \right)^{-1} \frac{\partial}{\partial \varphi} = \Theta \frac{\partial}{\partial v}, \quad (1.7)$$

where the function $\Theta = \Theta(\varphi)$ has the form [24]

$$\Theta = \frac{\sqrt{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi}}{a_3} \left[\frac{(a_3 \sin v)^2}{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi} + \cos^2 v \right]. \quad (1.8)$$

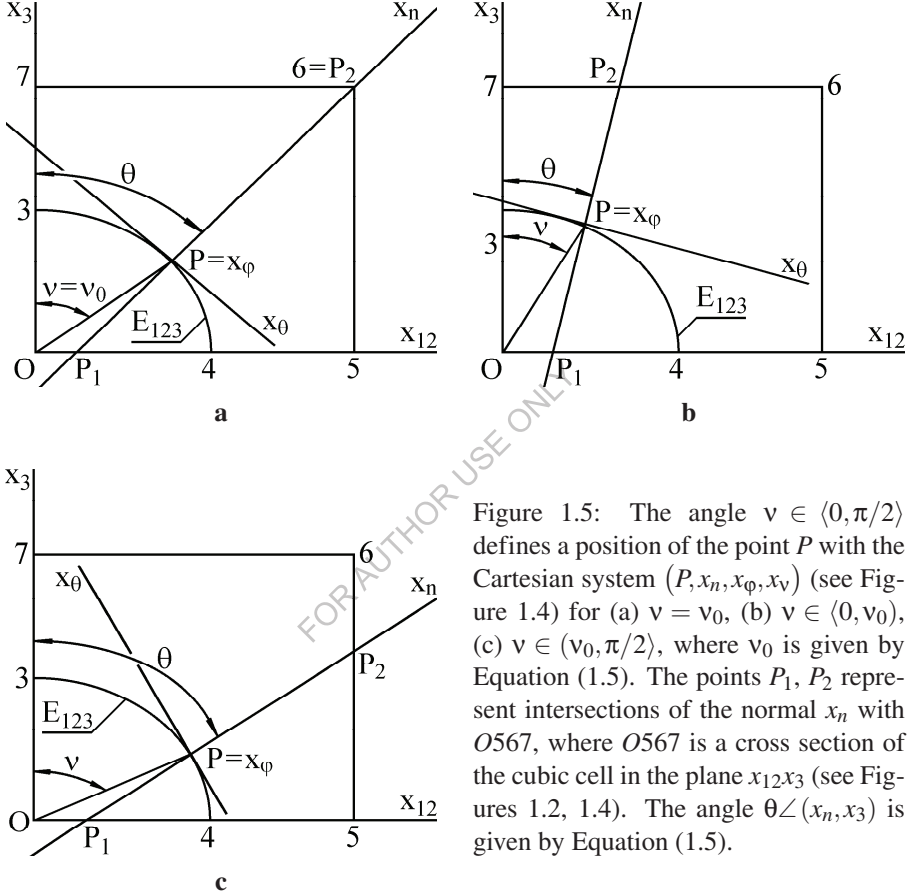


Figure 1.5: The angle $v \in \langle 0, \pi/2 \rangle$ defines a position of the point P with the Cartesian system $(P, x_n, x_\varphi, x_\theta)$ (see Figure 1.4) for (a) $v = v_0$, (b) $v \in \langle 0, v_0 \rangle$, (c) $v \in (v_0, \pi/2)$, where v_0 is given by Equation (1.5). The points P_1, P_2 represent intersections of the normal x_n with $O567$, where $O567$ is a cross section of the cubic cell in the plane $x_{12}x_3$ (see Figures 1.2, 1.4). The angle $\theta \angle (x_n, x_3)$ is given by Equation (1.5).

As analysed in [1]–[20], due to the symmetry of the model system, any point P on the matrix-inclusion boundary exhibits the displacement u_n along x_n . Consequently, any point P of the normal x_n exhibits u_n along x_n , i.e., $u_\varphi = u_v = 0$ [1]–[20], where u_φ, u_v are displacements along the axes x_φ, x_v , respectively.

As presented in [1]–[22], the thermal stresses, which are determined along the axes x_n, x_φ, x_θ of the Cartesian system $(P, x_n, x_\varphi, x_\theta)$, represent function of the spherical coordinates (x_n, φ, θ) for $\varphi, \theta \in \langle 0, \pi/2 \rangle$. The intervals $x_n \in \langle 0, x_{IN} \rangle$ and $x_n \in$

$\langle x_{IN}, x_M \rangle$ are related to the ellipsoidal inclusion and the cell matrix, where $P = P_1$, $P \subset E_{123}$ and $P = P_2$ for $x_n = 0$, $x_n = x_{IN}$ and $x_n = x_M$ (see Figure 1.5), respectively. Finally, we get [24]

$$\begin{aligned}
 x_{IN} &= P_1 P = a_3 \sqrt{\left(\frac{a_3 \sin v}{a_{12}}\right)^2 + \cos^2 v}, \\
 x_M &= P P_2 = \sqrt{\left(\frac{\sin v}{a_{12}}\right)^2 \left(\frac{d \cos v}{2 a_3} - a_3^2\right)^2 + \left(\frac{a_{12} \cos v}{a_3}\right)^2 (x_{122} - a_{12})^2}, \\
 x_{122} &= \frac{d}{2 f(\varphi) \sin v}, \quad a_{12} = \sqrt{a_1^2 \cos^2 \varphi + a_2^2 \sin^2 \varphi}.
 \end{aligned} \tag{1.9}$$

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Mechanics of Elastic Solid Continuum

2.1 Fundamental Equations

As analysed in [1]–[20], any point P of the normal x_n exhibits the displacement u_n along x_n . The thermal stresses are determined along the axes x_n, x_φ, x_θ of the Cartesian system $(P, x_n, x_\varphi, x_\theta)$. Fundamental equations of mechanics of a solid continuum are represented by Cauchy's equations, the equilibrium equations and Hooke's law. Cauchy's equations represent functions of strains and displacements. With respect to the normal displacement u_n , Cauchy's equations have the forms [1]–[20, 22]

$$\epsilon_n = \frac{\partial u_n}{\partial x_n}, \quad (2.1)$$

$$\epsilon_\varphi = \epsilon_\theta = \frac{u_n}{x_n}, \quad (2.2)$$

$$\epsilon_{n\varphi} = \epsilon_{\varphi n} = \frac{1}{x_n} \frac{\partial u_n}{\partial \varphi}, \quad (2.3)$$

$$\epsilon_{n\theta} = \epsilon_{\theta n} = \frac{\Theta}{x_n} \frac{\partial u_n}{\partial \nu}, \quad (2.4)$$

where ϵ_n is a normal strain along the axis x_n , and Θ is given by Equation (1.8). Consequently, ϵ_φ and ϵ_θ are tangential strains along the axes x_φ and x_θ , respectively. Finally, $\epsilon_{n\varphi}$, $\epsilon_{n\theta}$ and $\epsilon_{\varphi n}$, $\epsilon_{\theta n}$ represent shear strains along the axes x_n and x_φ , x_θ , respectively. Due to $u_\varphi = u_\nu = 0$, we get $\epsilon_{\varphi\nu} = \epsilon_{\nu\varphi} = 0$ [1]–[22], where u_φ, u_ν are displacements along the axes x_φ, x_ν , respectively, and $\epsilon_{\varphi\nu}$ is a shear strain. As presented in [1]–[22], the equilibrium equations are derived as

$$2\sigma_n - \sigma_\varphi - \sigma_\nu + x_n \frac{\partial \sigma_n}{\partial x_n} + \frac{\partial \sigma_{n\varphi}}{\partial \varphi} + \Theta \frac{\partial \sigma_{n\theta}}{\partial \nu} = 0, \quad (2.5)$$

$$\frac{\partial \sigma_\varphi}{\partial \varphi} + 3\sigma_{n\varphi} + x_n \frac{\partial \sigma_{n\varphi}}{\partial x_n} = 0, \quad (2.6)$$

$$\Theta \frac{\partial \sigma_\theta}{\partial v} + 3\sigma_{n\theta} + x_n \frac{\partial \sigma_{n\theta}}{\partial x_n} = 0, \quad (2.7)$$

where σ_n is a normal stress along the axis x_n . Consequently, σ_φ and σ_θ are tangential stresses along the axes x_φ and x_θ , respectively. Finally, $\sigma_{n\varphi}$, $\sigma_{n\theta}$ and $\sigma_{\varphi n}$, $\sigma_{\theta n}$ represent shear stresses along the axes x_n and x_φ , x_θ , respectively, where $\sigma_{n\varphi} = \sigma_{\varphi n}$, $\sigma_{n\theta} = \sigma_{\theta n}$. Due to $\varepsilon_{\varphi v} = \varepsilon_{v\varphi} = 0$, we get $\sigma_{\varphi v} = \sigma_{v\varphi} = 0$ [1]–[22], where $\sigma_{\varphi v}$ is a shear stress. With regard to $\varepsilon_{\varphi\theta} = 0$, $\sigma_{\varphi\theta} = 0$, Hooke's law has the form [1]–[20, 22]

$$\varepsilon_n = s_{11}\sigma_n + s_{12}(\sigma_\varphi + \sigma_\theta), \quad (2.8)$$

$$\varepsilon_\varphi = s_{12}(\sigma_n + \sigma_\theta) + s_{11}\sigma_\varphi, \quad (2.9)$$

$$\varepsilon_\theta = s_{12}(\sigma_n + \sigma_\varphi) + s_{11}\sigma_\theta, \quad (2.10)$$

$$\varepsilon_{n\theta} = s_{44}\sigma_{n\theta}, \quad (2.11)$$

$$\varepsilon_{n\varphi} = s_{44}\sigma_{n\varphi}, \quad (2.12)$$

where s_{11} , s_{12} , s_{44} are derived as [25]

$$s_{11} = \frac{1}{E}, \quad s_{12} = -\frac{\mu}{E}, \quad s_{44} = \frac{2(1+\mu)}{E}. \quad (2.13)$$

Finally, E and μ are Young's modulus and Poisson's ratio, respectively. In case of the ellipsoidal inclusion and the cell matrix, we get $E = E_{IN}$, $\mu = \mu_{IN}$ and $E = E_M$, $\mu = \mu_M$, respectively. With regard to Equations (2.1)–(2.4), (2.8)–(2.12), we get [1]–[22]

$$\sigma_n = (c_1 + c_2) \frac{\partial u_n}{\partial x_n} - 2c_2 \frac{u_n}{x_n}, \quad (2.14)$$

$$\sigma_\varphi = \sigma_\theta = -c_2 \frac{\partial u_n}{\partial x_n} + c_1 \frac{u_n}{x_n}, \quad (2.15)$$

$$\sigma_{n\varphi} = \frac{1}{s_{44}x_n} \frac{\partial u_n}{\partial \varphi}, \quad (2.16)$$

$$\sigma_{n\theta} = \frac{\Theta}{s_{44}x_n} \frac{\partial u_n}{\partial v}, \quad (2.17)$$

where c_1 , c_2 , c_3 (see Equation (2.24)) have the forms

$$c_1 = \frac{E}{(1+\mu)(1-2\mu)}, \quad c_2 = -\frac{\mu E}{(1+\mu)(1-2\mu)}, \quad c_3 = -4(1-\mu) < 0, \quad (2.18)$$

and $c_3 < 0$ due to $\mu < 0.5$ for real isotropic components [26].

Let $a_{1i} = \cos[\angle(x_1, x_i)]$ ($i = n, \varphi, \theta$) represent a direction cosine of an angle formed by the axes x_1, x_i (see Figures 1.4, 1.5). With regard to Figures 1.4, 1.5, the coefficient $a_{1i} = \cos[\angle(x_1, x_i)]$ ($i = n, \varphi, \theta$) is derived as

$$\begin{aligned} a_{1n} &= \cos \varphi \sin \theta, & a_{1\varphi} &= \sin \varphi \sin \theta, & a_{1\theta} &= \cos \theta, \\ a_{\varphi 1} &= -\sin \varphi, & a_{\theta 1} &= -\cos \varphi \cos \theta, \end{aligned} \quad (2.19)$$

where $\cos \theta, \sin \theta$ are given by Equation (1.6). The stress σ_1 along the axis x_1 has the form

$$\sigma_1 = a_{1n} \sigma_n + a_{1\varphi} \sigma_\varphi + a_{1\theta} \sigma_\theta + a_{1n} (\sigma_{n\varphi} + \sigma_{n\theta}) + a_{1\varphi} \sigma_{\varphi n} + a_{1\theta} \sigma_{\theta n}. \quad (2.20)$$

With regard to Equations (2.14)-(2.17) and due to $\sigma_{n\varphi} = \sigma_{\varphi n}$, $\sigma_{n\theta} = \sigma_{\theta n}$ [25], we get

$$\sigma_1 = \gamma_1 \frac{\partial u_n}{\partial x_n} + \gamma_2 \frac{u_n}{x_n} + \frac{1}{s_{44} x_n} \left(\gamma_3 \frac{\partial u_n}{\partial \varphi} + \gamma_4 \frac{\partial u_n}{\partial \nu} \right), \quad (2.21)$$

where γ_i ($i = 1, \dots, 4$) is derived as

$$\begin{aligned} \gamma_1 &= a_{1n}(c_1 + c_2) - (a_{1\varphi} + a_{1\theta})c_2, & \gamma_2 &= (a_{1\varphi} + a_{1\theta})c_1 - 2a_{1n}c_2, \\ \gamma_3 &= a_{1n} + a_{1\varphi}, & \gamma_4 &= \Theta(a_{1n} + a_{1\theta}), \end{aligned} \quad (2.22)$$

and Θ is given by Equation (1.8). As presented in Chapter 8, the analytical models of the micro-strengthening $\sigma_{st} = \sigma_{st}(x_1)$ and the macro-strengthening $\overline{\sigma_{st}}$ result from the stress σ_1 (see Equations (2.21), (2.22)).

Let Equations (2.14)–(2.17) be substituted to Equation (2.18) and to $[\partial \text{Eq. (2.6)} / \partial \varphi] + \Theta [\partial \text{Eq. (2.7)} / \partial \nu]$. Consequently, Equations (2.5)–(2.7) are derived as

$$x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} + 2x_n \frac{\partial u_n}{\partial x_n} - 2u_n + \frac{U_n}{s_{44}(c_1 + c_2)} = 0, \quad (2.23)$$

$$x_n \frac{\partial U_n}{\partial x_n} = c_3 U_n, \quad (2.24)$$

where U_n is derived as

$$U_n = \frac{\partial^2 u_n}{\partial \varphi^2} + \Theta^2 \frac{\partial^2 u_n}{\partial v^2}. \quad (2.25)$$

The system of the differential equations (2.23), (2.25) is solved by the mathematical procedures in Sections 3.1, 4.1, 5.1, 6.1, 7.1.

2.2 Elastic Energy

As analysed in [1]–[22] with respect to the different mathematical procedures (see Sections 3.1, 4.1, 5.1, 6.1, 7.1), such a mathematical solution, which exhibits a minimum value of the elastic energy W_C of the cubic cell, is considered, where W_{IN} and W_M is elastic energy, which is accumulated in the volume V_{IN} and V_M of the ellipsoidal inclusion and the cell matrix, respectively. The elastic energy density w is derived as [25]

$$w = \frac{1}{2} (\epsilon_n \sigma_n + \epsilon_\varphi \sigma_\varphi + \epsilon_\theta \sigma_\theta) + \epsilon_{n\varphi} \sigma_{n\varphi} + \epsilon_{n\theta} \sigma_{n\theta}, \quad (2.26)$$

and W_{IN} , W_M and W_C have the forms

$$\begin{aligned} W_{IN} &= \int_{V_{IN}} w_{IN} dV_{IN} = 8 \int_0^{\pi/2} \int_0^{\pi/2} \int_0^{x_{IN}} w_{IN} x_n^2 dx_n d\varphi dv, \\ W_M &= \int_{V_M} w_M dV_M = 8 \int_0^{\pi/2} \int_0^{\pi/2} \int_{x_{IN}}^{x_M} w_M x_n^2 dx_n d\varphi dv, \\ W_C &= W_{IN} + W_M. \end{aligned} \quad (2.27)$$

2.3 Boundary Conditions

The mathematical solutions of the system of the differential equations (2.23), (2.25) include integration constants. As presented in [1]–[22], these constants are determined, using Cramer's rule (see Chapter 8) [23], by the following boundary conditions for the ellipsoidal inclusion and the cell matrix.

2.3.1 Inclusion

In case of the ellipsoidal inclusion we get [1]–[22]

$$(u_n)_{x_n=0} = 0, \quad (2.28)$$

$$(\sigma_{nIN})_{x_n=x_{IN}} = -p_n, \quad (2.29)$$

where x_{IN} is given by Equation (1.9). Additionally, the conditions $(u_{nIN})_{x_n \rightarrow 0} \not\rightarrow \pm\infty$, $(\epsilon_{IN})_{x_n \rightarrow 0} \not\rightarrow \pm\infty$, $(\sigma_{IN})_{r \rightarrow 0} \not\rightarrow \pm\infty$ are required to be fulfilled [1]–[22].

2.3.2 Matrix

In case of the cell matrix we get [1]–[22]

$$(\sigma_{nM})_{x_n=x_{IN}} = -p_n, \quad (2.30)$$

$$(u_{nM})_{x_n=x_M} = 0. \quad (2.31)$$

As analysed in [1]–[22], the following boundary condition can be considered

$$(\epsilon_{nM})_{x_n=x_M} = 0. \quad (2.32)$$

With regard to $(\epsilon_{\varphi M})_{x_n=x_M} = -p_n \rho_M$, $(\epsilon_{\varphi IN})_{x_n=x_{IN}} = -p_n \rho_{IN}$ [1]–[22], the normal stress p_n on the matrix-inclusion boundary, i.e., for $x_n = P_1 P = x_{IN}$ (see Figure 1.5), which acts along the axis x_n (see Figures (1.4), (1.5)), has the form [1]–[22]

$$p_n = \frac{(\alpha_{IN} - \alpha_M)(T_r - T)}{\rho_M + \rho_{IN}}, \quad (2.33)$$

where $T_r = (0.35 - 0.4) \times T_m$ [26] and T_m is relaxation and melting temperature of a real composite system, respectively, and T is final temperature of a cooling process.

2.3.3 Stress-Field Interactions

With regard to Figure 1.2, the stresses in the cells B affect those in the cell A . Let P represent a point on the cell boundary with the coordinates (x_M, φ, v) and $(x_M, -\varphi, v)$ for the cells A and B , respectively. Let $(Px_{nA}x_{\varphi A}x_{\theta A})$ and $(Px_{nB}x_{\varphi B}x_{\theta B})$ represent coordinate systems at P in the cells A and B (see Figure 1.4), respectively.

As presented in [14], the effect of the cell B is represented by the normal stress σ_{nB} , which acts at the point P along the axis x_{nA} . The stress σ_{nB} , which is a projection of σ_{nB} , $\sigma_{\varphi B}$, $\sigma_{\theta B}$ onto x_{nA} at P (i.e., for $x_{nB} = x_M$), is derived as [14]

$$\begin{aligned}\sigma_{nB} = & \vartheta_1 (\sigma_{nM})_{x_n=x_M} + \vartheta_2 (\sigma_{\varphi M})_{x_n=x_M} + \vartheta_3 (\sigma_{\theta M})_{x_n=x_M} \\ & + (\vartheta_1 + \vartheta_2) (\sigma_{n\varphi M})_{x_n=x_M} + (\vartheta_1 + \vartheta_3) (\sigma_{n\theta M})_{x_n=x_M},\end{aligned}\quad (2.34)$$

where ϑ_i ($i = 1, 2, 3$) has the form [14]

$$\begin{aligned}\vartheta_1 = & 1 - 2 \sin^2 \varphi \sin^2 v, \quad \vartheta_2 = \sqrt{2} \sin \left(\frac{\pi}{4} - \varphi \right) \sin \varphi \sin v, \\ \vartheta_3 = & \frac{1}{2} \sin \left(2\varphi - \frac{\pi}{2} \right) \sin 2v.\end{aligned}\quad (2.35)$$

The total normal displacement u_{nTQ_1} , the total stresses σ_{nTQ_1} , $\sigma_{\varphi TQ_1}$, $\sigma_{\theta TQ_1}$, the total strains ε_{nTQ_1} , $\varepsilon_{\varphi TQ_1}$, $\varepsilon_{\theta TQ_1}$, the total elastic energy density w_T and the total energy W_T (see Equations (2.26), (2.27)) are determined by the superposition method [25]. As presented in [14], we get

$$\begin{aligned}u_{nTQ_1} = & u_{nQ_1} + u_{nQ_2}, \\ \sigma_{nTQ_1} = & \sigma_{nQ_1} + \sigma_{nQ_2}, \quad \sigma_{\varphi TQ_1} = \sigma_{\varphi Q_1} + \sigma_{\varphi Q_2}, \quad \sigma_{\theta TQ_1} = \sigma_{\theta Q_1} + \sigma_{\theta Q_2}, \\ \sigma_{n\varphi TQ_1} = & \sigma_{n\varphi Q_1} + \sigma_{n\varphi Q_2}, \quad \sigma_{n\theta TQ_1} = \sigma_{n\theta Q_1} + \sigma_{n\theta Q_2}, \\ \varepsilon_{nTQ_1} = & \varepsilon_{nQ_1} + \varepsilon_{nQ_2}, \quad \varepsilon_{\varphi TQ_1} = \varepsilon_{\varphi Q_1} + \varepsilon_{\varphi Q_2}, \quad \varepsilon_{\theta TQ_1} = \varepsilon_{\theta Q_1} + \varepsilon_{\theta Q_2}, \\ \varepsilon_{n\varphi TQ_1} = & \varepsilon_{n\varphi Q_1} + \varepsilon_{n\varphi Q_2}, \quad \varepsilon_{n\theta TQ_1} = \varepsilon_{n\theta Q_1} + \varepsilon_{n\theta Q_2}, \\ w_T = & w_{IN} + w_{INB} + w_M + w_{MB}, \quad W_T = W_{IN} + W_{INB} + W_M + W_{MB}, \\ Q_1 = IN \Rightarrow & Q_2 = INB; \quad Q_1 = M \Rightarrow Q_2 = MB,\end{aligned}\quad (2.36)$$

where σ_{nQ_1} , $\sigma_{\varphi Q_1}$, $\sigma_{\theta Q_1}$, $\sigma_{n\varphi Q_1}$, $\sigma_{n\theta Q_1}$, ε_{nQ_1} , $\varepsilon_{\varphi Q_1}$, $\varepsilon_{\theta Q_1}$, $\varepsilon_{n\varphi Q_1}$, $\varepsilon_{n\theta Q_1}$ and σ_{nQ_2} , $\sigma_{\varphi Q_2}$, $\sigma_{\theta Q_2}$, $\sigma_{n\varphi Q_2}$, $\sigma_{n\theta Q_2}$, ε_{nQ_2} , $\varepsilon_{\varphi Q_2}$, $\varepsilon_{\theta Q_2}$, $\varepsilon_{n\varphi Q_2}$, $\varepsilon_{n\theta Q_2}$, which induce w_{Q_1} , W_{Q_1} and w_{Q_2} , W_{Q_2} ($Q_1 = IN, M$; $Q_2 = INB, MB$), are determined by the mathematical boundary conditions (2.28)–(2.32) and (2.37)–(2.39), respectively.

Consequently, σ_{nMB} , $\sigma_{\varphi MB}$, $\sigma_{\theta MB}$, ε_{nMB} , $\varepsilon_{\varphi MB}$, $\varepsilon_{\theta MB}$, w_{MB} , W_{MB} , which result from σ_{nB} , are determined by the following mathematical boundary conditions

$$(\sigma_{nMB})_{x_n=x_M} = -\sigma_{nB}, \quad (2.37)$$

$$(u_{nMB})_{x_n=x_M} = 0. \quad (2.38)$$

Accordingly, σ_{nINB} , $\sigma_{\varphi INB}$, $\sigma_{\theta INB}$, ε_{nINB} , $\varepsilon_{\varphi INB}$, $\varepsilon_{\theta INB}$, w_{INB} , W_{INB} , which result from σ_{nB} , are determined by the following mathematical boundary condition

$$(u_{nINB})_{x_n=x_{IN}} = (u_{nMB})_{x_n=x_M}. \quad (2.39)$$

The integration constant C_{1INB} is a function of $(u_{nMB})_{x_n=x_M}$ (see Equation (2.39)). The absolute values $|u_{nMB}|$ and $|u_{nINN}|$ are decreasing and increasing functions of $x_n \in \langle x_{IN}, x_M \rangle$ and $x_n \in \langle 0, x_{IN} \rangle$, respectively. The conditions $(u_{nINB})_{r \rightarrow 0} \not\rightarrow \pm\infty$, $(\epsilon_{INB})_{r \rightarrow 0} \not\rightarrow \pm\infty$, $(\sigma_{INB})_{r \rightarrow 0} \not\rightarrow \pm\infty$ are required to be valid [1]–[22, 24].

The boundary condition (2.32), along with Equation (2.38), is not applicable to $(\epsilon_{nMB})_{x_n=x_M}$, i.e., $(\epsilon_{nMB})_{x_n=x_M} \neq 0$, otherwise we get $(\sigma_{nMB})_{x_n=x_M} = 0$ (see Equations (2.14), (2.38)), and the boundary condition (2.37) is not fulfilled.

As mentioned in Section (2.2), the different mathematical procedures in Sections 3.1, 4.1, 5.1, 6.1, 7.1 result in 19, 16 and 2 mathematical solutions for the elastic energy W_M , W_{MB} and W_{IN} , W_{INB} in the cell matrix and the ellipsoidal inclusion (see Equations (2.27), (2.36)), which are given by Equations (3.10), (4.10), (4.13), (4.16), (4.19), (5.9), (5.12), (5.15), (5.18), (6.8), (6.11), (6.14), (6.17), (7.9), (7.12), (7.15), (7.18), (7.21), (7.24) and (3.14), (6.21), respectively.

The normal stress p_n is included in formulae for the thermal stresses. Consequently, the coefficients ρ_M and ρ_{IN} are given by Equations (3.12), (4.12), (4.15), (4.18), (4.21), (5.11), (5.14), (5.17), (5.20), (6.10), (6.13), (6.16), (6.19), (7.11), (7.14), (7.17), (7.20), (7.23), (7.26) and (3.16), (6.22), respectively.

In case of a real material, such a combination of these mathematical solutions is considered to result in a minimum value of the elastic energy $W_T = W_C = W_{IN} + W_{INB} + W_M + W_{MB}$ of the cubic cell (see Equations (2.27), (2.36)). As an example, let the mathematical solutions for W_M , W_{MB} and W_{IN} , W_{INB} , which are given by Equations (6.17), (4.16) and (3.14), respectively, represent such a combination to result in a minimum value of W_T . In this case, the radial stress σ_{nB} , which is given by Equations (6.17), (6.18) for $Q=M$, is included in Equations (4.16), (3.14). Finally, the coefficients ρ_M , ρ_{IN} in Equation (2.33) are given by Equations (6.19), (3.16), respectively.

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Mathematical Model 1

3.1 Mathematical Procedure

Let the mathematical procedure $x_n [\partial \text{Eq. (2.24)} / \partial x_n]$ be performed, and then we get [1]–[22]

$$x_n^2 \frac{\partial^2 U_n}{\partial x_n^2} + (1 - c_3) x_n \frac{\partial U_n}{\partial x_n} = 0, \quad (3.1)$$

where $c_3 < 0$ and $U_n = U_n(x_n, \varphi, \theta)$ are given by Equations (2.18) and (2.25), respectively. Let Equation (2.24) be substituted to Equation (3.1), and then we get [1]–[22]

$$x_n^2 \frac{\partial^2 U_n}{\partial x_n^2} + c_3 (1 - c_3) U_n = 0. \quad (3.2)$$

Let U_n be assumed in the form $U_n = x_n^\lambda$, then we get [1]–[22]

$$U_n = C_1 x_n^{\lambda_1} + C_2 x_n^{\lambda_2}, \quad (3.3)$$

where C_1, C_2 are integration constants, which are determined by the boundary conditions in Section 2.3, and λ_1, λ_2 , with respect to $\mu < 0.5$ for a real isotropic material [26], have the forms [1]–[22]

$$\begin{aligned} \lambda_1 &= \frac{1}{2} \left[1 + \sqrt{1 + 16(1 - \mu)[1 + 4(1 - \mu)]} \right] > 3, \\ \lambda_2 &= \frac{1}{2} \left[1 - \sqrt{1 + 16(1 - \mu)[1 + 4(1 - \mu)]} \right] < -2. \end{aligned} \quad (3.4)$$

Let Equation (3.3) be substituted to Equation (2.23), and then we get [1]–[22]

$$x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} + 2x_n \frac{\partial u_n}{\partial x_n} - 2u_n = C_1 x_n^{\lambda_1} + C_2 x_n^{\lambda_2}. \quad (3.5)$$

The mathematical solution of Equation (3.5), which is determined by Wronskian's method (see Chapter 10) [23], is derived as

$$u_n = C_1 x_n^{\lambda_1} + C_2 x_n^{\lambda_2}. \quad (3.6)$$

With regard to Equations (2.1)–(2.4), (2.14)–(2.17), (2.21), (2.26), (3.6), we get

$$\begin{aligned} \varepsilon_n &= C_1 \lambda_1 x_n^{\lambda_1-1} + C_2 \lambda_2 x_n^{\lambda_2-1}, \\ \varepsilon_\varphi &= C_1 x_n^{\lambda_1-1} + C_2 x_n^{\lambda_2-1}, \\ \varepsilon_{n\varphi} &= s_{44} \sigma_{n\varphi} = \frac{\partial C_1}{\partial \varphi} x_n^{\lambda_1-1} + \frac{\partial C_2}{\partial \varphi} x_n^{\lambda_2-1}, \\ \varepsilon_{n\theta} &= s_{44} \sigma_{n\theta} = \Theta \left(\frac{\partial C_1}{\partial v} x_n^{\lambda_1-1} + \frac{\partial C_2}{\partial v} x_n^{\lambda_2-1} \right), \\ \sigma_n &= C_1 \xi_1 x_n^{\lambda_1-1} + C_2 \xi_2 x_n^{\lambda_2-1}, \\ \sigma_\varphi &= \sigma_\theta = C_1 \xi_3 x_n^{\lambda_1-1} + C_2 \xi_4 x_n^{\lambda_2-1}, \\ \sigma_1 &= \eta_1 x_n^{\lambda_1-1} + \eta_2 x_n^{\lambda_2-1}, \\ w &= \kappa_1 x_n^{2(\lambda_1-1)} + \kappa_2 x_n^{2(\lambda_2-1)} + \kappa_3 x_n^{\lambda_1+\lambda_2-2}, \end{aligned} \quad (3.7)$$

where Θ , s_{44} is given by Equations (1.8), (2.13), respectively. The coefficients ξ_i , ξ_{2+i} , ξ_{2+i+2j} , η_i , κ_j ($i = 1, 2$; $j = 1, 2, 3$) are derived as

$$\begin{aligned} \xi_i &= \frac{E [\lambda_i (1 - \mu) + 2\mu]}{(1 + \mu) (1 - 2\mu)}, \quad \xi_{2+i} = \frac{E (1 + \lambda_i \mu)}{(1 + \mu) (1 - 2\mu)}, \\ \xi_{2+i+2j} &= \frac{E \{ \lambda_i [\lambda_j (1 - \mu) + 4\mu] + 2 \}}{2 (1 + \mu) (1 - 2\mu)}, \\ \eta_i &= C_i (\lambda_i \gamma_1 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_i}{\partial \varphi} + \gamma_4 \Theta \frac{\partial C_i}{\partial v} \right), \\ \kappa_i &= C_i^2 \xi_{2+3i} + \frac{1}{s_{44}} \left[\left(\frac{\partial C_i}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_i}{\partial v} \right)^2 \right], \\ \kappa_3 &= C_1 C_2 (\xi_6 + \xi_7) + \frac{1}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_2}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_2}{\partial v} \right), \quad i, j = 1, 2, \end{aligned} \quad (3.8)$$

where γ_i ($i = 1, \dots, 4$) is given by Equation (2.22).

3.2 Matrix

The subscript $Q = M, MB$ and the stress σ_q in Section 3.2 are derived as

$$\begin{aligned} Q = M &\Rightarrow \sigma_q = p_n, \\ Q = MB &\Rightarrow \sigma_q = \sigma_{nB}, \end{aligned} \quad (3.9)$$

where p_n , σ_{nB} are given by Equations (2.33), (3.10), respectively. Consequently, the conditions in Equation (2.36) are considered. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (3.6), (3.7), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\sigma_q \left[\frac{\lambda_{1M}}{\zeta_{1Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{1M}-1} + \frac{\lambda_{2M}}{\zeta_{2Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{2M}-1} \right], \\
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\sigma_q \left[\frac{1}{\zeta_{1Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{1M}-1} + \frac{1}{\zeta_{2Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{2M}-1} \right], \\
\varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = -x_n^{\lambda_{1M}-1} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) - x_n^{\lambda_{2M}-1} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right), \\
\varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\Theta \left[x_n^{\lambda_{1M}-1} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) + x_n^{\lambda_{2M}-1} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right) \right], \\
\sigma_{nQ} &= -\sigma_q \left[\frac{\xi_{1M}}{\zeta_{1Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{1M}-1} + \frac{\xi_{2M}}{\zeta_{2Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{2M}-1} \right], \\
\sigma_{\varphi Q} &= \sigma_{\theta Q} = -\sigma_q \left[\frac{\xi_{3M}}{\zeta_{1Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{1M}-1} + \frac{\xi_{4M}}{\zeta_{2Q}} \left(\frac{x_n}{x_M} \right)^{\lambda_{2M}-1} \right], \\
\sigma_{1Q} &= \eta_{1Q} x_n^{\lambda_{1Q}-1} + \eta_{2Q} x_n^{\lambda_{2Q}-1}, \\
w_Q &= \kappa_{1Q} x_n^{2(\lambda_{1M}-1)} + \kappa_{2Q} x_n^{2(\lambda_{2M}-1)} + \kappa_{3Q} x_n^{\lambda_{1M}+\lambda_{2M}-2}, \\
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1Q} \left(x_M^{2\lambda_{1M}+1} - x_{IN}^{2\lambda_{1M}+1} \right)}{2\lambda_{1M}+1} + \frac{\kappa_{2Q} \left(x_M^{2\lambda_{2M}+1} - x_{IN}^{2\lambda_{2M}+1} \right)}{2\lambda_{2M}+1} \right. \\
&\quad \left. + \frac{\kappa_{3Q} \left(x_M^{\lambda_{1M}+\lambda_{2M}+1} - x_{IN}^{\lambda_{1M}+\lambda_{2M}+1} \right)}{\lambda_{1M}+\lambda_{2M}+1} \right] d\varphi dv, \\
\sigma_{nB} &= - \left[\rho_B p_n + \frac{\rho_B^{(\varphi)} + \rho_B^{(v)}}{s_{44M}} \right], \quad Q = M, MB.
\end{aligned} \tag{3.10}$$

where Θ , x_{IN} , x_M , s_{44M} , λ_{iM} , ξ_{jM} ($i=1,2$; $j=1, \dots, 8$) are given by Equations (1.8), (1.9), (2.13), (3.4), (3.10), respectively. The coefficients ζ_{iQ} , η_{iQ} , κ_{jQ} ($i=1,2$; $j=1,2,3$; $Q=M, MB$; see Equation (3.10)), ρ_B , $\rho_B^{(\tau)}$ ($\tau = \varphi, v$) have the forms

$$\zeta_{iM} = \xi_{iM} \left(\frac{x_{IN}}{x_M} \right)^{\lambda_{iM}-1} - \xi_{3-iM} \left(\frac{x_{IN}}{x_M} \right)^{\lambda_{3-iM}-1},$$

$$\begin{aligned}
\zeta_{iMB} &= \xi_{iM} - \xi_{3-iM}, \\
\eta_{iQ} &= -\frac{\sigma_q (\lambda_{iM} \gamma_{1M} + \gamma_{2M})}{\zeta_{iM} x_M^{\lambda_{iM}-1}} - \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{iM} x_M^{\lambda_{iM}-1}} \right) \\
&\quad - \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_{iM} x_M^{\lambda_{iM}-1}} \right), \\
\kappa_{iQ} &= \xi_{2+3iM} \left(\frac{\sigma_q}{\zeta_{iM} x_M^{\lambda_{iM}-1}} \right)^2 + \frac{1}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{iM} x_M^{\lambda_{iM}-1}} \right) \right]^2 \\
&\quad + \frac{\Theta^2}{s_{44M}} \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_{iM} x_M^{\lambda_{iM}-1}} \right) \right]^2, \\
\kappa_{3Q} &= \frac{\sigma_q^2 (\xi_{6M} + \xi_{7M})}{\zeta_{1Q} \zeta_{2Q} x_M^{\lambda_{1M} + \lambda_{2M} - 2}} + \frac{1}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right) \\
&\quad + \frac{\Theta^2}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right), \\
\rho_B &= \sum_{i=1}^2 \frac{\vartheta_1 \xi_{iM} + (\vartheta_2 + \vartheta_3) \xi_{2+iM}}{\zeta_{iM}} \\
\rho_B^{(\varphi)} &= (\vartheta_1 + \vartheta_2) \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) + \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right) \right] \\
\rho_B^{(v)} &= \Theta (\vartheta_1 + \vartheta_3) \left[\frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_{1Q} x_M^{\lambda_{1M}-1}} \right) + \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_{2Q} x_M^{\lambda_{2M}-1}} \right) \right], \\
i &= 1, 2, \quad Q = M, MB,
\end{aligned} \tag{3.11}$$

where γ_{iM} , ϑ_j ($i = 1, \dots, 4$; $j = 1, 2, 3$) are given by Equations (2.22), (2.35), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (3.10), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_{1Q}} \left(\frac{x_{IN}}{x_M} \right)^{\lambda_{1M}-1} + \frac{1}{\zeta_{2Q}} \left(\frac{x_{IN}}{x_M} \right)^{\lambda_{2M}-1}, \quad Q = M, MB. \tag{3.12}$$

3.3 Inclusion

The subscript $Q = IN, INB$ and the stress σ_q in Section 3.3 are derived as

$$\begin{aligned}
Q = IN &\Rightarrow \sigma_q = p_n, \quad \rho_Q = \rho_{IN} = \frac{1}{\xi_{1IN}} \\
Q = INB &\Rightarrow \sigma_q = \sigma_{nB}, \quad \rho_Q = \rho_{MB}
\end{aligned} \tag{3.13}$$

where p_n , ξ_{1IN} , σ_{nB} , ρ_{MB} , ρ_{IN} are given by Equations (2.33), (3.8), (3.10), (3.16), respectively. Consequently, the conditions in Equation (2.36) are considered. In case of the ellipsoidal inclusion, we get $C_{2IN} = 0$, otherwise we get $(u_{nIN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\varepsilon_{IN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\sigma_{IN})_{r \rightarrow 0} \rightarrow \pm \infty$ due to $\lambda_2 < -2$ (see Equations (3.4), (3.6)–(3.12)). With regard to Equations (2.28), (2.29), (3.6)–(3.14), (2.21), (2.26), (2.27), we get [1]–[22]

$$\begin{aligned}
\varepsilon_{nQ} &= -\sigma_q \rho_Q \lambda_{1IN} \left(\frac{x_n}{x_{IN}} \right)^{\lambda_{1IN}-1}, \\
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\sigma_q \rho_Q \left(\frac{x_n}{x_{IN}} \right)^{\lambda_{1IN}-1}, \\
\varepsilon_{n\varphi Q} &= s_{44IN} \sigma_{n\varphi Q} = -x_n^{\lambda_{1IN}-1} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q \rho_Q}{x_{IN}^{\lambda_{1IN}-1}} \right), \\
\varepsilon_{nvQ} &= s_{44IN} \sigma_{rvQ} = -\Theta x_n^{\lambda_{1IN}-1} \frac{\partial}{\partial v} \left(\frac{\sigma_q \rho_Q}{x_{IN}^{\lambda_{1IN}-1}} \right), \\
\sigma_{nQ} &= -\sigma_q \left(\frac{x_n}{x_{IN}} \right)^{\lambda_{1IN}-1}, \\
\sigma_{\varphi Q} &= \sigma_{vQ} = -\sigma_q \rho_Q \xi_{3IN} \left(\frac{x_n}{x_{IN}} \right)^{\lambda_{1IN}-1}, \\
\sigma_{1Q} &= \eta_{1Q} x_n^{\lambda_{1IN}-1}, \\
w_Q &= \kappa_{1Q} x_n^{2(\lambda_{1IN}-1)}, \\
W_Q &= \frac{4}{2\lambda_{1IN}+1} \int_0^{\pi/2} \int_0^{\pi/2} \kappa_{1Q} x_{IN}^{2\lambda_{1IN}+1} d\varphi dv, \quad Q = IN, INB,
\end{aligned} \tag{3.14}$$

where Θ ; x_{IN} ; s_{44IN} ; λ_{1IN} ; ξ_{1IN} , ξ_{3IN} , ξ_{5IN} are given by Equations (1.8); (1.9); (2.13); (3.4); (3.8); respectively. The coefficients η_{1Q} , κ_{1Q} ($Q = M, MB$; see Equation (3.8)) have the forms

$$\begin{aligned}
\eta_{1Q} &= -\frac{\sigma_q (\lambda_{1IN} \gamma_{1IN} + \gamma_{2IN})}{\xi_{1IN} x_n^{\lambda_{1IN}-1}} - \frac{\gamma_{3IN}}{s_{44IN}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\xi_{1IN} x_n^{\lambda_{1IN}-1}} \right) \\
&\quad - \frac{\gamma_{4IN}}{s_{44IN}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\xi_{1IN} x_n^{\lambda_{1IN}-1}} \right),
\end{aligned}$$

$$\begin{aligned} \kappa_{1Q} = & \xi_{5IN} \left(\frac{\sigma_q}{\xi_{1IN} x_{IN}^{\lambda_{1IN}-1}} \right)^2 + \frac{1}{s_{44IN}} \left[\frac{\partial C_1}{\partial \phi} \left(\frac{\sigma_q}{\xi_{1IN} x_{IN}^{\lambda_{1IN}-1}} \right) \right]^2 \\ & + \frac{\Theta^2}{s_{44IN}} \left[\frac{\partial C_1}{\partial v} \left(\frac{\sigma_q}{\xi_{1IN} x_{IN}^{\lambda_{1IN}-1}} \right) \right]^2, \quad Q = IN, INB, \end{aligned} \quad (3.15)$$

where γ_{iIN} ($i=1, \dots, 4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (3.14), the coefficient ρ_{IN} in Equation (2.33) is derived as

$$\rho_{IN} = \frac{(1 + \mu_{IN})(1 - 2\mu_{IN})}{E_{IN} [\lambda_{1IN}(1 - \mu_{IN}) + 2\mu_{IN}]}. \quad (3.16)$$

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Mathematical Model 2

4.1 Mathematical Procedure

Let the mathematical procedure $\partial^2 \text{Eq. (2.24)} / \partial x_n^2$ be performed, and then we get [1]–[22]

$$x_n \frac{\partial^3 U_n}{\partial x_n^3} + (2 - c_3) \frac{\partial^2 U_n}{\partial x_n^2} = 0, \quad (4.1)$$

where $c_3 < 0$ and $U_n = U_n(x_n, \phi, v)$ are given by Equations (2.18) and (2.25), respectively. Let U_b be assumed in the form $U_n = x_n^\lambda$, and then we get

$$U_n = C_1 x_n + C_2 x_n^{c_3} + C_3, \quad (4.2)$$

where C_1, C_2, C_3 are integration constants, which are determined by the boundary conditions in Section 2.3. Let Equation (2.28) be substituted to Equation (2.23), and then we get

$$x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} + 2x_n \frac{\partial u_n}{\partial x_n} - 2u_n = C_1 x_n + C_2 x_n^{c_3} + C_3 x_n^2. \quad (4.3)$$

The mathematical solution of Equation (4.3), which is determined by Wronskian's method (see Chapter 10) [23], is derived as

$$u_n = C_1 x_n \left(\frac{1}{3} - \ln x_n \right) + C_2 x_n^{c_3} + C_3. \quad (4.4)$$

With regard to Equations (2.1)–(2.4), (2.14)–(2.17), (2.26), (4.4), we get

$$\begin{aligned} \varepsilon_n &= -C_1 \left(\frac{2}{3} + \ln x_n \right) + C_2 c_3 x_n^{c_3-1}, \\ \varepsilon_\phi &= \varepsilon_\theta = C_1 \left(\frac{1}{3} - \ln x_n \right) + C_2 x_n^{c_3-1} + \frac{C_3}{x_n}, \\ \varepsilon_{n\phi} &= s_{44} \sigma_{n\phi} = \left(\frac{1}{3} - \ln x_n \right) \frac{\partial C_1}{\partial \phi} + x_n^{c_3-1} \frac{\partial C_2}{\partial \phi} + \frac{1}{x_n} \frac{\partial C_3}{\partial \phi}, \end{aligned}$$

$$\begin{aligned}
\varepsilon_{n\theta} &= s_{44} \sigma_{n\theta} = \Theta \left[\left(\frac{1}{3} - \ln x_n \right) \frac{\partial C_1}{\partial v} + x_n^{c_3-1} \frac{\partial C_2}{\partial v} + \frac{1}{x_n} \frac{\partial C_3}{\partial v} \right], \\
\sigma_n &= -C_1 \left[\frac{2(c_1+2c_2)}{3} + (c_1-c_2) \ln x_n \right] + C_2 [(c_1+c_2)c_3 - 2c_2] x_n^{c_3-1} - \frac{2C_3 c_2}{x_n}, \\
\sigma_\varphi &= \sigma_\theta = C_1 \xi_1 \left[\frac{c_1+2c_2}{3} - (c_1-c_2) \ln x_n \right] + C_2 \xi_2 (c_1 - c_2 c_3) x_n^{c_3-1} + \frac{C_3 \xi_3 c_1}{x_n}, \\
\sigma_1 &= \eta_1 + \eta_2 \ln x_n + \eta_3 x_n^{c_3-1} + \frac{\eta_4}{x_n}, \\
w &= C_1^2 \kappa_1 + C_2^2 \kappa_2 + C_3^2 \kappa_3 + C_1 C_2 \kappa_4 + C_1 C_3 \kappa_5 + C_2 C_3 \kappa_6 \\
&\quad + \frac{\chi_1}{s_{44}} \left[\left(\frac{\partial C_1}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_1}{\partial v} \right)^2 \right] + \frac{\chi_2}{s_{44}} \left[\left(\frac{\partial C_2}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_2}{\partial v} \right)^2 \right] \\
&\quad + \frac{\chi_3}{s_{44}} \left[\left(\frac{\partial C_3}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_3}{\partial v} \right)^2 \right] + \frac{\chi_4}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_2}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_2}{\partial v} \right) \\
&\quad + \frac{\chi_5}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_3}{\partial v} \right) + \frac{\chi_6}{s_{44}} \left(\frac{\partial C_2}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_2}{\partial v} \frac{\partial C_3}{\partial v} \right), \quad (4.5)
\end{aligned}$$

where Θ , c_i ($i = 1, 2, 3$), s_{44} are given by Equations (1.8), (2.18), (2.13), respectively. The coefficients η_j , κ_k , χ_k ($j = 1, \dots, 4$; $k = 1, \dots, 6$) are derived as

$$\begin{aligned}
\eta_1 &= \frac{1}{3} \left[C_1 (\gamma_2 - 2\gamma_1) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_1}{\partial \varphi} + \gamma_4 \frac{\partial C_1}{\partial v} \right) \right], \\
\eta_2 &= - \left[C_1 (\gamma_1 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_1}{\partial \varphi} + \gamma_4 \frac{\partial C_1}{\partial v} \right) \right], \\
\eta_3 &= C_2 (\gamma_1 c_3 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_2}{\partial \varphi} + \gamma_4 \frac{\partial C_2}{\partial v} \right), \\
\eta_4 &= C_3 \gamma_2 + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_3}{\partial \varphi} + \gamma_4 \frac{\partial C_3}{\partial v} \right), \\
\kappa_1 &= \frac{c_2 - c_1}{2} \ln^2 x_n + \frac{2(c_2 - c_1)}{3} \ln x_n + \frac{7c_1 + 2c_2}{9}, \\
\kappa_2 &= \left[\frac{c_3^2 (c_1 + c_2)}{2} + c_1 (1 - 2c_3) \right] x_n^{2(c_3-1)}, \quad \kappa_3 = \frac{c_1}{x_n^2}, \\
\kappa_4 &= c_3 (c_1 - c_2) x_n^{c_3-1} \ln x_n + 2 \left[c_1 - \frac{c_3 (2c_1 + c_2)}{3} \right] x_n^{c_3-1}, \\
\kappa_5 &= \frac{2c_1}{x_n}, \quad \kappa_6 = 0, \\
\chi_1 &= \ln^2 x_n - \frac{2}{3} \ln x_n + \frac{1}{9}, \quad \chi_2 = x_n^{2(c_3-1)}, \quad \chi_3 = \frac{1}{x_n^2},
\end{aligned}$$

$$\chi_4 = \frac{2}{3}x_n^{c_3-1} - 2x_n^{c_3-1} \ln x_n, \quad \chi_5 = \frac{2}{3x_n} - \frac{2 \ln x_n}{x_n}, \quad \chi_6 = x_n^{c_3-2}, \quad (4.6)$$

where γ_i ($i=1, \dots, 4$) is given by Equation (2.22). The integrals Φ_{iM} , Ψ_{iM} of the $\kappa_{jM} = \kappa_{jM}(x_n)$, $\chi_{jM} = \chi_{jM}(x_n)$ ($i=1, \dots, 6$), respectively, have the forms

$$\Phi_i = \int_{x_{IN}}^{x_M} \kappa_{iM} x_n^2 dx_n, \quad \Psi_i = \int_{x_{IN}}^{x_M} \chi_{iM} x_n^2 dx_n, \quad i=1, \dots, 6, \quad (4.7)$$

where x_{IN} , x_M are given by Equation (1.9), respectively. The integrals are determined by the formulae in Chapter 10 (see Equations (10.10)–(10.12)) and consequently, we get

$$\begin{aligned} \Phi_{1M} &= \frac{c_{2M} - c_{1M}}{6} \left\{ x_M^3 \left[\left(\ln x_M - \frac{1}{3} \right)^2 + \frac{1}{9} \right] - x_{IN}^3 \left[\left(\ln x_{IN} - \frac{1}{3} \right)^2 + \frac{1}{9} \right] \right\} \\ &\quad + \frac{2(c_{2M} - c_{1M})}{9} \left[x_M^3 \left(\ln x_M - \frac{1}{3} \right) - x_{IN}^3 \left(\ln x_{IN} - \frac{1}{3} \right) \right] \\ &\quad + \frac{(7c_{1M} + 2c_{2M})(x_M^3 - x_{IN}^3)}{27}, \\ \Phi_{2M} &= \frac{1}{2c_{3M} + 1} \left[\frac{c_{3M}^2(c_{1M} + c_{2M})}{2} + c_{1M}(1 - 2c_{3M}) \right] (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}), \\ \Phi_{3M} &= c_{1M}(x_M - x_{IN}), \\ \Phi_{4M} &= \frac{c_{3M}(c_{1M} - c_{2M})}{c_{3M} + 2} \left[x_M^{c_{3M}+2} \left(\ln x_M - \frac{1}{c_{3M} + 2} \right) - x_{IN}^{c_{3M}+2} \left(\ln x_{IN} - \frac{1}{c_{3M} + 2} \right) \right] \\ &\quad + \frac{2}{c_{3M} + 2} \left[c_{1M} - \frac{c_{3M}(2c_{1M} + c_{2M})}{3} \right] (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}), \\ \Phi_{5M} &= c_{1M}(x_M^2 - x_{IN}^2), \quad \Phi_{6M} = 0, \\ \Psi_{1M} &= \frac{x_M^3}{3} \left[(\ln x_M - 1) \left(\ln x_M - \frac{1}{3} \right) + \frac{2}{9} \right] - \frac{x_{IN}^3}{3} \left[(\ln x_{IN} - 1) \left(\ln x_{IN} - \frac{1}{3} \right) + \frac{2}{9} \right], \\ \Psi_{2M} &= \frac{x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}}{2c_{3M} + 1}, \quad \Psi_{3M} = x_M - x_{IN}, \\ \Psi_{4M} &= \frac{2}{c_{3M} + 2} \left\{ x_M^{c_{3M}+2} \left[\frac{c_{3M} + 5}{3(c_{3M} + 2)} - \ln x_M \right] - x_{IN}^{c_{3M}+2} \left[\frac{c_{3M} + 5}{3(c_{3M} + 2)} - \ln x_{IN} \right] \right\}, \\ \Psi_{5M} &= x_M^2 \left(\frac{5}{6} - \ln x_M \right) - x_{IN}^2 \left(\frac{5}{6} - \ln x_{IN} \right), \quad \Psi_{6M} = \frac{x_M^{c_3+1} - x_{IN}^{c_3+1}}{c_3 + 1}. \end{aligned} \quad (4.8)$$

In case of the ellipsoidal inclusion, we get $(u_{nIN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\epsilon_{IN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\sigma_{IN})_{r \rightarrow 0} \rightarrow \pm \infty$ due to $(\ln x_n)_{x_n \rightarrow 0} \rightarrow \pm \infty$ and $(x_n^{c_3})_{x_n \rightarrow 0} \rightarrow \pm \infty$ for

$c_3 < 0$ (see Equations (2.18), (4.4)). Accordingly, the mathematical solution (4.4) is suitable for the matrix.

4.2 Matrix

The integration constants C_{1M} , C_{2M} , C_{3M} for the matrix (see Equation (4.4)) are determined by the boundary conditions (2.30), (2.31) or (2.30)–(2.32). The boundary conditions result in the following combinations of C_{1M} , C_{2M} , C_{3M} . Finally, such a combination is considered to exhibit a minimum value of the elastic energy W_C of the cubic cell (see Equation (2.27)). The subscript $Q = M, MB$ and the stress σ_q in Section 4.2 are derived as

$$\begin{aligned} Q = M &\Rightarrow \sigma_q = p_n, \\ Q = MB &\Rightarrow \sigma_q = \sigma_{nB}, \end{aligned} \quad (4.9)$$

where p_n and σ_{nB} are given by Equations (2.33) and (4.10), (4.13), (4.17), (4.20), respectively. Consequently, the conditions in Equation (2.36) are considered.

Conditions $C_{1M} \neq 0$, $C_{2M} \neq 0$, $C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (4.4), (4.5), we get

$$\begin{aligned} \varepsilon_{nQ} &= \frac{\sigma_q}{\zeta_Q} \left[\frac{2}{3} + \ln x_n + c_{3M} \left(\frac{1}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\ \varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = - \frac{\sigma_q}{\zeta_Q} \left[\frac{1}{3} - \ln x_n - \left(\frac{1}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\ \varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = \left(\ln x_n - \frac{1}{3} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \\ &\quad + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right], \\ \varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = \Theta \left\{ \left(\ln x_n - \frac{1}{3} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right. \\ &\quad \left. + x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right] \right\}, \\ \sigma_{nQ} &= \frac{\sigma_q}{\zeta_Q} \left\{ \frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_n \right. \end{aligned}$$

$$\begin{aligned}
& + [(c_{1M} + c_{2M})c_{3M} - 2c_{2M}] \left(\frac{1}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \Bigg\}, \\
\sigma_{\varphi Q} = \sigma_{\theta Q} = & - \frac{\sigma_q}{\zeta_Q} \left[\frac{c_{1M} + 2c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right. \\
& \left. - (c_{1M} - c_{2M}c_{3M}) \left(\frac{1}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\
\sigma_{1Q} = & \eta_{1Q} + \eta_{2Q} \ln x_n + \eta_{3Q} x_n^{c_{3M}-1}, \\
w_Q = & \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left\{ \kappa_{1Q} + \kappa_{2Q} \left(\frac{1 - 3 \ln x_M}{3x_M^{c_{3M}-1}} \right)^2 + \frac{\kappa_{4Q}(3 \ln x_M - 1)}{3x_M^{c_{3M}-1}} \right\} \\
& + \frac{\chi_{1M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} \\
& + \frac{\chi_{2M}}{s_{44M}} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q(1 - 3 \ln x_M)}{3\zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q(1 - 3 \ln x_M)}{3\zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right) \\
& + \frac{\chi_{4M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q(3 \ln x_M - 1)}{3\zeta_Q x_M^{c_{3M}-1}} \right] \\
& + \frac{\chi_{4M}\Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q(3 \ln x_M - 1)}{3\zeta_Q x_M^{c_{3M}-1}} \right], \\
W_Q = & 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left\{ \Phi_{1M} + \Phi_{2M} \left(\frac{1 - 3 \ln x_M}{3x_M^{c_{3M}-1}} \right)^2 + \frac{\Phi_{4M}(3 \ln x_M - 1)}{3x_M^{c_{3M}-1}} \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{1M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q(1 - 3 \ln x_M)}{3\zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \Theta^2 \left(\left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q(1 - 3 \ln x_M)}{3\zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{4M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q(3 \ln x_M - 1)}{3\zeta_Q x_M^{c_{3M}-1}} \right] d\varphi dv
\end{aligned}$$

$$\begin{aligned}
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{4M} \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q (3 \ln x_M - 1)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right] \\
& + \frac{\rho_{2B} p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) + \frac{\rho_{2B}^{(\varphi)}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right] \\
& + \frac{\rho_{2B}^{(v)}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right], \quad Q = M, MB,
\end{aligned} \tag{4.10}$$

where Θ , x_M , s_{44M} , c_{iM} ; κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ($i=1,2,3$; $j=1,2,4$) are given by Equations (1.8), (1.9), (2.13), (2.18); (4.6); (4.8), respectively. The coefficients ζ_Q , ζ_{iQ} , η_{jQ} , ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2$; $j=1,2,3$; $\tau = \varphi, v$; $Q = M, MB$; see Equation (4.6)) have the forms

$$\begin{aligned}
\zeta_Q &= \zeta_{2Q} - \zeta_{1Q} \left(\frac{1}{3} - \ln x_M \right), \quad \zeta_{1M} = \zeta_{1MB} \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1}, \\
\zeta_{2M} &= - \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_{IN} \right], \\
\zeta_{1MB} &= (c_{1M} + c_{2M}) c_{3M} - 2c_{2M}, \\
\zeta_{2MB} &= - \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_M \right], \\
\eta_{1Q} &= - \frac{1}{3} \left\{ \frac{\sigma_q (\gamma_{2M} - 2\gamma_{1M})}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right] \right\}, \\
\eta_{2Q} &= \frac{\sigma_q (\gamma_{1M} + \gamma_{2M})}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\eta_{3Q} &= \frac{\sigma_q (\gamma_{1M} c_{3M} + \gamma_{2M})}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right] \\
&+ \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{1}{3} - \ln x_M \right) \right], \\
\rho_{1B} &= \frac{c_{1M} + 2c_{2M}}{3} (\vartheta_2 + \vartheta_3 - 2\vartheta_1) + (c_{2M} - c_{1M}) (\vartheta_1 + \vartheta_2 + \vartheta_3) \ln x_M, \\
\rho_{2B} &= \left\{ \vartheta_1 [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] + (\vartheta_2 + \vartheta_3) (c_{1M} - c_{2M} c_{3M}) \right\} x_M^{c_{3M}-1}, \\
\rho_{1B}^{(\varphi)} &= (\vartheta_1 + \vartheta_2) \left(\frac{1}{3} - \ln x_M \right), \quad \rho_{1B}^{(v)} = \Theta (\vartheta_1 + \vartheta_3) \left(\frac{1}{3} - \ln x_M \right),
\end{aligned}$$

$$\rho_{2B}^{(\varphi)} = (\vartheta_1 + \vartheta_2) x_M^{c_{3M}-1}, \quad \rho_{2B}^{(v)} = \Theta (\vartheta_1 + \vartheta_3) x_M^{c_{3M}-1}, \quad Q = M, MB, \quad (4.11)$$

where γ_{iM} , ϑ_j ($i = 1, \dots, 4$; $j = 1, 2, 3$) are given by Equations (2.22), (2.35), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (4.10), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\frac{1}{3} - \ln x_{IN} - \left(\frac{1}{3} - \ln x_M \right) \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} \right], \quad Q = M, MB. \quad (4.12)$$

Conditions $C_{1M} \neq 0$, $C_{3M} \neq 0$, $C_{2M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (4.4), (4.5), we get

$$\begin{aligned} \varepsilon_{nQ} &= \frac{\sigma_q}{\zeta_Q x_M} \left(\frac{2}{3} + \ln x_n \right), \\ \varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = - \frac{\sigma_q}{\zeta_Q} \left[\frac{1}{x_M} \left(\frac{1}{3} - \ln x_n \right) - \frac{1}{x_n} \left(\frac{1}{3} - \ln x_M \right) \right], \\ \varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = - \left(\frac{1}{3} - \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right], \\ \varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = \\ &\quad - \Theta \left\{ \left(\frac{1}{3} - \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) - \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \right\}, \\ \sigma_{nQ} &= \frac{\sigma_q}{\zeta_Q} \left\{ \frac{1}{x_M} \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_n \right] - \frac{2c_{2M}}{x_n} \left(\frac{1}{3} - \ln x_M \right) \right\}, \\ \sigma_{\varphi Q} &= \sigma_{\theta Q} = \\ &\quad - \frac{\sigma_q}{\zeta_Q} \left\{ \frac{1}{x_M} \left[\frac{c_{1M} + 2c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] - \frac{c_{1M}}{x_n} \left(\frac{1}{3} - \ln x_M \right) \right\}, \\ \sigma_{1Q} &= \eta_{1Q} + \eta_{2Q} \ln x_n + \frac{\eta_{4Q}}{x_n}, \\ w_Q &= \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\frac{\kappa_{1M}}{x_M^2} + \kappa_{3M} \left(\frac{1}{3} - \ln x_M \right)^2 + \frac{\kappa_{5M} (3 \ln x_M - 1)}{3 x_M} \right] \\ &\quad + \frac{\chi_{1M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right]^2 \right\} \\ &\quad + \frac{\chi_{3M}}{s_{44M}} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \right\}^2 + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \right\}^2 \right) \\ &\quad + \frac{\chi_{5M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (3 \ln x_M - 1)}{3 \zeta_Q} \right] \end{aligned}$$

$$\begin{aligned}
& + \frac{\chi_{5M} \Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q (3 \ln x_M - 1)}{3 \zeta_Q} \right], \\
W_Q = & 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\frac{\Phi_{1M}}{x_M^2} + \Phi_{3M} \left(\frac{1}{3} - \ln x_M \right)^2 + \frac{\Phi_{5M} (3 \ln x_M - 1)}{3 x_M} \right] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{1M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{3M} \left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \right\}^2 d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{3M} \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \right\}^2 d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{5M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (3 \ln x_M - 1)}{3 \zeta_Q} \right] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{5M} \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q (3 \ln x_M - 1)}{3 \zeta_Q} \right] d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n}{\zeta_M x_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M x_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M x_M} \right) \right] \\
& + \frac{\rho_{3B} p_n}{\zeta_M} \left(\frac{1}{3} - \ln x_M \right) + \frac{\rho_{3B}^{(\varphi)}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{3} - \ln x_M \right) \right] \\
& + \frac{\rho_{3B}^{(v)}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{3} - \ln x_M \right) \right], \quad Q = M, MB, \tag{4.13}
\end{aligned}$$

where Θ , x_M , s_{44M} , c_{iM} , κ_{jM} , χ_{jM} , Φ_{jM} , Ψ_{jM} ; ρ_{1B} , $\rho_{1B}^{(\tau)}$ ($i=1,2,3$; $j=1,3,5$; $\tau=\varphi, v$) are given by Equations (1.8), (1.9), (2.13), (2.18), (4.6); (4.8); (4.11), respectively. The coefficients ζ_Q , η_{iQ} , ρ_{3B} , $\rho_{3B}^{(\tau)}$ ($i=1,2,4$; $\tau=\varphi, v$; $Q=M, MB$; see Equation (4.6)) have the forms

$$\begin{aligned}
\zeta_M &= \frac{1}{x_M} \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_{IN} \right] + \frac{2c_{2M}}{x_{IN}} \left(\frac{1}{3} - \ln x_M \right), \\
\zeta_{MB} &= \frac{1}{x_M} \left\{ \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_M \right] + 2c_{2M} \left(\frac{1}{3} - \ln x_M \right) \right\},
\end{aligned}$$

$$\begin{aligned}
\eta_{1Q} &= -\frac{1}{3} \left\{ \frac{\sigma_q (\gamma_{2M} - 2\gamma_{1M})}{\zeta_Q x_M} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_M x_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right] \right\}, \\
\eta_{2Q} &= \frac{\sigma_q (\gamma_{1M} + \gamma_{2M})}{\zeta_Q x_M} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M} \right) \right], \\
\eta_{4Q} &= \frac{\sigma_q \gamma_{2M} (1 - 3 \ln x_M)}{3 \zeta_Q} + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right] \\
&\quad + \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q (1 - 3 \ln x_M)}{3 \zeta_Q} \right], \\
\rho_{3B} &= \frac{1}{x_M} \left[c_{1M} (\vartheta_2 + \vartheta_3) - 2 c_{1M} \vartheta_1 \right], \\
\rho_{3B}^{(\varphi)} &= \frac{\vartheta_1 + \vartheta_2}{x_M}, \quad \rho_{3B}^{(v)} = \frac{\Theta (\vartheta_1 + \vartheta_3)}{x_M}, \quad Q = M, MB,
\end{aligned} \tag{4.14}$$

where γ_{iM} , ϑ_j ($i = 1, \dots, 4$; $j = 1, 2, 3$) are given by Equations (2.22), (2.35), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (4.13), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\frac{1}{x_M} \left(\frac{1}{3} - \ln x_{IN} \right) - \frac{1}{x_{IN}} \left(\frac{1}{3} - \ln x_M \right) \right], \quad Q = M, MB. \tag{4.15}$$

Conditions $C_{2M} \neq 0$, $C_{3M} \neq 0$, $C_{1M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (4.4), (4.5), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\frac{\sigma_q c_{3M}}{\zeta_Q x_M} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1}, \\
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = \frac{\sigma_q}{\zeta_Q x_n} \left[1 - \left(\frac{x_n}{x_M} \right)^{c_{3M}} \right], \\
\varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = -\frac{1}{x_n} \left[x_n^{c_{3M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) - \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\frac{\Theta}{x_n} \left[x_n^{c_{3M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) - \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left\{ \frac{c_{3M} (c_{1M} + c_{2M}) - 2 c_{2M}}{x_M} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} + \frac{2 c_{2M}}{x_n} \right\}, \\
\sigma_{\varphi Q} &= \sigma_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[\frac{c_{1M} - c_{2M} c_{3M}}{x_M} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - \frac{c_{1M}}{x_n} \right], \\
\sigma_{1Q} &= \eta_{3Q} x_n^{c_{3M}-1} + \frac{\eta_{4Q}}{x_n},
\end{aligned}$$

$$\begin{aligned}
w_Q &= \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left(\frac{\kappa_{2M}}{x_M^{2c_{3M}}} + \kappa_{3M} - \frac{\kappa_{6M}}{x_M^{c_{3M}}} \right) \\
&+ \frac{\chi_{2M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \right]^2 \right\} \\
&+ \frac{\chi_{3M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} \\
&- \frac{\chi_{6M}}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left(\frac{\Phi_{2M}}{x_M^{2c_{3M}}} + \Phi_{3M} - \frac{\Phi_{6M}}{x_M^{c_{3M}}} \right) d\varphi dv \\
&+ \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \right]^2 \right\} d\varphi dv \\
&+ \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{3M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} d\varphi dv \\
&- \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{6M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) d\varphi dv \\
&- \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{6M} \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) d\varphi dv, \\
\sigma_{nB} &= - \frac{\rho_{1B} p_n}{\zeta_M x_M^{c_{3M}}} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}}} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}}} \right) \right] \\
&+ \frac{\rho_{3B} p_n}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (4.16)
\end{aligned}$$

where Θ ; x_M ; s_{44M} ; c_{iM} ($i=2,3,6$); κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ($j=1,3,5$); ρ_{kB} , $\rho_{kB}^{(\tau)}$ ($k=2,3$; $\tau=\varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (4.13), (4.15), respectively. The coefficients ζ_Q , η_{iQ} ($i=3,4$; $Q=M, MB$; see Equation (4.6)) have the forms

$$\begin{aligned}
\zeta_M &= \frac{1}{x_{IN}} \left\{ [c_{3M}(c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}} + 2c_{2M} \right\}, \\
\zeta_{MB} &= \frac{c_{3M}(c_{1M} + c_{2M})}{x_M},
\end{aligned}$$

$$\begin{aligned}\eta_{3Q} &= -\frac{\sigma_q(\gamma_{1M}c_{3M} + \gamma_{2M})}{\zeta_Q x_M^{c_{3M}}} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) - \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}}} \right) \right], \\ \eta_{4Q} &= \frac{\sigma_q \gamma_{2M}}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \quad Q = M, MB, \quad (4.17)\end{aligned}$$

where γ_{iM} ($i=1, \dots, 4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (4.17), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\left(\frac{x_{1M}}{x_M} \right)^{c_{3M}} - 1 \right], \quad Q = M, MB. \quad (4.18)$$

Conditions $C_{1M} \neq 0, C_{2M} \neq 0, C_{3M} \neq 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (4.4), (4.5), we get

$$\begin{aligned}\varepsilon_{nM} &= -\frac{p_n}{\zeta_M} \left[\zeta_{1M} \left(\frac{2}{3} + \ln x_n \right) - \zeta_{2M} c_{3M} x_n^{c_{3M}-1} \right], \\ \varepsilon_{\varphi M} = \varepsilon_{\theta M} &= \frac{p_n}{\zeta_M} \left[\zeta_{1M} \left(\frac{1}{3} - \ln x_n \right) + \zeta_{2M} x_n^{c_{3M}-1} + \frac{\zeta_{3M}}{x_n} \right], \\ \varepsilon_{n\varphi M} = s_{44M} \sigma_{n\varphi M} &= \left(\frac{1}{3} - \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_3-1} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \\ &\quad + \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right), \\ \varepsilon_{n\theta M} = s_{44M} \sigma_{n\theta M} &= \Theta \left[\left(\frac{1}{3} - \ln x_n \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_3-1} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right. \\ &\quad \left. + \frac{1}{x_n} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\ \sigma_{nM} &= -\frac{p_n}{\zeta_M} \left\{ \zeta_{1M} \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_n \right] \right. \\ &\quad \left. - \zeta_{2M} [(c_{1M} + c_{2M})c_{3M} - 2c_{2M}] x_n^{c_{3M}-1} + \frac{2c_{2M} \zeta_{3M}}{x_n} \right\}, \\ \sigma_{\varphi M} = \sigma_{\theta M} &= \frac{p_n}{\zeta_M} \left\{ \zeta_{1M} \left[\frac{c_{1M} + 2c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] \right. \\ &\quad \left. + \zeta_{2M} (c_{1M} - c_{2M} c_{3M}) x_n^{c_{3M}-1} + \frac{c_{1M} \zeta_{3M}}{x_n} \right\}, \\ \sigma_{1M} &= \eta_{1M} + \eta_{2M} \ln x_n + \eta_{3M} x_n^{c_{3M}-1} + \frac{\eta_{4M}}{x_n}, \\ w_M &= \left(\frac{p_n}{\zeta_M} \right)^2 \left(\kappa_{1M} \zeta_{1M}^2 + \kappa_{2M} \zeta_{2M}^2 + \kappa_{3M} \zeta_{3M}^2 \right)\end{aligned}$$

$$\begin{aligned}
& + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \Big] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{6M} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right. \\
& \quad \left. + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] d\varphi dv, \\
\sigma_{nB} = & \sum_{i=1}^3 \frac{p_n \rho_{iB} \zeta_{iM}}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{iB}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{iM}}{\zeta_M} \right) + \rho_{iB}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{iM}}{\zeta_M} \right) \right], \quad (4.19)
\end{aligned}$$

where Θ , x_M , s_{44M} , c_{iM} ; κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ; ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2,3$; $j=1,\dots,6$; $\tau=\varphi, v$); are given by Equations (1.8), (1.9), (2.13), (2.18); (4.6); (4.8); (4.11), (4.15); respectively. The coefficients ζ_{iM} , ζ_M , η_{jM} ($i=1,2,3$; $j=1,\dots,4$; see Equation (4.13)) have the forms

$$\begin{aligned}
\zeta_{1M} &= c_{3M} x_M^{c_{3M}-1}, \quad \zeta_{2M} = \frac{2}{3} + \ln x_M, \\
\zeta_{3M} &= -x_M^{c_{3M}} \left[\frac{2}{3} + \ln x_M + c_{3M} \left(\frac{1}{3} - \ln x_M \right) \right], \\
\zeta_M &= c_{3M} \left\{ \left[\frac{2(c_{1M} + 2c_{2M})}{3} + (c_{1M} - c_{2M}) \ln x_{IN} \right] - \frac{2c_{2M} x_M}{x_{IN}} \left(\frac{1}{3} - \ln x_M \right) \right\} x_M^{c_{3M}-1} \\
&\quad - \left\{ [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_{IN}^{c_{3M}-1} + \frac{2c_{2M} x_M^{c_{3M}}}{x_{IN}} \right\} \left(\frac{2}{3} + \ln x_M \right), \\
\eta_{1M} &= \frac{p_n \zeta_{1M} (\gamma_{2M} - 2\gamma_{1M})}{3\zeta_M} + \frac{1}{3s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right], \\
\eta_{2M} &= -\frac{p_n \zeta_{1M} (\gamma_{1M} + \gamma_{2M})}{\zeta_M} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right], \\
\eta_{3M} &= \frac{p_n \zeta_{2M} (\gamma_{1M} c_3 + \gamma_{2M})}{\zeta_M} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right], \\
\eta_{4M} &= \frac{p_n \zeta_{3M} \gamma_{2M}}{\zeta_M} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \quad (4.20)
\end{aligned}$$

where γ_{iM} ($i=1,\dots,4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (4.19), the coefficient ρ_M in Equations (2.33), (3.13) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left[\zeta_{1M} \left(\ln x_{IN} - \frac{1}{3} \right) - \zeta_{2M} x_{IN}^{c_{3M}-1} - \frac{\zeta_{3M}}{x_{IN}} \right]. \quad (4.21)$$

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Mathematical Model 3

5.1 Mathematical Procedure

Let the mathematical procedure $\partial^2 \text{Eq. (2.23)} / \partial x_n^2$ be performed, and then we get [1]–[22]

$$r \frac{\partial^3 u_n}{\partial x_n^3} + 4x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} + \frac{x_n}{s_{44}(c_1 + c_2)} \frac{\partial U_n}{\partial x_n} = 0, \quad (5.1)$$

where s_{44} , c_i ($i=1,2,3$) and $U_n = U_n(r, \varphi, v)$ are given by Equations (2.13), (2.18) and (2.25), respectively. With regard to Equations (2.24), (4.2), we get

$$x_n \frac{\partial U_n}{\partial x_n} = c_3 (C_1 x_n + C_2 x_n^{c_3} + C_3), \quad (5.2)$$

where C_1 , C_2 , C_3 are integration constants, which are determined by the boundary conditions in Section 2.3. Let Equation (5.2) be substituted to Equation (5.1), and then we get

$$x_n^3 \frac{\partial^3 u_n}{\partial x_n^3} + 4x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} = C_1 x_n^3 + C_2 x_n^{c_3} + C_3. \quad (5.3)$$

The mathematical solution of Equation (5.3), which is determined by Wronskian's method (see Chapter 10) [23], is derived as

$$u_n = C_1 x_n \left(\frac{4}{3} - \ln x_n \right) + C_2 x_n^{c_3} + C_3 \left(\frac{1}{2} + \ln x_n \right). \quad (5.4)$$

With regard to Equations (2.1)–(2.4), (2.14)–(2.17), (2.26), (5.4), we get

$$\begin{aligned} \varepsilon_n &= C_1 \left(\frac{1}{3} - \ln x_n \right) + C_2 c_3 x_n^{c_3-1} + \frac{C_3}{x_n}, \\ \varepsilon_\varphi &= \varepsilon_\theta = C_1 \left(\frac{4}{3} - \ln x_n \right) + C_2 x_n^{c_3-1} + \frac{C_3}{x_n} \left(\frac{1}{2} + \ln x_n \right), \\ \varepsilon_{n\varphi} &= s_{44} \sigma_{n\varphi} = \left(\frac{4}{3} - \ln x_n \right) \frac{\partial C_1}{\partial \varphi} + x_n^{c_3-1} \frac{\partial C_2}{\partial \varphi} + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial C_3}{\partial \varphi}, \\ \varepsilon_{n\theta} &= s_{44} \sigma_{n\theta} = \Theta \left[\left(\frac{4}{3} - \ln x_n \right) \frac{\partial C_1}{\partial v} + x_n^{c_3-1} \frac{\partial C_2}{\partial v} + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial C_3}{\partial v} \right], \end{aligned}$$

$$\begin{aligned}
\sigma_n &= C_1 \left[\frac{c_1 - 7c_2}{3} - (c_1 - c_2) \ln x_n \right] + C_2 [(c_1 + c_2) c_3 - 2c_2] x_n^{c_3-1} \\
&\quad + \frac{C_3}{x_n} (c_1 - 2c_2 \ln x_n), \\
\sigma_\phi &= \sigma_\theta = C_1 \left[\frac{4c_1 - c_2}{3} - (c_1 - c_2) \ln x_n \right] + C_2 (c_1 - c_2 c_3) x_n^{c_3-1} \\
&\quad + \frac{C_3}{x_n} \left(\frac{c_1 - 2c_2}{2} + c_1 \ln x_n \right), \\
\sigma_1 &= \eta_1 + \eta_2 \ln x_n + \eta_3 x_n^{c_3-1} + \frac{\eta_4 + \eta_5 \ln x_n}{x_n}, \\
w &= C_1^2 \kappa_1 + C_2^2 \kappa_2 + C_3^2 \kappa_3 + C_1 C_2 \kappa_4 + C_1 C_3 \kappa_5 + C_2 C_3 \kappa_6 \\
&\quad + \frac{\chi_1}{s_{44}} \left[\left(\frac{\partial C_1}{\partial \phi} \right)^2 + \Theta^2 \left(\frac{\partial C_1}{\partial v} \right)^2 \right] + \frac{\chi_2}{s_{44}} \left[\left(\frac{\partial C_2}{\partial \phi} \right)^2 + \Theta^2 \left(\frac{\partial C_2}{\partial v} \right)^2 \right] \\
&\quad + \frac{\chi_3}{s_{44}} \left[\left(\frac{\partial C_3}{\partial \phi} \right)^2 + \Theta^2 \left(\frac{\partial C_3}{\partial v} \right)^2 \right] + \frac{\chi_4}{s_{44}} \left(\frac{\partial C_1}{\partial \phi} \frac{\partial C_2}{\partial \phi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_2}{\partial v} \right) \\
&\quad + \frac{\chi_5}{s_{44}} \left(\frac{\partial C_1}{\partial \phi} \frac{\partial C_3}{\partial \phi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_3}{\partial v} \right) + \frac{\chi_6}{s_{44}} \left(\frac{\partial C_2}{\partial \phi} \frac{\partial C_3}{\partial \phi} + \Theta^2 \frac{\partial C_2}{\partial v} \frac{\partial C_3}{\partial v} \right), \quad (5.5)
\end{aligned}$$

where Θ is given by Equation (1.8). The coefficients η_i , κ_j , χ_j ($i = 1, \dots, 4$; $j = 1, \dots, 6$) are derived as

$$\begin{aligned}
\eta_1 &= \frac{1}{3} \left[C_1 (\gamma_1 + 4\gamma_2) + \frac{4}{s_{44}} \left(\gamma_3 \frac{\partial C_1}{\partial \phi} + \gamma_4 \frac{\partial C_1}{\partial v} \right) \right], \\
\eta_2 &= - \left[C_1 (\gamma_1 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_1}{\partial \phi} + \gamma_4 \frac{\partial C_1}{\partial v} \right) \right], \\
\eta_3 &= C_2 (\gamma_1 c_3 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_2}{\partial \phi} + \gamma_4 \frac{\partial C_2}{\partial v} \right), \\
\eta_4 &= C_3 \left(\gamma_1 + \frac{\gamma_2}{2} \right) + \frac{1}{2s_{44}} \left(\gamma_3 \frac{\partial C_3}{\partial \phi} + \gamma_4 \frac{\partial C_3}{\partial v} \right), \\
\eta_5 &= C_3 \gamma_2 + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_3}{\partial \phi} + \gamma_4 \frac{\partial C_3}{\partial v} \right), \\
\kappa_1 &= \frac{c_2 - c_1}{2} \ln^2 x_n + \frac{c_1 - c_2}{3} \ln x_n + \frac{17c_1 + c_2}{18}, \\
\kappa_2 &= \left[\frac{c_3^2 (c_1 + c_2)}{2} + c_1 (1 - 2c_3) \right] x_n^{2(c_3-1)}, \\
\kappa_3 &= \frac{c_1 \ln^2 x_n}{x_n^2} - \frac{c_1 \ln x_n}{x_n^2} + \frac{c_2 - 2c_1}{4x_n^2},
\end{aligned}$$

$$\begin{aligned}
\kappa_4 &= c_3 (c_1 - c_2) x_n^{c_3-1} \ln x_n + \left[2c_1 + \frac{c_3 (c_2 - 7c_1)}{3} \right] x_n^{c_3-1}, \\
\kappa_5 &= (3c_1 - c_2) \frac{\ln x_n}{x_n} - \frac{4c_1 - c_2}{3x_n}, \\
\kappa_6 &= 2c_1 (1 - c_3) x_n^{c_3-2} \ln x_n + (c_2 c_3 - c_1) x_n^{c_3-2}, \\
\chi_1 &= \ln^2 x_n - \frac{8}{3} \ln x_n + \frac{16}{9}, \quad \chi_2 = x_n^{2(c_3-1)}, \\
\chi_3 &= \frac{\ln^2 x_n}{x_n^2} + \frac{\ln x_n}{x_n^2} + \frac{1}{4x_n^2}, \quad \chi_4 = \frac{8}{3} x_n^{c_3-1} - 2x_n^{c_3-1} \ln x_n, \\
\chi_5 &= \frac{4}{3x_n} + \frac{5 \ln x_n}{3x_n} - \frac{2 \ln^2 x_n}{x_n}, \quad \chi_6 = 2x_n^{c_3-2} \ln x_n + x_n^{c_3-2},
\end{aligned} \tag{5.6}$$

where γ_i ($i=1, \dots, 4$) is given by Equation (2.22). With regard to Equations (4.7), (5.6), we get

$$\begin{aligned}
\Phi_{1M} &= \frac{c_{2M} - c_{1M}}{6} \left\{ x_M^3 \left[\left(\ln x_M - \frac{1}{3} \right)^2 + \frac{1}{9} \right] - x_{IN}^3 \left[\left(\ln x_{IN} - \frac{1}{3} \right)^2 + \frac{1}{9} \right] \right\} \\
&+ \frac{c_{1M} - c_{2M}}{9} \left[x_M^3 \left(\ln x_M - \frac{1}{3} \right) - x_{IN}^3 \left(\ln x_{IN} - \frac{1}{3} \right) \right] + \frac{17c_{1M} + c_{2M}}{54} (x_M^3 - x_{IN}^3), \\
\Phi_{2M} &= \frac{1}{2c_{3M} + 1} \left[\frac{c_{3M}^2 (c_{1M} + c_{2M})}{2} + c_{1M} (1 - 2c_{3M}) \right] (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}), \\
\Phi_{3M} &= c_{1M} \left[x_M (\ln^2 x_M - 2 \ln x_M + 2) - x_{IN} (\ln^2 x_{IN} - 2 \ln x_{IN} + 2) \right] \\
&- c_{1M} [x_M (\ln x_M - 1) - x_{IN} (\ln x_{IN} - 1)] + \frac{c_{2M} - 2c_{1M}}{4} (x_M - x_{IN}), \\
\Phi_{4M} &= \frac{c_{3M} (c_{1M} - c_{2M})}{c_{3M} + 2} \\
&\times \left[x_M^{c_{3M}+2} \left(\ln x_M - \frac{1}{c_{3M} + 2} \right) - x_{IN}^{c_{3M}+2} \left(\ln x_{IN} - \frac{1}{c_{3M} + 2} \right) \right] \\
&+ \frac{1}{c_{3M} + 2} \left[2c_{1M} + \frac{c_{3M} (c_{2M} - 7c_{1M})}{3} \right] (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}), \\
\Phi_{5M} &= \frac{3c_{1M} - c_{2M}}{2} \left[x_M^2 \left(\ln x_M - \frac{1}{2} \right) - x_{IN}^2 \left(\ln x_{IN} - \frac{1}{2} \right) \right] \\
&- \frac{4c_{1M} - c_{2M}}{6} (x_M^2 - x_{IN}^2), \\
\Phi_{6M} &= \frac{2c_{1M} (1 - c_{3M})}{c_{3M} + 1} \left[x_M^{c_{3M}+1} \left(\ln x_M - \frac{1}{c_{3M} + 1} \right) - x_{IN}^{c_{3M}+1} \left(\ln x_{IN} - \frac{1}{c_{3M} + 1} \right) \right] \\
&+ \frac{c_{2M} c_{3M} - c_{1M}}{c_{3M} + 1} (x_M^{c_{3M}+1} - x_{IN}^{c_{3M}+1}),
\end{aligned}$$

$$\begin{aligned}
\Psi_{1M} &= \frac{x_M^3}{3} \left[(\ln x_M - 3) \left(\ln x_M - \frac{1}{3} \right) + \frac{17}{9} \right] \\
&\quad - \frac{x_{IN}^3}{3} \left[(\ln x_{IN} - 3) \left(\ln x_{IN} - \frac{1}{3} \right) + \frac{17}{9} \right], \\
\Psi_{2M} &= \frac{x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}}{2c_{3M}+1}, \\
\Psi_{3M} &= x_M \ln x_M (\ln x_M - 1) - x_{IN} \ln x_{IN} (\ln x_{IN} - 1) + \frac{5(x_M - x_{IN})}{4}, \\
\Psi_{4M} &= \frac{2}{c_{3M}+2} \left\{ x_M^{c_{3M}+2} \left[\frac{4c_{3M}+11}{3(c_{3M}+2)} - \ln x_M \right] - x_{IN}^{c_{3M}+2} \left[\frac{4c_{3M}+11}{3(c_{3M}+2)} - \ln x_{IN} \right] \right\}, \\
\Psi_{5M} &= \frac{2(x_M^2 - x_{IN}^2)}{3} + \frac{5}{6} \left[x_M^2 \left(\ln x_M - \frac{1}{2} \right) - x_{IN}^2 \left(\ln x_{IN} - \frac{1}{2} \right) \right] \\
&\quad - x_M^2 \left(\ln^2 x_M - \ln x_M + \frac{1}{2} \right) + x_{IN}^2 \left(\ln^2 x_{IN} - \ln x_{IN} + \frac{1}{2} \right), \\
\Psi_{6M} &= \frac{2}{c_{3M}+1} \left[x_M^{c_{3M}+1} \left(\ln x_M - \frac{1}{c_{3M}+1} \right) - x_{IN}^{c_{3M}+1} \left(\ln x_{IN} - \frac{1}{c_{3M}+1} \right) \right] \\
&\quad + \frac{1}{c_{3M}+1} (x_M^{c_{3M}+1} - x_{IN}^{c_{3M}+1}), \tag{5.7}
\end{aligned}$$

where x_{IN} , x_M are given by Equation (1.9), respectively. The integrals (4.14), which consider Equation (5.7), are determined by the formulae in Chapter 10 (see Equations (10.10)–(10.12)).

In case of the ellipsoidal inclusion, we get $(u_{nIN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\epsilon_{IN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\sigma_{IN})_{r \rightarrow 0} \rightarrow \pm \infty$ due to $(\ln x_n)_{x_n \rightarrow 0} \rightarrow \pm \infty$ and $(x_n^{c_3})_{x_n \rightarrow 0} \rightarrow \pm \infty$ for $c_3 < 0$ (see Equations (2.18), (5.4)). Accordingly, the mathematical solutions (5.4) are suitable for the matrix.

5.2 Matrix

The integration constants C_{1M} , C_{2M} , C_{3M} for the matrix (see Equation (5.4)) are determined by the boundary conditions (2.30), (2.31) or (2.30)–(2.32). The boundary conditions result in the following combinations of C_{1M} , C_{2M} , C_{3M} . Finally, such a combination is considered to exhibit a minimum value of the elastic energy W_C of the cubic cell (see Equation (2.27)). The subscript $Q = M, MB$ and the stress σ_q in Section 4.2 are derived as

$$\begin{aligned}
Q = M &\Rightarrow \sigma_q = p_n, \\
Q = MB &\Rightarrow \sigma_q = \sigma_{nB}, \tag{5.8}
\end{aligned}$$

where p_n and σ_{nB} are given by Equations (2.33) and (5.9), (5.12), (5.15), (5.18), respectively. Consequently, the conditions in Equation (2.36) are considered.

Conditions $C_{1M} \neq 0, C_{2M} \neq 0, C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (5.4), (5.5), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[\frac{1}{3} - \ln x_n - c_{3M} \left(\frac{4}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[\frac{4}{3} - \ln x_n - \left(\frac{4}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\
\varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = \left(\ln x_n - \frac{4}{3} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \\
&\quad + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right], \\
\varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = \Theta \left\{ \left(\ln x_n - \frac{4}{3} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right. \\
&\quad \left. + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}, \\
\sigma_{nQ} &= \frac{\sigma_q}{\zeta_Q} \left\{ \frac{7c_{2M} - c_{1M}}{3} + (c_{1M} - c_{2M}) \ln x_n \right. \\
&\quad \left. + [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] \left(\frac{4}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right\}, \\
\sigma_{\varphi Q} &= \sigma_{\theta Q} = \frac{\sigma_q}{\zeta_Q} \left[\frac{c_{2M} - 4c_{1M}}{3} + (c_{1M} - c_{2M}) \ln x_n \right. \\
&\quad \left. + (c_{1M} - c_{2M} c_{3M}) \left(\frac{4}{3} - \ln x_M \right) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\
\sigma_{1Q} &= \eta_{1Q} + \eta_{2Q} \ln x_n + \eta_{3Q} x_n^{c_{3M}-1}, \\
w_Q &= \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left\{ \kappa_{1M} + \kappa_{2M} \left(\frac{4 - 3 \ln x_M}{3 x_M^{c_{3M}-1}} \right)^2 + \frac{\kappa_{4M} (3 \ln x_M - 4)}{3 x_M^{c_{3M}-1}} \right\} \\
&\quad + \frac{\chi_{1M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} \\
&\quad + \frac{\chi_{2M}}{s_{44M}} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (4 - 3 \ln x_M)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q (4 - 3 \ln x_M)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right)
\end{aligned}$$

$$\begin{aligned}
& + \frac{\chi_{4M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (3 \ln x_M - 4)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] \\
& + \frac{\chi_{4M} \Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q (3 \ln x_M - 4)}{3 \zeta_Q x_M^{c_{3M}-1}} \right], \\
W_Q = & 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left\{ \Phi_{1M} + \Phi_{2M} \left(\frac{4 - 3 \ln x_M}{3 x_M^{c_{3M}-1}} \right)^2 + \frac{\Phi_{4M} (3 \ln x_M - 4)}{3 x_M^{c_{3M}-1}} \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{1M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (4 - 3 \ln x_M)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \Theta^2 \left(\left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q (4 - 3 \ln x_M)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{4M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q (3 \ln x_M - 4)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{4M} \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left[\frac{\sigma_q (3 \ln x_M - 4)}{3 \zeta_Q x_M^{c_{3M}-1}} \right] d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right] \\
& + \frac{\rho_{2B} p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) + \frac{\rho_{2B}^{(\varphi)}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right] \\
& + \frac{\rho_{2B}^{(v)}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right], \quad Q = M, MB, \tag{5.9}
\end{aligned}$$

where Θ , x_M , s_{44M} , c_{iM} ; κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ($i=1,2,3$; $j=1,2,4$) are given by Equations (1.8), (1.9), (2.13), (2.18); (5.6); (5.7), respectively. The coefficients ζ_Q , ζ_{iQ} , η_{jQ} , ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2$; $j=1,2,3$; $\tau = \varphi, v$; $Q = M, MB$; see Equation (5.6)) have the forms

$$\zeta_Q = \zeta_{2Q} - \zeta_{1Q} \left(\frac{4}{3} - \ln x_M \right),$$

$$\begin{aligned}
\zeta_{1M} &= \zeta_{1MB} \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1}, \quad \zeta_{2M} = \frac{c_{1M}-7c_{2M}}{3} - (c_{1M}-c_{2M}) \ln x_{IN}, \\
\zeta_{1MB} &= (c_{1M}+c_{2M})c_{3M}-2c_{2M}, \quad \zeta_{2MB} = \frac{c_{1M}-7c_{2M}}{3} - (c_{1M}-c_{2M}) \ln x_M, \\
\eta_{1Q} &= -\frac{1}{3} \left\{ \frac{\sigma_q(\gamma_{1M}+4\gamma_{2M})}{\zeta_Q} + \frac{4}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right] \right\}, \\
\eta_{2Q} &= \frac{\sigma_q(\gamma_{1M}+\gamma_{2M})}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\eta_{3Q} &= \frac{\sigma_q(\gamma_{1M}c_{3M}+\gamma_{2M})}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right] \\
&\quad + \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \left(\frac{4}{3} - \ln x_M \right) \right], \\
\rho_{1B} &= \frac{1}{3} \left\{ \gamma_{1M}(c_{1M}-7c_{2M}) + (\gamma_{2M}+\gamma_{3M})(4c_{1M}-c_{2M}) \right\} \\
&\quad + (c_{2M}-c_{1M})(\gamma_{1M}+\gamma_{2M}+\gamma_{3M}) \ln x_M, \\
\rho_{2B} &= \left\{ \gamma_{1M}[(c_{1M}+c_{2M})c_{3M}-2c_{2M}] + (\gamma_{2M}+\gamma_{3M})(c_{1M}-c_{2M}c_{3M}) \right\} x_M^{c_{3M}-1}, \\
\rho_{1B}^{(\varphi)} &= (\gamma_{1M}+\gamma_{2M}) \left(\frac{4}{3} - \ln x_M \right), \quad \rho_{1B}^{(v)} = \Theta(\gamma_{1M}+\gamma_{3M}) \left(\frac{4}{3} - \ln x_M \right), \\
\rho_{2B}^{(\varphi)} &= (\gamma_{1M}+\gamma_{2M}) x_M^{c_{3M}-1}, \quad \rho_{2B}^{(v)} = \Theta(\gamma_{1M}+\gamma_{3M}) x_M^{c_{3M}-1}, \quad Q = M, MB, \quad (5.10)
\end{aligned}$$

where γ_{iM} , ϑ_j ($i=1, \dots, 4$; $j=1,2,3$) are given by Equations (2.22), (2.35), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (5.9), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\frac{4}{3} - \ln x_{IN} - \left(\frac{4}{3} - \ln x_M \right) \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} \right], \quad Q = M, MB. \quad (5.11)$$

Conditions $C_{1M} \neq 0$, $C_{3M} \neq 0$, $C_{2M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (5.4), (5.5), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{1}{2} + \ln x_M \right) \left(\frac{1}{3} - \ln x_n \right) - \frac{x_M}{x_n} \left(\frac{4}{3} - \ln x_M \right) \right], \\
\varepsilon_{\varphi Q} = \varepsilon_{\theta Q} &= -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{1}{2} + \ln x_M \right) \left(\frac{4}{3} - \ln x_n \right) - \frac{x_M}{x_n} \left(\frac{4}{3} - \ln x_M \right) \left(\frac{1}{2} + \ln x_n \right) \right],
\end{aligned}$$

$$\begin{aligned}
\epsilon_{n\phi Q} &= s_{44M} \sigma_{n\phi Q} = \left(\ln x_n - \frac{4}{3} \right) \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \\
&\quad + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial \phi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right], \\
\epsilon_{nVM} &= s_{44M} \sigma_{n\phi Q} = \Theta \left\{ \left(\ln x_n - \frac{4}{3} \right) \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right. \\
&\quad \left. + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial \phi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right] \right\}, \\
\sigma_{nQ} &= \frac{\sigma_q}{\zeta_Q} \left\{ \left(\frac{1}{2} + \ln x_M \right) \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] \right. \\
&\quad \left. + \frac{x_M}{x_n} \left(\frac{4}{3} - \ln x_M \right) (c_{1M} - 2c_{2M} \ln x_n) \right\}, \\
\sigma_{\phi Q} &= \sigma_{\theta Q} = \frac{\sigma_q}{\zeta_Q} \left\{ \left(\frac{1}{2} + \ln x_M \right) \left[\frac{4c_{1M} - c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] \right. \\
&\quad \left. + \frac{x_M}{x_n} \left(\frac{4}{3} - \ln x_M \right) \left(\frac{c_{1M} - c_{2M}}{2} + c_{3M} \ln x_n \right) \right\}, \\
\sigma_{1Q} &= \eta_{1Q} + \eta_{2Q} \ln x_n + \frac{\eta_{4M} + \eta_{5M} \ln x_n}{x_n}, \\
w_Q &= \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\kappa_{1M} \left(\frac{1}{2} + \ln x_M \right) + \kappa_{3M} x_M^2 \left(\frac{4}{3} - \ln x_M \right)^2 \right. \\
&\quad \left. + \kappa_{5M} x_M \left(\frac{1}{2} + \ln x_M \right) \left(\frac{4}{3} - \ln x_M \right) \right] \\
&\quad + \frac{\chi_{1M}}{s_{44M}} \left(\left\{ \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right\}^2 + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right\}^2 \right) \\
&\quad + \frac{\chi_{3M}}{s_{44M}} \left(\left\{ \frac{\partial}{\partial \phi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}^2 + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}^2 \right) \\
&\quad + \frac{\chi_{5M}}{s_{44M}} \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial \phi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] \\
&\quad + \frac{\chi_{5M} \Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right], \\
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\Phi_{1M} \left(\frac{1}{2} + \ln x_M \right) + \Phi_{3M} x_M^2 \left(\frac{4}{3} - \ln x_M \right)^2 \right. \\
&\quad \left. + \Phi_{5M} x_M \left(\frac{1}{2} + \ln x_M \right) \left(\frac{4}{3} - \ln x_M \right) \right] d\phi dv
\end{aligned}$$

$$\begin{aligned}
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{1M} \left(\left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right\}^2 \right. \\
& \quad \left. + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \left(\Psi_{3M} \left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}^2 \right. \\
& \quad \left. + \Theta^2 \left\{ \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}^2 \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{5M} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Phi_{5M} \Theta^2 \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\frac{4}{3} - \ln x_M \right) \right] d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) - \frac{\rho_{3B} p_n x_M}{\zeta_M} \left(\frac{4}{3} - \ln x_M \right) \\
& - \frac{1}{s_{44M}} \left\{ \rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] \right\} \\
& - \frac{1}{s_{44M}} \left\{ \rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left[\frac{p_n x_M}{\zeta_M} \left(\frac{4}{3} - \ln x_M \right) \right] + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left[\frac{p_n x_M}{\zeta_M} \left(\frac{4}{3} - \ln x_M \right) \right] \right\}, \\
Q = M, MB, & \tag{5.12}
\end{aligned}$$

where Θ , x_M , s_{44M} , c_{iM} , κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ; ρ_{1B} , $\rho_{1B}^{(\tau)}$ ($i = 1, 2, 3$; $j = 1, 3, 5$; $\tau = \varphi, v$) are given by Equations (1.8), (1.9), (2.13), (2.18), (5.6); (5.7); (5.10), respectively. The coefficients ζ_Q , ζ_{iQ} , η_{jQ} , ρ_{3B} , $\rho_{3B}^{(\tau)}$ ($i = 1, 2$; $j = 1, 2, 4, 5$; $\tau = \varphi, v$; $Q = M, MB$; see Equation (5.6)) have the forms

$$\begin{aligned}
\zeta_Q &= \frac{\zeta_{2Q}}{x_M} \left(\frac{1}{2} + \ln x_M \right) - \zeta_{1Q} \left(\frac{4}{3} - \ln x_M \right), \\
\zeta_{1M} &= \frac{x_M}{x_{IN}} (c_{1M} - 2c_{2M} \ln x_{IN}), \quad \zeta_{2M} = x_M \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_{IN} \right], \\
\zeta_{1MB} &= c_{1M} - 2c_{2M} \ln x_M, \quad \zeta_{2MB} = x_M \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_M \right], \\
\eta_{1Q} &= - \frac{\sigma_q (\gamma_{1M} + 4\gamma_{2M})}{3\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) - \frac{4\gamma_{3M}}{3s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right]
\end{aligned}$$

$$\begin{aligned}
& -\frac{4\gamma_{4M}}{3s_{44M}} \frac{\partial C_1}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right], \\
\eta_{2Q} &= \frac{\sigma_q(\gamma_{1M} + \gamma_{2M})}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \\
&+ \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right], \\
\eta_{4Q} &= \frac{\sigma_q x_M (2\gamma_{1M} + \gamma_{2M})}{2\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) + \frac{\gamma_{3M}}{2s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right] \\
&+ \frac{\gamma_{4M}}{2s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right], \\
\eta_{5M} &= \frac{\sigma_q x_M \gamma_{2M}}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right] \\
&+ \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q x_M}{\zeta_Q} \left(\ln x_M - \frac{4}{3} \right) \right], \\
\rho_{3B} &= \frac{1}{x_M} \left\{ c_{1M} \gamma_{1M} + \frac{(c_{1M} - 2c_{2M})(\gamma_{2M} + \gamma_{3M})}{2} \right. \\
&\quad \left. + [c_{1M}(\gamma_{2M} + \gamma_{3M}) - 2c_{2M}\gamma_{1M}] \ln x_M \right\}, \\
\rho_{3B}^{(\varphi)} &= \frac{(\gamma_{1M} + \gamma_{2M})}{x_M} \left(\frac{1}{2} + \ln x_M \right), \quad \rho_{3B}^{(v)} = \frac{\Theta(\gamma_{1M} + \gamma_{3M})}{x_M} \left(\frac{1}{2} + \ln x_M \right), \\
Q &= M, MB,
\end{aligned} \tag{5.13}$$

where γ_{iM} , ϑ_j ($i = 1, \dots, 4$; $j = 1, 2, 3$) are given by Equations (2.22), (2.35), respectively. With regard to Equation (5.12), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\begin{aligned}
\rho_Q &= \frac{1}{\zeta_Q} \left[\left(\frac{1}{2} + \ln x_M \right) \left(\frac{4}{3} - \ln x_{IN} \right) - \frac{x_M}{x_{IN}} \left(\frac{4}{3} - \ln x_M \right) \left(\frac{1}{2} + \ln x_{IN} \right) \right], \\
Q &= M, MB.
\end{aligned} \tag{5.14}$$

Conditions $C_{2M} \neq 0$, $C_{3M} \neq 0$, $C_{1M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (5.4), (5.5), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[c_{3M} \left(\frac{1}{2} + \ln x_M \right) x_n^{c_{3M}-1} - \frac{x_M^{c_{3M}}}{x_n} \right], \\
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{1}{2} + \ln x_M \right) x_n^{c_{3M}-1} - \frac{x_M^{c_{3M}}}{x_n} \left(\frac{1}{2} + \ln x_n \right) \right], \\
\varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right)
\end{aligned}$$

$$\begin{aligned}
& -x_n^{c_{3M}-1} \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right], \\
\epsilon_{nVM} = s_{44M} \sigma_{nVM} = & \Theta \left\{ \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \right. \\
& \left. - x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \right\}, \\
\sigma_{nQ} = & - \frac{\sigma_q x_n^{c_{3M}-1}}{\zeta_Q} \\
& \times \left\{ [c_{3M} (c_{1M} + c_{2M}) - 2 c_{2M}] \left(\frac{1}{2} + \ln x_M \right) - \frac{x_M}{x_n} (c_{1M} - 2 c_{2M} \ln x_n) \right\}, \\
\sigma_{\phi Q} = \sigma_{\theta Q} = & - \frac{\sigma_q x_n^{c_{3M}-1}}{\zeta_Q} \left[(c_{1M} - c_{2M} c_{3M}) \left(\frac{1}{2} + \ln x_M \right) - \frac{x_M}{x_n} \left(\frac{c_{1M} - 2 c_{2M}}{2} + c_{1M} \ln x_n \right) \right], \\
\sigma_{1Q} = & \eta_{3Q} x_n^{c_{3M}-1} + \frac{\eta_{4M} + \eta_{5M} \ln x_n}{x_n}, \\
w_Q = & \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\kappa_{2M} \left(\frac{1}{2} + \ln x_M \right)^2 + \kappa_{3M} x_M^{2c_{3M}} + \kappa_{6M} x_M^{c_{3M}} \left(\frac{1}{2} + \ln x_M \right) \right] \\
& + \frac{\chi_{2M}}{s_{44M}} \left\{ \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right]^2 + \Theta^2 \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right]^2 \right\} \\
& + \frac{\chi_{3M}}{s_{44M}} \left[\frac{\partial C_{3M}}{\partial \phi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right)^2 + \Theta^2 \frac{\partial C_{3M}}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right)^2 \right] \\
& - \frac{\chi_{6M} \Theta}{s_{44M}} \left\{ \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial \phi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \right. \\
& \left. + \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \right\}, \\
W_Q = & 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \left[\Phi_{2M} \left(\frac{1}{2} + \ln x_M \right)^2 + \Phi_{3M} x_M^{2c_{3M}} \right. \\
& \left. + \Phi_{6M} x_M^{c_{3M}} \left(\frac{1}{2} + \ln x_M \right) \right] d\phi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \left\{ \frac{\partial}{\partial \phi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right]^2 + \Theta^2 \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right]^2 \right\} d\phi dv
\end{aligned}$$

$$\begin{aligned}
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{3M} \left[\frac{\partial C_{3M}}{\partial \varphi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right)^2 + \Theta^2 \frac{\partial C_{3M}}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right)^2 \right] d\varphi dv \\
& - \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{6M} \Theta \left\{ \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \right. \\
& \quad \left. + \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \right\} d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) + \frac{\rho_{3B} p_n x_M^{c_{3M}}}{\zeta_M} \\
& - \frac{1}{s_{44M}} \left\{ \rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] \right\} \\
& + \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n x_M^{c_{3M}}}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n x_M^{c_{3M}}}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (5.15)
\end{aligned}$$

where Θ ; x_M ; s_{44M} ; c_{iM} ($i = 1, 2, 3$); κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ($j = 2, 3, 6$); ρ_{kB} , $\rho_{kB}^{(\tau)}$ ($k = 2, 3$; $\tau = \varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (5.6), (5.7), respectively. The coefficients ζ_Q , ζ_{iQ} , η_{jQ} ($i = 1, 2$; $j = 3, 4, 5$; $Q = M, MB$; see Equation (4.6)) have the forms

$$\begin{aligned}
\zeta_Q &= \frac{\zeta_{2Q}}{x_M} \left(\frac{1}{2} + \ln x_M \right) - \zeta_{1Q} x_M^{c_{3M}-1}, \\
\zeta_{1M} &= \frac{x_M}{x_{IN}} (c_{1M} - 2c_{2M} \ln x_{IN}), \quad \zeta_{2M} = x_M [c_{3M} (c_{1M} + c_{2M}) - 2c_{2M}] x_{IN}^{c_{3M}-1}, \\
\zeta_{1MB} &= c_{1M} - 2c_{2M} \ln x_M, \quad \zeta_{2MB} = [c_{3M} (c_{1M} + c_{2M}) - 2c_{2M}] x_M^{c_{3M}}, \\
\eta_{3Q} &= \frac{\sigma_q x_M^{c_{3M}} (\gamma_{1M} c_{3M} + \gamma_{2M})}{\zeta_Q} + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right) \\
& \quad + \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^{c_{3M}}}{\zeta_Q} \right), \\
\eta_{4M} &= \frac{\sigma_q (2\gamma_{1M} + \gamma_{2M})}{2\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) + \frac{\gamma_{3M}}{2s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \\
& \quad + \frac{\gamma_{4M}}{2s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right], \\
\eta_{5M} &= \frac{\sigma_q \gamma_{2M}}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) + \frac{\gamma_{3M}}{s_{44M}} \frac{\partial}{\partial \varphi} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right] \\
& \quad + \frac{\gamma_{4M}}{s_{44M}} \frac{\partial}{\partial v} \left[\frac{\sigma_q}{\zeta_Q} \left(\frac{1}{2} + \ln x_M \right) \right], \quad Q = M, MB, \quad (5.16)
\end{aligned}$$

where γ_{iM} ($i = 1, \dots, 4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (5.15), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\left(\frac{1}{2} + \ln x_M \right) x_{IN}^{c_{3M}-1} - \frac{x_M^{c_{3M}}}{x_{IN}} \left(\frac{1}{2} + \ln x_{IN} \right) \right], \quad Q = M, MB. \quad (5.17)$$

Conditions $C_{1M} \neq 0, C_{2M} \neq 0, C_{3M} \neq 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (5.4), (5.5), we get

$$\begin{aligned} \varepsilon_{nM} &= -\frac{p_n}{\zeta_M} \left[\zeta_{1M} \left(\frac{1}{3} - \ln x_n \right) + \zeta_{2M} c_{3M} x_n^{c_{3M}-1} + \frac{\zeta_{3M}}{x_n} \right], \\ \varepsilon_{\varphi M} = \varepsilon_{\theta M} &= -\frac{p_n}{\zeta_M} \left[\zeta_{1M} \left(\frac{4}{3} - \ln x_n \right) + \zeta_{2M} x_n^{c_{3M}-1} + \frac{\zeta_{3M}}{x_n} \left(\frac{1}{2} + \ln x_n \right) \right], \\ \varepsilon_{n\varphi M} = s_{44M} \sigma_{n\varphi M} &= - \left[\left(\frac{4}{3} - \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right. \\ &\quad \left. + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\ \varepsilon_{n\nu M} = s_{44M} \sigma_{n\nu M} &= -\Theta \left[\left(\frac{4}{3} - \ln x_n \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial \nu} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right. \\ &\quad \left. + \frac{1}{x_n} \left(\frac{1}{2} + \ln x_n \right) \frac{\partial}{\partial \nu} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\ \sigma_{nM} &= -\frac{p_n}{\zeta_M} \left\{ \zeta_{1M} \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] \right. \\ &\quad \left. + \zeta_{2M} [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_n^{c_{3M}-1} + \frac{\zeta_{3M} (c_{1M} - 2c_{2M} \ln x_n)}{x_n} \right\}, \\ \sigma_{\varphi M} = \sigma_{\theta M} &= -\frac{p_n}{\zeta_M} \left\{ \zeta_{1M} \left[\frac{4c_{1M} - c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_n \right] \right. \\ &\quad \left. + \zeta_{2M} (c_{1M} - c_{2M} c_{3M}) x_n^{c_{3M}-1} + \zeta_{3M} \left(\frac{c_{1M} - 2c_{2M}}{2} + c_{1M} \ln x_n \right) \right\}, \\ \sigma_{1M} &= \eta_{1M} + \eta_{2M} \ln x_n + \eta_{3M} x_n^{c_{3M}-1} + \frac{\eta_{4M} + \eta_{5M} \ln x_n}{x_n}, \\ w_M &= \left(\frac{p_n}{\zeta_M} \right)^2 \left(\kappa_{1M} \zeta_{1M}^2 + \kappa_{2M} \zeta_{2M}^2 + \kappa_{3M} \zeta_{3M}^2 \right. \\ &\quad \left. + \kappa_{4M} \zeta_{1M} \zeta_{2M} + \kappa_{5M} \zeta_{1M} \zeta_{3M} + \kappa_{6M} \zeta_{2M} \zeta_{3M} \right) \\ &\quad + \frac{\chi_{1M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial \nu} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 \right\} \end{aligned}$$

$$\begin{aligned}
& + \frac{\chi_{2M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right]^2 \right\} \\
& + \frac{\chi_{3M}}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 \right\} \\
& + \frac{\chi_{4M}}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right] \\
& + \frac{\chi_{5M}}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] \\
& + \frac{\chi_{6M}}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\
W_M = & 4 \int_0^{\pi/2} \int_0^{\pi/2} \left(\frac{p_n}{\zeta_M} \right)^2 \left(\Phi_{1M} \zeta_{1M}^2 + \Phi_{2M} \zeta_{2M}^2 + \Phi_{3M} \zeta_{3M}^2 + \Phi_{4M} \zeta_{1M} \zeta_{2M} \right. \\
& \left. + \Phi_{5M} \zeta_{1MM} \zeta_{3M} + \Phi_{6M} \zeta_{2M} \zeta_{3M} \right) d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{1M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{2M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{3M} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 \right\} d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{4M} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right. \\
& \quad \left. + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right] d\varphi dv \\
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{5M} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right. \\
& \quad \left. + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] d\varphi dv
\end{aligned}$$

$$\begin{aligned}
& + \frac{4}{s_{44M}} \int_0^{\pi/2} \int_0^{\pi/2} \Psi_{6M} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right. \\
& \quad \left. + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] d\varphi dv, \\
\sigma_{nB} = & - \sum_{i=1}^3 \frac{\rho_{iB} p_n \zeta_{iM}}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{iB}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{iM}}{\zeta_M} \right) + \rho_{iB}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{iM}}{\zeta_M} \right) \right], \quad (5.18)
\end{aligned}$$

where Θ , x_M , s_{44M} , c_{iM} ; κ_{jM} , χ_{jM} ; Φ_{jM} , Ψ_{jM} ; ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2,3$; $j=1,\dots,6$; $\tau=\varphi, v$); are given by Equations (1.8), (1.9), (2.13), (2.18); (5.6); (5.7); (5.10), (5.13); respectively. The coefficients ζ_{iM} , ζ_M , η_{jM} ($i=1,2,3$; $j=1,\dots,4$; see Equation (4.13)) have the forms

$$\begin{aligned}
\zeta_{1M} &= x_M^{c_{3M}-1} \left[c_{3M} \left(\frac{1}{2} + \ln x_M \right) - 1 \right], \\
\zeta_{2M} &= \frac{4}{3} - \ln x_M - \left(\frac{1}{2} + \ln x_M \right) \left(\frac{1}{3} - \ln x_M \right), \\
\zeta_{3M} &= x_M^{c_{3M}} \left[\frac{1}{3} - \ln x_M - c_{3M} \left(\frac{4}{3} - \ln x_M \right) \right], \\
\zeta_M &= x_M^{c_{3M}-1} \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_{IN} \right] \\
&+ [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] \left(\frac{1}{2} + \ln x_M \right) \left(\frac{1}{3} - \ln x_M \right) x_{IN}^{c_{3M}-1} \\
&+ (c_{1M} - 2c_{2M} \ln x_{IN}) \left(\frac{4}{3} - \ln x_M \right) \frac{c_{3M} x_M^{c_{3M}}}{x_{IN}} \\
&- \left\{ c_{3M} \left[\frac{c_{1M} - 7c_{2M}}{3} - (c_{1M} - c_{2M}) \ln x_{IN} \right] \left(\frac{1}{2} + \ln x_M \right) x_M^{c_{3M}-1} \right. \\
&+ [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] \left(\frac{4}{3} - \ln x_M \right) x_{IN}^{c_{3M}-1} \\
&+ \left. \frac{(c_{1M} - 2c_{2M} \ln x_{IN}) x_M^{c_{3M}}}{x_{IN}} \left(\frac{1}{3} - \ln x_M \right) \right\}, \\
\eta_{1M} &= - \frac{p_n \zeta_{1M} (\gamma_{1M} + 4\gamma_{2M})}{3\zeta_M} \\
&- \frac{4}{3s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right], \\
\eta_{2M} &= \frac{p_n \zeta_{1M} (\gamma_{1M} + \gamma_{2M})}{\zeta_M} \\
&+ \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right],
\end{aligned}$$

$$\begin{aligned}
\eta_{3M} &= -\frac{p_n \zeta_{2M} (\gamma_{1M} c_{3M} + \gamma_{2M})}{\zeta_M} \\
&\quad - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \phi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right], \\
\eta_{4M} &= -\frac{p_n \zeta_{3M} (2\gamma_{1M} + \gamma_{2M})}{2\zeta_M} \\
&\quad - \frac{1}{2s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \phi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\
\eta_{5M} &= -\frac{p_n \zeta_{3M} \gamma_{2M}}{\zeta_M} \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \phi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \quad (5.19)
\end{aligned}$$

where γ_{iM} ($i=1, \dots, 4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (5.18), the coefficient ρ_M in Equations (2.33), (3.13) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left[\zeta_{1M} \left(\frac{4}{3} - \ln x_{IN} \right) + \zeta_{2M} x_{IN}^{c_{3M}-1} + \frac{\zeta_{3M}}{x_{IN}} \left(\frac{1}{2} + \ln x_{IN} \right) \right]. \quad (5.20)$$

Mathematical Model 4

6.1 Mathematical Procedure

The differential equation (2.23) is transformed to the form

$$U_n = -s_{44} (c_1 + c_2) \left(x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} + 2x_n \frac{\partial u_n}{\partial x_n} - 2u_n \right), \quad (6.1)$$

where s_{44} , c_i ($i = 1, 2$) and $U_n = U_n(x_n, \varphi, v)$ are given by Equations (2.13), (2.18) and (2.25), respectively. Let $x_n [\partial \text{Eq. (6.1)} / \partial x_n]$ be performed, and then we get

$$x_n \frac{\partial U_n}{\partial x_n} = -s_{44} (c_1 + c_2) \left(x_n^3 \frac{\partial^3 u_n}{\partial x_n^3} + 4x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} \right). \quad (6.2)$$

Let Equations (6.1), (6.2) be substituted to Equation (2.24), and then we get

$$x_n^3 \frac{\partial^3 u_n}{\partial x_n^3} + (4 - c_3) x_n^2 \frac{\partial^2 u_n}{\partial x_n^2} - 2c_3 x_n \frac{\partial u_n}{\partial x_n} + 2c_3 u_n = 0. \quad (6.3)$$

Let u_n be assumed in the form $u_n = x_n^\lambda$, then we get [1]–[22]

$$u_n = C_1 x_n + C_2 x_n^{c_3} + \frac{C_3}{x_n^2}, \quad (6.4)$$

where $c_3 < 0$ is given by Equation (2.18), and C_1, C_2, C_3 are integration constants, which are determined by the boundary conditions in Section 2.3. With regard to Equations (2.1)–(2.4), (2.14)–(2.17), (2.26), (6.6), we get

$$\begin{aligned} \varepsilon_n &= C_1 + C_2 c_3 x_n^{c_3-1} - \frac{2C_3}{x_n^3}, \\ \varepsilon_\varphi &= \varepsilon_\theta = C_1 + C_2 x_n^{c_3-1} + \frac{C_3}{x_n^3}, \\ \varepsilon_{n\varphi} &= s_{44} \sigma_{n\varphi} = \frac{\partial C_1}{\partial \varphi} + x_n^{c_3-1} \frac{\partial C_2}{\partial \varphi} + \frac{1}{x_n^3} \frac{\partial C_3}{\partial \varphi}, \\ \varepsilon_{n\theta} &= s_{44} \sigma_{n\theta} = \Theta \left[\frac{\partial C_1}{\partial v} + x_n^{c_3-1} \frac{\partial C_2}{\partial v} + \frac{1}{x_n^3} \frac{\partial C_3}{\partial v} \right], \end{aligned}$$

$$\begin{aligned}
\sigma_n &= C_1 (c_1 - c_2) + C_2 [(c_1 + c_2) c_3 - 2 c_2] x_n^{c_3-1} - \frac{2 C_3 (c_1 + 2 c_2)}{x_n^3}, \\
\sigma_\varphi &= \sigma_\theta = C_1 (c_1 - c_2) + C_2 (c_1 - c_2 c_3) x_n^{c_3-1} + \frac{C_3 (c_1 + 2 c_2)}{x_n^3}, \\
\sigma_1 &= \eta_1 + \eta_2 x_n^{c_3-1} + \frac{\eta_3}{x_n^3}, \\
w &= \kappa_1 + \kappa_2 x_n^{2(c_3-1)} + \frac{\kappa_3}{x_n^6} + \kappa_4 x_n^{c_3-1} + \frac{\kappa_5}{x_n^3} + \kappa_6 x_n^{c_3-4}, \tag{6.5}
\end{aligned}$$

where Θ is given by Equation (1.8). The coefficients η , κ_j ($i = 1, 2, 3$; $j = 1, \dots, 6$) are derived as

$$\begin{aligned}
\eta_1 &= C_1 (\gamma_1 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_1}{\partial \varphi} + \gamma_4 \frac{\partial C_1}{\partial v} \right), \\
\eta_2 &= C_2 (\gamma_1 c_3 + \gamma_2) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_2}{\partial \varphi} + \gamma_4 \frac{\partial C_2}{\partial v} \right), \\
\eta_3 &= C_3 (\gamma_2 - 2 \gamma_1) + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_3}{\partial \varphi} + \gamma_4 \frac{\partial C_3}{\partial v} \right), \\
\kappa_1 &= \frac{3(c_1 - c_2) C_1^2}{2} + \frac{1}{s_{44}} \left[\left(\frac{\partial C_1}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_1}{\partial v} \right)^2 \right], \\
\kappa_2 &= \left[\frac{(c_1 + c_2) c_3^2}{2} + c_1 - 2 c_2 c_3 \right] C_2^2 + \frac{1}{s_{44}} \left[\left(\frac{\partial C_2}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_2}{\partial v} \right)^2 \right], \\
\kappa_3 &= 3(c_1 + 2 c_2) C_3^2 + \frac{1}{s_{44}} \left[\left(\frac{\partial C_3}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_3}{\partial v} \right)^2 \right], \\
\kappa_4 &= (c_1 - c_2) (2 + c_3) C_1 C_2 + \frac{2}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_2}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_2}{\partial v} \right), \\
\kappa_5 &= \frac{2}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_3}{\partial v} \right), \\
\kappa_6 &= [2 c_2 (1 - c_3) - c_1] C_2 C_3 + \frac{2}{s_{44}} \left(\frac{\partial C_2}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_2}{\partial v} \frac{\partial C_3}{\partial v} \right), \tag{6.6}
\end{aligned}$$

where γ_i ($i = 1, \dots, 4$) is given by Equation (2.22).

6.2 Matrix

The integration constants C_{1M} , C_{2M} , C_{3M} for the matrix (see Equation (6.4)) are determined by the boundary conditions (2.30), (2.31) or (2.30)–(2.32). The boundary conditions result in the following combinations of C_{1M} , C_{2M} , C_{3M} . Finally, such a

combination is considered to exhibit a minimum value of the elastic energy W_C of the cubic cell (see Equation (2.27)). The subscript $Q = M, MB$ and the stress σ_q in Section 4.2 are derived as

$$\begin{aligned} Q = M &\Rightarrow \sigma_q = p_n, \\ Q = MB &\Rightarrow \sigma_q = \sigma_{nB}, \end{aligned} \quad (6.7)$$

where p_n and σ_{nB} are given by Equations (2.33) and (6.8), (6.11), (6.14), (6.17), respectively. Consequently, the conditions in Equation (2.36) are considered.

Conditions $C_{1M} \neq 0, C_{2M} \neq 0, C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (6.4), (6.5), we get

$$\begin{aligned} \varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[1 - c_{3M} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\ \varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[1 - \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\ \varepsilon'_{n\varphi M} &= s_{44M} \sigma_{n\varphi Q} = - \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) - x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right], \\ \varepsilon'_{n\theta M} &= s_{44M} \sigma_{n\theta Q} = -\Theta \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) - x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right], \\ \sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left\{ c_{1M} - c_{2M} - [c_{3M}(c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right\}, \\ \sigma_{\varphi Q} &= \sigma_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[c_{1M} - c_{2M} - (c_{1M} - c_{2M} c_{3M}) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} \right], \\ w_Q &= \kappa_{1Q} + \kappa_{2Q} x_n^{2(c_{3M}-1)} + \kappa_{4Q} x_n^{c_{3M}-1}, \\ W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1Q}}{3} (x_M^3 - x_{IN}^3) + \frac{\kappa_{2Q}}{2c_{3M}+1} (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}) \right. \\ &\quad \left. + \frac{\kappa_{4Q}}{c_{3M}+2} (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}) \right] d\varphi dv, \\ \sigma_{nB} &= -\frac{\rho_{1B} p_n}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right] \\ &\quad + \frac{\rho_{2B} p_n}{\zeta_M x_M^{c_{3M}-1}} + \frac{1}{s_{44M}} \left[\rho_{2B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \right) + \rho_{2B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \right) \right], \\ Q &= M, MB, \end{aligned} \quad (6.8)$$

where Θ ; x_{IN} , x_M ; s_{44M} ; c_{iM} ($i=1,2,3$) are given by Equations (1.8); (1.9); (2.13); (2.18), respectively. The coefficients ζ_Q , η_{iQ} , κ_{jM} , ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2$; $j=1,2,4$; $\tau = \varphi, v$; $Q = M, MB$; see Equation (6.6)) have the forms

$$\begin{aligned}
\zeta_M &= c_{1M} - c_{2M} - [c_{3M}(c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1}, \\
\zeta_{MB} &= (c_{1M} + c_{2M})(1 - c_{3M}), \\
\eta_{1Q} &= -\frac{\sigma_q(\gamma_{1M} + \gamma_{2M})}{\zeta_Q} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\eta_{2Q} &= \frac{\sigma_q(\gamma_{1M} c_{3M} + \gamma_{2M})}{\zeta_Q x_M^{c_{3M}-1}} \\
&\quad + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right], \\
\kappa_{1Q} &= \frac{3(c_{1M} - c_{2M})}{2} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 + \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\}, \\
\kappa_{2Q} &= \left[\frac{(c_{1M} + c_{2M})c_{3M}^2}{2} + c_{1M} - 2c_{2M}c_{3M} \right] \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right)^2 \\
&\quad + \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right]^2 \right\}, \\
\kappa_{4Q} &= \frac{(c_{2M} - c_{1M})(2 + c_{3M})}{x_M^{c_{3M}-1}} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \\
&\quad - \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \right], \\
\rho_{1B} &= (\vartheta_1 + \vartheta_2 + \vartheta_3)(c_{1M} - c_{2M}), \\
\rho_{2B} &= \left\{ \vartheta_1 [(c_{1M} + c_{2M})c_{3M} - 2c_{2M}] + (\vartheta_2 + \vartheta_3)(c_{1M} - c_{2M}c_{3M}) \right\} x_M^{c_{3M}-1}, \\
\rho_{1B}^{(\varphi)} &= \vartheta_1 + \vartheta_2, \quad \rho_{1B}^{(v)} = \Theta(\vartheta_1 + \vartheta_3), \\
\rho_{2B}^{(\varphi)} &= (\vartheta_1 + \vartheta_2)x_M^{c_{3M}-1}, \quad \rho_{2B}^{(v)} = \Theta(\vartheta_1 + \vartheta_3)x_M^{c_{3M}-1}, \quad Q = M, MB, \quad (6.9)
\end{aligned}$$

where γ_{iM} , ϑ_j ($i=1, \dots, 4$; $j=1,2,3$) are given by Equations (2.22), (2.35), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (6.9), the coefficient ρ_Q ($Q = M, MB$) in Equations (2.33), (3.13) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[1 - \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} \right], \quad Q = M, MB. \quad (6.10)$$

Conditions $C_{1M} \neq 0, C_{3M} \neq 0, C_{2M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (6.4), (6.5), we get

$$\begin{aligned} \varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[1 - c_{3M} \left(\frac{x_M}{x_n} \right)^3 \right], \\ \varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[1 - \left(\frac{x_M}{x_n} \right)^3 \right], \\ \varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = - \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) - \frac{1}{x_n^3} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right], \\ \varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\Theta \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) - \frac{1}{x_n^3} \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right], \\ \sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[c_{1M} - c_{2M} + 2(c_{1M} + 2c_{2M}) \left(\frac{x_M}{x_n} \right)^3 \right], \\ \sigma_{\varphi Q} &= \sigma_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[c_{1M} - c_{2M} - (c_{1M} + 2c_{2M}) \left(\frac{x_M}{x_n} \right)^3 \right], \\ \sigma_{1Q} &= \eta_{1Q} + \frac{\eta_{3Q}}{x_n^3}, \\ w_Q &= \kappa_{1Q} + \frac{\kappa_{3Q}}{x_n^6} + \frac{\kappa_{5Q}}{x_n^3}, \\ W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1Q}}{3} (x_M^3 - x_{IN}^3) + \frac{\kappa_{3Q}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) + \kappa_{5Q} \ln \left(\frac{x_M}{x_{IN}} \right) \right] d\varphi dv, \\ \sigma_{nB} &= -\frac{\rho_{1B} p_n}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right] \\ &\quad + \frac{\rho_{3B} p_n x_M^3}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n x_M^3}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n x_M^3}{\zeta_M} \right) \right], \\ Q &= M, MB, \end{aligned} \quad (6.11)$$

where $\Theta; x_M; s_{44M}; c_{iM}; \rho_{1B}, \rho_{1B}^{(\tau)}$ ($i=1,2,3; \tau = \varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), respectively. The coefficients $\zeta_Q, \eta_{3Q}, \kappa_{iQ}, \rho_{3B}, \rho_{3B}^{(\tau)}$

($i=3,5$; $\tau = \varphi, v$; $Q = M, MB$; see Equation (6.6)) have the forms

$$\begin{aligned}
\zeta_M &= c_{1M} - c_{2M} + 2(c_{1M} + 2c_{2M}) \left(\frac{x_M}{x_{IN}} \right)^3, \quad \zeta_{MB} = 3(c_{1M} + c_{2M}), \\
\eta_{3Q} &= \frac{\sigma_q x_M^3 (\gamma_{2M} - 2\gamma_{1M})}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right], \\
\kappa_{3Q} &= 3(c_{1M} + 2c_{2M}) \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right)^2 + \frac{1}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right]^2 \\
&\quad + \frac{\Theta^2}{s_{44M}} \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right]^2, \\
\kappa_{5Q} &= -\frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right], \\
\rho_{3B} &= \frac{(\vartheta_2 + \vartheta_3 - 2\vartheta_1)(c_{1M} + 2c_{2M})}{x_M^3}, \\
\rho_{3B}^{(\varphi)} &= \frac{\vartheta_1 + \vartheta_2}{x_M^3}, \quad \rho_{3B}^{(v)} = \frac{\Theta(\vartheta_1 + \vartheta_3)}{x_M^3}, \quad Q = M, MB,
\end{aligned} \tag{6.12}$$

where γ_{iM} , ϑ_j ($i=1, \dots, 4$; $j=1,2,3$) are given by Equations (2.22), (2.35), respectively. The coefficients η_{1Q} , κ_{1Q} ($Q = M, MB$) are given by Equation (6.9), where ζ_Q in Equation (6.9) is given by Equation (6.12). The normal stress p_n is given by Equation (2.33). With regard to Equation (6.11), the coefficient ρ_Q ($Q = M, MB$) in Equation (2.33) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[1 - \left(\frac{x_M}{x_{IN}} \right)^{-3} \right], \quad Q = M, MB. \tag{6.13}$$

Conditions $C_{2M} \neq 0$, $C_{3M} \neq 0$, $C_{1M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (6.4), (6.5), we get

$$\begin{aligned}
\varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left[c_{3M} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - 2 \left(\frac{x_M}{x_n} \right)^3 \right], \\
\varepsilon_{\varphi Q} = \varepsilon_{\theta Q} &= -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - \left(\frac{x_M}{x_n} \right)^3 \right], \\
\varepsilon_{n\varphi Q} = s_{44M} \sigma_{n\varphi Q} &= -\left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) x_n^{c_{3M}-1} - \frac{1}{x_n^3} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right],
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\Theta \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) x_n^{c_{3M}-1} - \frac{1}{x_n^3} \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \right], \\
\sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left\{ [c_{3M}(c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - 2(c_{1M} + 2c_{2M}) \left(\frac{x_M}{x_n} \right)^3 \right\}, \\
\sigma_{\varphi Q} &= \sigma'_{\theta M} = -\frac{\sigma_q}{\zeta_Q} \left[(c_{1M} - c_{2M}c_{3M}) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} + (c_{1M} + 2c_{2M}) \left(\frac{x_M}{x_n} \right)^3 \right], \\
\sigma_{1Q} &= \eta_{2Q} x_n^{c_{3M}-1} + \frac{\eta_{3Q}}{x_n^3}, \\
w_Q &= \kappa_{2Q} x_n^{2(c_{3M}-1)} + \frac{\kappa_{3Q}}{x_n^6} + \kappa_{6Q} x_n^{c_{3M}-4}, \\
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{2Q}}{2c_{3M}+1} (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}) + \frac{\kappa_{3Q}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) \right. \\
&\quad \left. + \frac{\kappa_{6Q}}{c_{3M}-1} (x_M^{c_{3M}-1} - x_{IN}^{c_{3M}-1}) \right] d\varphi dv, \\
\sigma_{nB} &= -\frac{\rho_{1B} p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) + \frac{\rho_{3B} p_n x_M^{c_{3M}}}{\zeta_M} \\
&\quad - \frac{1}{s_{44M}} \left\{ \rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left[\frac{p_n}{\zeta_M} \left(\frac{1}{2} + \ln x_M \right) \right] \right\} \\
&\quad + \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n x_M^{c_{3M}}}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n x_M^{c_{3M}}}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (6.14)
\end{aligned}$$

where Θ ; x_M ; s_{44M} ; c_{iM} ; ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i = 1, 3$; $\tau = \varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), (6.12), respectively. The coefficients ζ_Q , κ_{6Q} ($Q = M, MB$); see Equation (4.6)) have the forms

$$\begin{aligned}
\zeta_M &= \left\{ [c_{3M}(c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}+2} + 2(c_{1M} + 2c_{2M}) \right\} \left(\frac{x_M}{x_{IN}} \right)^3, \\
\zeta_{MB} &= (c_{1M} + c_{2M})(c_{3M} + 2), \\
\kappa_{6Q} &= -\frac{x_M^3 [2c_{2M}(1 - c_{3M}) - c_{1M}]}{x_M^{c_{3M}-1}} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 \\
&\quad - \frac{2}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right) \\
&\quad - \frac{2\Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q x_M^3}{\zeta_Q} \right), \quad Q = M, MB. \quad (6.15)
\end{aligned}$$

The coefficients η_{2Q} , κ_{2Q} and η_{3Q} , κ_{3Q} ($Q = M, MB$) are given by Equations (6.9) and (6.12), respectively, where ζ_Q in Equations (6.9), (6.12) is given by Equation (6.15). The normal stress p_n is given by Equation (2.33). With regard to Equation (6.14), the coefficient ρ_Q ($Q = M, MB$) in Equation (2.33) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} - \left(\frac{x_M}{x_{IN}} \right)^3 \right], \quad Q = M, MB. \quad (6.16)$$

Conditions $C_{1M} \neq 0$, $C_{2M} \neq 0$, $C_{3M} \neq 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (6.4), (6.5), we get

$$\begin{aligned} \varepsilon_{nM} &= -\frac{p_n}{\zeta_M} \left(\zeta_{1M} + \zeta_{2M} c_{3M} x_n^{c_{3M}-1} - \frac{2\zeta_{3M}}{x_n^3} \right), \\ \varepsilon_{\varphi M} = \varepsilon_{\theta M} &= -\frac{p_n}{\zeta_M} \left(\zeta_{1M} + \zeta_{2M} x_n^{c_{3M}-1} + \frac{\zeta_{3M}}{x_n^3} \right), \\ \varepsilon_{n\varphi M} = s_{44M} \sigma_{n\varphi M} &= \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right), \\ \varepsilon_{n\theta M} = s_{44M} \sigma_{n\theta M} &= \Theta \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\ \sigma_{nM} &= -\frac{p_n}{\zeta_M} \left\{ \zeta_{1M} (c_{1M} - c_{2M}) + \zeta_{2M} [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_n^{c_{3M}-1} \right. \\ &\quad \left. - \frac{2\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} \right\}, \\ \sigma_{\varphi M} = \sigma_{\theta M} &= -\frac{p_n}{\zeta_M} \left[\zeta_{1M} (c_{1M} - c_{2M}) + \zeta_{2M} (c_{1M} - c_{2M} c_{3M}) x_n^{c_{3M}-1} \right. \\ &\quad \left. + \frac{\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} \right], \\ \sigma_{1M} &= \eta_{1M} + \eta_{2M} x_n^{c_{3M}-1} + \frac{\eta_{3M}}{x_n^3}, \\ w_M &= \kappa_{1M} + \kappa_{2M} x_n^{2(c_{3M}-1)} + \frac{\kappa_{3M}}{x_n^6} + \kappa_{4M} x_n^{c_{3M}-1} + \frac{\kappa_{5M}}{x_n^3} + \kappa_{6M} x_n^{c_{3M}-4}, \\ W_M &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1M}}{3} (x_M^3 - x_{IN}^3) + \frac{\kappa_{2M}}{2c_{3M}+1} (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}) \right. \\ &\quad \left. + \frac{\kappa_{3M}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) + \frac{\kappa_{4M}}{c_{3M}+2} (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}) \right] \end{aligned}$$

$$\begin{aligned}
& + \kappa_{5M} \ln \left(\frac{x_M}{x_{IN}} \right) + \frac{\kappa_{6M}}{c_{3M}-1} \left(x_M^{c_{3M}-1} - x_{IN}^{c_{3M}-1} \right) \Big] d\varphi dv, \\
\sigma_{nB} = & - \frac{\rho_{1B} p_n \zeta_{1M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right] \\
& + \frac{\rho_{2B} p_n \zeta_{2M}}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{2B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \rho_{2B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right], \quad (6.17)
\end{aligned}$$

where Θ ; x_{IN} ; x_M ; s_{44M} ; c_{iM} ; ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2,3$; $\tau=\varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), (6.12), respectively. The coefficients ζ_{iM} , ζ_M , η_{iM} , κ_{jM} ($i=1,2,3$; $j=2 \dots, 6$; Equation (6.6)) have the forms

$$\begin{aligned}
\zeta_{1M} &= (2 + c_{3M}) x_M^{c_{3M}-3}, \quad \zeta_{2M} = \frac{3}{x_M}, \quad \zeta_{3M} = (c_{3M} - 1) x_M^{c_{3M}}, \\
\zeta_M &= (c_{2M} - c_{1M}) (2 + c_{3M}) x_M^{c_{3M}-3} + \frac{3[(c_{1M} + c_{2M}) c_{3M} - 2 c_{2M}] x_{IN}^{c_{3M}-1}}{x_M^2} \\
&+ \frac{2(c_{1M} + 2c_{2M})(1 - c_{3M}) x_M^{c_{3M}}}{x_{IN}^3}, \\
\eta_{1M} &= - \frac{p_n \zeta_{1M} (\gamma_{1M} + \gamma_{2M})}{\zeta_M} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right], \\
\eta_{2M} &= - \frac{p_n \zeta_{2M} (\gamma_{1M} c_{3M} + \gamma_{2M})}{\zeta_M} \\
&- \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right], \\
\eta_{3M} &= - \frac{p_n \zeta_{3M} (\gamma_{2M} - 2\gamma_{1M})}{\zeta_M} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\
\kappa_{1M} &= \frac{3(c_{1M} - c_{2M})}{2} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right)^2 \\
&+ \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 \right\}, \\
\kappa_{2M} &= \left[\frac{(c_{1M} + c_{2M}) c_{3M}^2}{2} + c_{1M} - 2 c_{2M} c_{3M} \right] \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right)^2 \\
&+ \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left(\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right)^2 \right\}, \\
\kappa_{3M} &= 3(c_{1M} + 2c_{2M}) \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right)^2 \\
&+ \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]^2 \right\},
\end{aligned}$$

$$\begin{aligned}
\kappa_{4M} &= \zeta_{1M} \zeta_{2M} (c_{1M} - c_{2M}) (2 + c_{3M}) \left(\frac{p_n}{\zeta_M} \right)^2 \\
&\quad + \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right], \\
\kappa_{5M} &= \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\
\kappa_{6M} &= \zeta_{2M} \zeta_{3M} [2c_{2M} (1 - c_{3M}) - c_{1M}] \left(\frac{p_n}{\zeta_M} \right)^2 \\
&\quad + \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right],
\end{aligned} \tag{6.18}$$

where γ_{iM} ($i=1, \dots, 4$) is given by Equation (2.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (6.17), the coefficient ρ_M in Equation (2.33) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left\{ 1 - \frac{1}{c_{3M} + 2} \left[3 \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} + (c_{3M} - 1) \left(\frac{x_M}{x_{IN}} \right)^3 \right] \right\}. \tag{6.19}$$

6.3 Inclusion

The subscript $Q = IN, INB$ and the stress σ_q in Section 6.3 are derived as

$$\begin{aligned}
Q = IN &\Rightarrow \sigma_q = p_n, \quad \rho_Q = \rho_{IN} = \frac{1}{\xi_{1IN}} \\
Q = INB &\Rightarrow \sigma_q = \sigma_{nB}, \quad \rho_Q = \rho_{MB}
\end{aligned} \tag{6.20}$$

where p_n , ξ_{1IN} , σ_{nB} , ρ_{MB} , ρ_{IN} are given by Equations (2.33), (3.8), (3.10), (3.16), respectively. Consequently, the conditions in Equation (2.36) are considered. In case of the ellipsoidal inclusion, we get $C_{2IN} = C_{3IN} = 0$, otherwise we get $(u_{nIN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\varepsilon_{IN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\sigma_{IN})_{r \rightarrow 0} \rightarrow \pm \infty$ due to $c_3 < 0$ (see Equations (2.18), (6.4)–(6.10)). With regard to Equations (2.28), (2.29), (6.4)–(6.6), (2.21), (2.26), (2.27), we get [1]–[22]

$$\begin{aligned}
\varepsilon_{nQ} &= \varepsilon_{\varphi Q} = \varepsilon_{\theta Q} = -\sigma_q \rho_Q, \\
\varepsilon_{n\varphi Q} &= s_{44IN} \sigma_{n\varphi Q} = -\rho_Q \frac{\partial \sigma_q}{\partial \varphi},
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{n\theta Q} &= s_{44IN} \sigma_{n\theta Q} = -\Theta \rho_Q \frac{\partial \sigma_q}{\partial v}, \\
\sigma_{nQ} &= \sigma_{\varphi Q} = \sigma_{\theta Q} = -\sigma_q, \\
\sigma_{1Q} &= -\rho_Q \left[\sigma_q (\gamma_{1IN} + \gamma_{2IN}) + \frac{1}{s_{44IN}} \left(\gamma_{3IN} \frac{\partial \sigma_q}{\partial \varphi} + \gamma_{4IN} \frac{\partial \sigma_q}{\partial v} \right) \right], \\
w_Q &= \rho_Q^2 \left\{ \frac{3\sigma_q^2}{2\rho_Q} + \frac{2}{s_{44IN}} \left[\left(\frac{\partial \sigma_q}{\partial \varphi} \right)^2 + \left(\frac{\partial \sigma_q}{\partial v} \right)^2 \right] \right\}, \\
W_Q &= \frac{4\rho_Q^2}{3} \int_0^{\pi/2} \int_0^{\pi/2} x_{IN}^3 \left\{ \frac{3\sigma_q^2}{2\rho_Q} + \frac{2}{s_{44IN}} \left[\left(\frac{\partial \sigma_q}{\partial \varphi} \right)^2 + \left(\frac{\partial \sigma_q}{\partial v} \right)^2 \right] \right\} d\varphi dv, \\
Q &= M, MB,
\end{aligned} \tag{6.21}$$

where Θ , s_{44IN} , γ_{iIN} ($i=1, \dots, 4$) are given by Equations (1.8), (2.13), (2.22), respectively. The normal stress p_n is given by Equation (2.33). With regard to Equation (6.20), the coefficient ρ_{IN} in Equation (2.33) is derived as

$$\rho_{IN} = \frac{1 - 2\mu_{IN}}{E_{IN}}. \tag{6.22}$$

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Mathematical Model 5

7.1 Mathematical Procedure

Let the mathematical procedures $\partial \text{Eq. (2.24)} / \partial r$, $\text{Eq. (6.2)} / r$ be performed, and then we get

$$x_n \frac{\partial^2 U_n}{\partial x_n^2} + (1 - c_3) \frac{\partial U_n}{\partial x_n} = 0, \quad (7.1)$$

$$\frac{\partial U_n}{\partial x_n} = -s_{44} (c_1 + c_2) \left(x_n^2 \frac{\partial^3 u_n}{\partial x_n^3} + 4x_n \frac{\partial^2 u_n}{\partial x_n^2} \right), \quad (7.2)$$

where s_{44} and $c_1, c_2, c_3 < 0$ are given by Equations (2.13) and (2.18), respectively. Let the mathematical procedure $\partial \text{Eq. (7.2)} / \partial r$ be performed, and then we get

$$\frac{\partial^2 U_n}{\partial x_n^2} = -s_{44} (c_1 + c_2) \left(x_n^2 \frac{\partial^4 u_n}{\partial x_n^4} + 6x_n \frac{\partial^3 u_n}{\partial x_n^3} + 4 \frac{\partial^2 u_n}{\partial x_n^2} \right). \quad (7.3)$$

Let Equations (6.2), (6.3) be substituted to (7.1), and then we get

$$x_n^2 \frac{\partial^4 u_n}{\partial x_n^4} + (7 - c_3) x_n \frac{\partial^3 u_n}{\partial x_n^3} + 4(2 - c_3) \frac{\partial^2 u_n}{\partial x_n^2} = 0. \quad (7.4)$$

Let u_n be assumed in the form $u_n = x_n^\lambda$, then we get

$$u_n = C_1 x_n + C_2 x_n^{c_3} + \frac{C_3}{x_n^2} + C_4, \quad (7.5)$$

where C_1, \dots, C_4 are integration constants, which are determined by the boundary conditions in Section 2.3. With regard to Equations (2.1)–(2.4), (2.14)–(2.17), (2.26), (7.6), we get

$$\begin{aligned} \varepsilon_n &= C_1 + C_2 c_3 x_n^{c_3-1} - \frac{2C_3}{x_n^3}, \\ \varepsilon_\varphi = \varepsilon_\theta &= C_1 + C_2 x_n^{c_3-1} + \frac{C_3}{x_n^3} + \frac{C_4}{x_n}, \end{aligned}$$

$$\begin{aligned}
\varepsilon_{n\varphi} &= s_{44} \sigma_{n\varphi} = \frac{\partial C_1}{\partial \varphi} + x_n^{c_3-1} \frac{\partial C_2}{\partial \varphi} + \frac{1}{x_n^3} \frac{\partial C_3}{\partial \varphi} + \frac{1}{x_n} \frac{\partial C_4}{\partial \varphi}, \\
\varepsilon_{n\theta} &= s_{44} \sigma_{n\theta} = \Theta \left[\frac{\partial C_1}{\partial v} + x_n^{c_3-1} \frac{\partial C_2}{\partial v} + \frac{1}{x_n^3} \frac{\partial C_3}{\partial v} + \frac{1}{x_n} \frac{\partial C_4}{\partial v} \right], \\
\sigma_n &= C_1 (c_1 - c_2) + C_2 [(c_1 + c_2) c_3 - 2 c_2] x_n^{c_3-1} - \frac{2 C_3 (c_1 + 2 c_2)}{x_n^3} - \frac{2 c_2 C_4}{x_n}, \\
\sigma_\varphi &= \sigma_\theta = C_1 (c_1 - c_2) + C_2 (c_1 - c_2 c_3) x_n^{c_3-1} + \frac{C_3 (c_1 + 2 c_2)}{x_n^3} + \frac{c_1 C_4}{x_n}, \\
\sigma_1 &= \eta_1 + \eta_2 x_n^{c_3-1} + \frac{\eta_3}{x_n^3} + \frac{\eta_4}{x_n}, \\
w &= \kappa_1 + \kappa_2 x_n^{2(c_3-1)} + \frac{\kappa_3}{x_n^6} + \frac{\kappa_4}{x_n^2} + (\kappa_5 + \kappa_9) x_n^{c_3-1} \\
&\quad + \frac{\kappa_6}{x_n^3} + \kappa_7 x_n^{c_3-4} + \frac{\kappa_8}{x_n} + \frac{\kappa_{10}}{x_n^4}, \tag{7.6}
\end{aligned}$$

where Θ and η_i, κ_i ($i=1,2,3$) ($i=1,2,3$) are given by Equations (1.8) and (6.6), respectively. The coefficients η_4, κ_j ($j=4, \dots, 6$) are derived as

$$\begin{aligned}
\eta_4 &= C_4 \gamma_2 + \frac{1}{s_{44}} \left(\gamma_3 \frac{\partial C_4}{\partial \varphi} + \gamma_4 \frac{\partial C_4}{\partial v} \right), \\
\kappa_4 &= c_1 C_4^2 + \frac{1}{s_{44}} \left[\left(\frac{\partial C_4}{\partial \varphi} \right)^2 + \Theta^2 \left(\frac{\partial C_4}{\partial v} \right)^2 \right], \\
\kappa_5 &= (c_1 - c_2) (2 + c_3) C_1 C_2 + \frac{2}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_2}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_2}{\partial v} \right), \\
\kappa_6 &= \frac{2}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_3}{\partial v} \right), \\
\kappa_7 &= [2 c_2 (1 - c_3) - c_1] C_2 C_3 + \frac{2}{s_{44}} \left(\frac{\partial C_2}{\partial \varphi} \frac{\partial C_3}{\partial \varphi} + \Theta^2 \frac{\partial C_2}{\partial v} \frac{\partial C_3}{\partial v} \right), \\
\kappa_8 &= (c_1 - c_2) C_1 C_4 + \frac{1}{s_{44}} \left(\frac{\partial C_1}{\partial \varphi} \frac{\partial C_4}{\partial \varphi} + \Theta^2 \frac{\partial C_1}{\partial v} \frac{\partial C_4}{\partial v} \right), \\
\kappa_9 &= (c_1 - c_2 c_3) C_2 C_4 + \frac{1}{s_{44}} \left(\frac{\partial C_2}{\partial \varphi} \frac{\partial C_4}{\partial \varphi} + \Theta^2 \frac{\partial C_2}{\partial v} \frac{\partial C_4}{\partial v} \right), \\
\kappa_{10} &= (c_1 + 2 c_2) C_3 C_4 + \frac{1}{s_{44}} \left(\frac{\partial C_3}{\partial \varphi} \frac{\partial C_4}{\partial \varphi} + \Theta^2 \frac{\partial C_3}{\partial v} \frac{\partial C_4}{\partial v} \right), \tag{7.7}
\end{aligned}$$

where γ_i ($i=1, \dots, 4$) is given by Equation (2.22). In case of the ellipsoidal inclusion, we get $C_{2IN} = C_{3IN} = C_{4IN} = 0$, otherwise we get $(u_{nIN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\varepsilon_{IN})_{x_n \rightarrow 0} \rightarrow \pm \infty$, $(\sigma_{IN})_{r \rightarrow 0} \rightarrow \pm \infty$ due to $c_3 < 0$ (see Equations (2.18), (6.4)–

(6.10)). In case of $C_{1IN} \neq 0$ (see Equations (6.4), (7.5)), the mathematical solutions for the ellipsoidal inclusion is presented in Section 6.3.

7.2 Matrix

The integration constants $C_{1M}, C_{2M}, C_{3M}, C_{4M}$ for the matrix (see Equation (4.4)) are determined by the boundary conditions (2.30), (2.31) or (2.30)–(2.32). The boundary conditions result in the following combinations of $C_{1M}, C_{2M}, C_{3M}, C_{4M}$, where the combinations of C_{1M}, C_{2M}, C_{3M} are presented in Section (6.2). Finally, such a combination is considered to exhibit a minimum value of the elastic energy W_C of the cubic cell (see Equation (2.27)). The subscript $Q = M, MB$ and the stress σ_q in Section 7.2 are derived as

$$\begin{aligned} Q = M &\Rightarrow \sigma_q = p_n, \\ Q = MB &\Rightarrow \sigma_q = \sigma_{nB}, \end{aligned} \quad (7.8)$$

where p_n and σ_{nB} are given by Equations (2.33) and (5.9), (5.12), (5.15), (5.18), respectively. Consequently, the conditions in Equation (2.36) are considered.

Conditions $C_{1M} \neq 0, C_{4M} \neq 0, C_{2M} = C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (7.5), (7.6), we get

$$\begin{aligned} \varepsilon_{nQ} &= -\frac{\sigma_q}{\zeta_Q}, \\ \varepsilon_{\varphi Q} = \varepsilon_{\theta Q} &= -\frac{\sigma_q}{\zeta_Q} \left(1 - \frac{1}{x_n}\right), \\ \varepsilon_{n\varphi Q} = s_{44M} \sigma_{n\varphi Q} &= -\left(1 - \frac{1}{x_n}\right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q}\right), \\ \varepsilon_{n\theta Q} = s_{44M} \sigma_{n\theta Q} &= -\Theta \left(1 - \frac{1}{x_n}\right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q}\right), \\ \sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left(c_{1M} - c_{2M} + \frac{2c_{Mm}}{x_n}\right), \\ \sigma_{\varphi Q} = \sigma_{\theta Q} &= -\frac{\sigma_q}{\zeta_Q} \left(c_{1M} - c_{2M} - \frac{c_{1M}}{x_n}\right), \\ \sigma_{1Q} &= \eta_{1Q} + \frac{\eta_{4Q}}{x_n}, \\ w_Q &= \kappa_{1Q} + \frac{\kappa_{4Q}}{x_n^2} + \frac{\kappa_{8Q}}{x_n}, \end{aligned}$$

$$\begin{aligned}
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1Q}}{3} (x_M^3 - x_{IN}^3) + \kappa_{4Q} (x_M - x_{IN}) + \frac{\kappa_{8Q}}{2} (x_M^2 - x_{IN}^2) \right] d\varphi dv, \\
\sigma_{nB} &= -\frac{\rho_{1B} p_n}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right] \\
&\quad + \frac{\rho_{4B} p_n}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (7.9)
\end{aligned}$$

where $\Theta; x_{IN}; x_M; s_{44M}; c_{iM}; \rho_{1B}, \rho_{1B}^{(\tau)}$ ($i=1,2; \tau=\varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), respectively. The coefficients $\zeta_Q, \eta_{4Q}, \kappa_{jQ}$ ($j=4,8; Q=M, MB$; see Equation (7.7)) have the forms

$$\begin{aligned}
\zeta_M &= c_{1M} - c_{2M} + \frac{2c_{2M}x_M}{x_{IN}}, \quad \zeta_{MB} = c_{1M} + c_{2M}, \\
\eta_{4Q} &= \frac{\sigma_q \gamma_{2M}}{\zeta_Q} + \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\kappa_{4Q} &= c_{1M} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 + \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\}, \\
\kappa_{8Q} &= (c_{2M} - c_{1M}) \left(\frac{\sigma_q}{\zeta_Q} \right)^2 - \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]^2 \right\}, \\
\rho_{4B} &= \frac{(\vartheta_2 + \vartheta_3) c_{1M} - 2\vartheta_1 c_{2M}}{x_M}, \\
\rho_{4B}^{(\varphi)} &= \frac{\vartheta_1 + \vartheta_2}{x_M}, \quad \rho_{4B}^{(v)} = \frac{\Theta(\vartheta_1 + \vartheta_3)}{x_M}, \quad Q = M, MB, \quad (7.10)
\end{aligned}$$

where γ_{iM}, ϑ_j ($i=2,3,4; j=1,2,3$) are given by Equations (2.22), (2.35), respectively. The coefficients η_{1Q}, κ_{1Q} ($Q=M, MB$) are given by Equation (6.9), where ζ_Q in Equation (6.9) is given by Equation (7.9). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.9), the coefficient ρ_Q ($Q=M, MB$) in Equation (2.33) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left(1 - \frac{1}{x_{IN}} \right), \quad Q = M, MB. \quad (7.11)$$

Conditions $C_{2M} \neq 0, C_{4M} \neq 0, C_{1M} = C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (7.5), (7.6), we get

$$\epsilon_{nQ} = -\frac{\sigma_q c_{3M}}{\zeta_Q} \left(\frac{x_n}{x_M} \right)^{c_{3M}-1},$$

$$\begin{aligned}
\varepsilon_{\varphi Q} &= \varepsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - \frac{1}{x_n} \right], \\
\varepsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = - \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) - \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\varepsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\Theta \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) - \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right], \\
\sigma_{nQ} &= -\frac{\sigma_q}{\zeta_Q} \left\{ [c_{3M} (c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} + \frac{2c_{2M}}{x_n} \right\}, \\
\sigma_{\varphi Q} &= \sigma_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[(c_{1M} - c_{2M} c_{3M}) \left(\frac{x_n}{x_M} \right)^{c_{3M}-1} - \frac{c_{1M}}{x_n} \right], \\
\sigma_{1Q} &= \eta_{2Q} x_n^{c_{3M}-1} + \frac{\eta_{4Q}}{x_n}, \\
w_Q &= \kappa_{2Q} x_n^{2(c_{3M}-1)} + \frac{\kappa_{4Q}}{x_n^2} + \kappa_{9Q} x_n^{c_{3M}-1}, \\
W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{2Q}}{2c_{3M}+1} \left(x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1} \right) + \kappa_{4Q} (x_M - x_{IN}) \right. \\
&\quad \left. + \frac{\kappa_{9Q}}{c_{3M}+2} \left(x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2} \right) \right] d\varphi dv, \\
\sigma_{nB} &= -\frac{\rho_{2B} p_n}{\zeta_M x_M^{c_{3M}-1}} - \frac{1}{s_{44M}} \left[\rho_{2B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \right) + \rho_{2B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M x_M^{c_{3M}-1}} \right) \right] \\
&\quad + \frac{\rho_{4B} p_n}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (7.12)
\end{aligned}$$

where Θ ; x_{IN} ; x_M ; s_{44M} ; c_{iM} ; ρ_{jB} ; $\rho_{jB}^{(\tau)}$ ($i=1,2$; $j=2,4$; $\tau = \varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), (7.10), respectively, and ζ_Q , κ_{9Q} ($Q = M, MB$); see Equation (7.7)) have the forms

$$\begin{aligned}
\zeta_M &= [c_{3M} (c_{1M} + c_{2M}) - 2c_{2M}] \left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} + \frac{2c_{2M} x_M}{x_{IN}}, \\
\zeta_{MB} &= c_{3M} (c_{1M} + c_{2M}), \\
\kappa_{9Q} &= -\frac{c_{1M} - c_{2M} c_{3M}}{x_M^{c_{3M}-1}} \left(\frac{\sigma_q}{\zeta_Q} \right)^2 - \frac{1}{s_{44M}} \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right)
\end{aligned}$$

$$-\frac{\Theta^2}{s_{44M}} \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q x_M^{c_{3M}-1}} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right), \quad Q = M, MB. \quad (7.13)$$

The coefficients η_{2Q} , κ_{2Q} and η_{4Q} , κ_{4Q} ($Q = M, MB$) are given by Equations (6.9) and (7.9), respectively, where ζ_Q in Equations (6.9), (7.9) is given by Equation (7.12). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.12), the coefficient ρ_Q ($Q = M, MB$) in Equation (2.33) is derived as

$$\rho_Q = \frac{1}{\zeta_Q} \left[\left(\frac{x_{IN}}{x_M} \right)^{c_{3M}-1} - \frac{1}{x_{IN}} \right], \quad Q = M, MB. \quad (7.14)$$

Conditions $C_{3M} \neq 0$, $C_{4M} \neq 0$, $C_{1M} = C_{2M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30), (2.31), (2.34), (2.37), (2.38), (7.5), (7.6), we get

$$\begin{aligned} \epsilon_{nQ} &= \frac{2\sigma_q}{\zeta_Q} \left(\frac{x_{IN}}{x_n} \right)^3, \\ \epsilon_{\varphi Q} &= \epsilon_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[\left(\frac{x_{IN}}{x_n} \right)^3 - \frac{1}{x_n} \right], \\ \epsilon_{n\varphi Q} &= s_{44M} \sigma_{n\varphi Q} = -\left[\left(\frac{x_{IN}}{x_n} \right)^3 - \frac{1}{x_n} \right] \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right), \\ \epsilon_{n\theta Q} &= s_{44M} \sigma_{n\theta Q} = -\left[\left(\frac{x_{IN}}{x_n} \right)^3 - \frac{1}{x_n} \right] \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right), \\ \sigma_{nQ} &= \frac{2\sigma_q}{\zeta_Q} \left[(c_{1M} + 2c_{2M}) \left(\frac{x_{IN}}{x_n} \right)^3 - \frac{c_{2M}}{x_n} \right], \\ \sigma_{\varphi Q} &= \sigma_{\theta Q} = -\frac{\sigma_q}{\zeta_Q} \left[(c_{1M} - 2c_{2M}) \left(\frac{x_{IN}}{x_n} \right)^3 - \frac{c_{1M}}{x_n} \right], \\ \sigma_{1Q} &= \frac{\eta_{3Q}}{x_n^3} + \frac{\eta_{4Q}}{x_n}, \\ w_Q &= \frac{\kappa_{3Q}}{x_n^6} + \frac{\kappa_{4Q}}{x_n^2} + \frac{\kappa_{10Q}}{x_n^4}, \\ W_Q &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{3Q}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) + \kappa_{4Q} (x_M - x_{IN}) + \kappa_{10Q} \left(\frac{1}{x_{IN}} - \frac{1}{x_M} \right) \right] d\varphi dv, \\ \sigma_{nB} &= -\frac{\rho_{3B} p_n}{\zeta_M x_M^3} - \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M x_M^3} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M x_M^3} \right) \right] \end{aligned}$$

$$+ \frac{\rho_{4B} p_n}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n}{\zeta_M} \right) \right], \quad Q = M, MB, \quad (7.15)$$

where Θ ; x_{IN} ; x_M ; s_{44M} ; c_{iM} ; ρ_{jB} , $\rho_{jB}^{(\tau)}$ ($i=1,2$; $j=3,4$; $\tau = \varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.12), (7.10), respectively, and ζ_Q , κ_{10Q} ($Q = M, MB$; see Equation (7.7)) have the forms

$$\begin{aligned} \zeta_M = & - \left[2(c_{1M} + 2c_{2M}) + 2c_{2M} \left(\frac{x_{IN}}{x_M} \right)^2 \right], \quad \zeta_{MB} = -2(c_{1M} + 3c_{2M}), \\ \kappa_{10Q} = & -x_{IN}^3 (c_{1M} + 2c_{2M}) \left(\frac{\sigma_q}{\zeta_Q} \right)^2 - \frac{1}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{\sigma_q x_{IN}^3}{\zeta_Q} \right) \frac{\partial}{\partial \varphi} \left(\frac{\sigma_q}{\zeta_Q} \right) \right] \\ & - \frac{\Theta^2}{s_{44M}} \left[\frac{\partial}{\partial v} \left(\frac{\sigma_q x_{IN}^3}{\zeta_Q} \right) \frac{\partial}{\partial v} \left(\frac{\sigma_q}{\zeta_Q} \right) \right]. \end{aligned} \quad (7.16)$$

The coefficients η_{3Q} , κ_{3Q} and η_{4Q} , κ_{4Q} are given by Equations (6.12) and (7.9), respectively, where ζ_Q in Equations (6.12), (7.9) is given by Equation (7.15). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.15), the coefficient ρ_Q ($Q = M, MB$) in Equation (2.33) is derived as

$$\rho_Q = \frac{x_{IN} - 1}{\zeta_Q x_{IN}}, \quad Q = M, MB. \quad (7.17)$$

Conditions $C_{1M} \neq 0$, $C_{2M} \neq 0$, $C_{4M} \neq 0$, $C_{3M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (7.5), (7.6), we get

$$\begin{aligned} \varepsilon_{nM} = & - \frac{p_n}{\zeta_M} \left(\zeta_{1M} + \zeta_{2M} c_{3M} x_n^{c_{3M}-1} \right), \\ \varepsilon_{\varphi M} = \varepsilon_{\theta M} = & - \frac{p_n}{\zeta_M} \left(\zeta_{1M} + \zeta_{2M} x_n^{c_{3M}-1} + \frac{\zeta_{4M}}{x_n} \right), \\ \varepsilon_{n\varphi M} = s_{44M} \sigma_{n\varphi M} = & \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right), \\ \varepsilon_{n\theta M} = s_{44M} \sigma_{n\theta M} = & \Theta \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \\ \sigma_{nM} = & - \frac{p_n}{\zeta_M} \left\{ \zeta_{1M} (c_{1M} - c_{2M}) + \zeta_{2M} [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_n^{c_{3M}-1} - \frac{2\zeta_{4M} c_{2M}}{x_n} \right\}, \\ \sigma_{\varphi M} = \sigma_{\theta M} = & \end{aligned}$$

$$\begin{aligned}
& -\frac{p_n}{\zeta_M} \left[\zeta_{1M} (c_{1M} - c_{2M}) + \zeta_{2M} (c_{1M} - c_{2M} c_{3M}) x_n^{c_{3M}-1} + \frac{\zeta_{4M} c_{1M}}{x_n} \right], \\
\sigma_{1M} &= \eta_{1M} + \eta_{2M} x_n^{c_{3M}-1} + \frac{\eta_{4M}}{x_n}, \\
w_M &= \kappa_{1M} + \kappa_{2M} x_n^{2(c_{3M}-1)} + \frac{\kappa_{4M}}{x_n^2} + (\kappa_{5M} + \kappa_{9M}) x_n^{c_{3M}-1} + \frac{\kappa_{8M}}{x_n}, \\
W_M &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1M}}{3} (x_M^3 - x_{IN}^3) + \frac{\kappa_{2M}}{2c_{3M}+1} (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}) \right. \\
& \quad + \kappa_{4M} (x_M - x_{IN}) + \frac{\kappa_{5M} + \kappa_{9M}}{c_{3M}+2} (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}) \\
& \quad \left. + \frac{\kappa_{8M}}{2} (x_M^2 - x_{IN}^2) \right] d\varphi dv, \\
\sigma_{nB} &= -\frac{\rho_{1B} p_n \zeta_{1M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right] \\
& \quad - \frac{\rho_{2B} p_n \zeta_{2M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{2B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \rho_{2B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right] \\
& \quad - \frac{\rho_{4B} p_n \zeta_{4M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \quad (7.18)
\end{aligned}$$

where Θ ; x_{IN} , x_M ; s_{44M} ; c_{iM} ; ρ_{jB} , $\rho_{jB}^{(\tau)}$ ($i=1,2,3$; $j=1,2,4$; $\tau=\varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), (7.10); respectively. The coefficients ζ_{iM} , ζ_M , η_{4M} , κ_{jM} , ρ_{4B} , $\rho_{4B}^{(\tau)}$ ($i=1,2,4$; $j=4,5,8,9$; $\tau=\varphi, v$; see Equation (7.7)) have the forms

$$\begin{aligned}
\zeta_{1M} &= -c_{3M} x_M^{c_{3M}-1}, \quad \zeta_{2M} = 1, \quad \zeta_{4M} = (c_{3M} - 1) x_M^{c_{3M}} \\
\zeta_M &= (c_{2M} - c_{1M}) c_{3M} x_M^{c_{3M}-1} + [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_{IN}^{c_{3M}-1} \\
& \quad + \frac{2c_{2M} (1 - c_{3M}) x_M^{c_{3M}}}{x_{IN}}, \\
\eta_{4M} &= -\frac{p_n \zeta_{4M} \gamma_{2M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\gamma_{3M} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \gamma_{4M} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \\
\kappa_{4M} &= c_{1M} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right)^2 + \frac{1}{s_{44M}} \left\{ \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right]^2 + \Theta^2 \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right]^2 \right\}, \\
\kappa_{5M} &= \zeta_{1M} \zeta_{2M} (c_{1M} - c_{2M}) (2 + c_{3M}) \left(\frac{p_n}{\zeta_M} \right)^2 \\
& \quad + \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right],
\end{aligned}$$

$$\begin{aligned}
\kappa_{8M} &= \zeta_{1M} \zeta_{4M} (c_{1M} - c_{2M}) \left(\frac{p_n}{\zeta_M} \right)^2 \\
&+ \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \\
\kappa_{9M} &= \zeta_{2M} \zeta_{4M} (c_{1M} - c_{2M} c_{3M}) \left(\frac{p_n}{\zeta_M} \right)^2 \\
&+ \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right],
\end{aligned} \tag{7.19}$$

where γ_{iM} , ϑ_j ($i=2,3,4$; $j=1,2,3$) are given by Equations (2.22), (2.35), respectively. The coefficients η_{iM} , κ_{iM} , ρ_{iB} , $\rho_{iB}^{(\tau)}$ ($i=1,2$; $\tau=\varphi, v$) are given by Equation (6.18), respectively, where ζ_{iM} , ζ_M in Equation (6.18) are given by Equation (7.19). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.18), the coefficient ρ_M in Equation (2.33) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left(\zeta_{1M} + \zeta_{2M} x_{IN}^{c_{3M}} + \frac{\zeta_{4M}}{x_{IN}} \right), \tag{7.20}$$

Conditions $C_{1M} \neq 0$, $C_{3M} \neq 0$, $C_{4M} \neq 0$, $C_{2M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (7.5), (7.6), we get

$$\begin{aligned}
\varepsilon_{nM} &= -\frac{p_n}{\zeta_M} \left(\zeta_{1M} - \frac{2\zeta_{3M}}{x_n^3} \right), \\
\varepsilon_{\varphi M} &= \varepsilon_{\theta M} = -\frac{p_n}{\zeta_M} \left(\zeta_{1M} + \frac{\zeta_{3M}}{x_n^3} + \frac{\zeta_{4M}}{x_n} \right), \\
\varepsilon_{n\varphi M} &= s_{44M} \sigma_{n\varphi M} = \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right), \\
\varepsilon_{n\theta M} &= s_{44M} \sigma_{n\theta M} = \Theta \left[\frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \\
\sigma_{nM} &= \\
&- \frac{p_n}{\zeta_M} \left\{ \zeta_{1M} (c_{1M} - c_{2M}) - \frac{2\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} - \frac{2\zeta_{4M} c_{2M}}{x_n} \right\}, \\
\sigma_{\varphi M} &= \sigma_{\theta M} = \\
&- \frac{p_n}{\zeta_M} \left[\zeta_{1M} (c_{1M} - c_{2M}) + \frac{\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} + \frac{\zeta_{4M} c_{1M}}{x_n} \right], \\
\sigma_{1M} &= \eta_{1M} + \frac{\eta_{3M}}{x_n^3} + \frac{\eta_{4M}}{x_n},
\end{aligned}$$

$$\begin{aligned}
w_M &= \kappa_{1M} + \frac{\kappa_{3M}}{x_n^6} + \frac{\kappa_{4M}}{x_n^2} + \frac{\kappa_{6M}}{x_n^3} + \frac{\kappa_{8M}}{x_n} + \frac{\kappa_{10M}}{x_n^4}, \\
W_M &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{1M}}{3} (x_M^3 - x_{IN}^3) + \frac{\kappa_{3M}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) + \kappa_{4M} (x_M - x_{IN}) \right. \\
&\quad \left. + \kappa_{6M} \ln \left(\frac{x_M}{x_{IN}} \right) + \frac{\kappa_{8M}}{2} (x_M^2 - x_{IN}^2) + \kappa_{10M} \left(\frac{1}{x_{IN}} - \frac{1}{x_M} \right) \right] d\varphi dv, \\
\sigma_{nB} &= - \frac{\rho_{1B} p_n \zeta_{1M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{1B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) + \rho_{1B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \right] \\
&\quad + \frac{\rho_{3B} p_n \zeta_{3M}}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] \\
&\quad + \frac{\rho_{4B} p_n \zeta_{4M}}{\zeta_M} + \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \quad (7.21)
\end{aligned}$$

where Θ ; x_{IN} , x_M ; s_{44M} ; c_{iM} ; ρ_{jB} , $\rho_{jB}^{(\tau)}$ ($i=1,2,3$; $j=1,3,4$; $\tau=\varphi, v$) are given by Equations (1.8); (1.9); (2.13); (2.18); (6.9), (7.10); respectively. The coefficients ζ_{iM} , ζ_M , η_{4M} , κ_{jM} , ρ_{4B} , $\rho_{4B}^{(\tau)}$ ($i=1,3,4$; $j=4,5,8,9$; $k=1,2$; $\tau=\varphi, v$; see Equation (7.7)) have the forms

$$\begin{aligned}
\zeta_{1M} &= \frac{2}{x_M^3}, \quad \zeta_{3M} = 1, \quad \zeta_{4M} = -\frac{3}{x_M^2}, \\
\zeta_M &= \frac{2(c_{1M} - c_{2M})}{x_M^3} - \frac{2(c_{1M} + 2c_{3M})}{x_{IN}^3} + \frac{6c_{2M}}{x_{IN}x_M^2}, \\
\kappa_{6M} &= \frac{2}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{1M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right], \\
\kappa_{10M} &= \zeta_{3M} \zeta_{4M} (c_{1M} + 2c_{2M}) \left(\frac{p_n}{\zeta_M} \right)^2 \\
&\quad + \frac{1}{s_{44M}} \left[\frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right]. \quad (7.22)
\end{aligned}$$

The coefficients η_{iM} , κ_{iM} ($i=1,3$) and η_{4M} , κ_{4M} , κ_{8M} are given by Equations (6.18) and (7.19), respectively, where ζ_{jM} ($j=1,3,4$), ζ_M in Equations (6.18), (7.19) are given by Equation (7.22). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.21), the coefficient ρ_M in Equation (2.33) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left(\zeta_{1M} + \frac{\zeta_{3M}}{x_{IN}^3} + \frac{\zeta_{4M}}{x_{IN}} \right). \quad (7.23)$$

Conditions $C_{2M} \neq 0, C_{3M} \neq 0, C_{4M} \neq 0, C_{1M} = 0$. With regard to Equations (2.21), (2.26), (2.27), (2.30)–(2.32), (2.34), (7.5), (7.6), we get

$$\begin{aligned}
\varepsilon_{nM} &= -\frac{P_n}{\zeta_M} \left(\zeta_{2M} c_{3M} x_n^{c_{3M}-1} - \frac{2\zeta_{3M}}{x_n^3} \right), \\
\varepsilon_{\varphi M} = \varepsilon_{\theta M} &= -\frac{P_n}{\zeta_M} \left(\zeta_{2M} x_n^{c_{3M}-1} + \frac{\zeta_{3M}}{x_n^3} + \frac{\zeta_{4M}}{x_n} \right), \\
\varepsilon_{n\varphi M} = s_{44M} \sigma_{n\varphi M} &= \\
& x_n^{c_{3M}-1} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right), \\
\varepsilon_{n\theta M} = s_{44M} \sigma_{n\theta M} &= \\
& -\Theta \left[x_n^{c_{3M}-1} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \frac{1}{x_n^3} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \frac{1}{x_n} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \\
\sigma_{nM} &= -\frac{P_n}{\zeta_M} \left\{ \zeta_{2M} [(c_{1M} + c_{2M}) c_{3M} - 2c_{2M}] x_n^{c_{3M}-1} \right. \\
& \quad \left. - \frac{2\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} - \frac{2\zeta_{4M} c_{2M}}{x_n} \right\}, \\
\sigma_{\varphi M} = \sigma_{\theta M} &= \\
& -\frac{P_n}{\zeta_M} \left[\zeta_{2M} (c_{1M} - c_{2M} c_{3M}) x_n^{c_{3M}-1} + \frac{\zeta_{3M} (c_{1M} + 2c_{2M})}{x_n^3} + \frac{\zeta_{4M} c_{1M}}{x_n} \right], \\
\sigma_{1M} &= \eta_{2M} x_n^{c_{3M}-1} + \frac{\eta_{3M}}{x_n^3} + \frac{\eta_{4M}}{x_n}, \\
W_M &= \kappa_{2M} x_n^{2(c_{3M}-1)} + \frac{\kappa_{3M}}{x_n^6} + \frac{\kappa_{4M}}{x_n^2} + \kappa_{7M} x_n^{c_{3M}-4} + \kappa_{9M} x_n^{c_{3M}-1} + \frac{\kappa_{10M}}{x_n^4}, \\
W_M &= 4 \int_0^{\pi/2} \int_0^{\pi/2} \left[\frac{\kappa_{2M}}{2c_{3M}+1} (x_M^{2c_{3M}+1} - x_{IN}^{2c_{3M}+1}) + \frac{\kappa_{3M}}{3} \left(\frac{1}{x_{IN}^3} - \frac{1}{x_M^3} \right) \right. \\
& \quad \left. + \kappa_{4M} (x_M - x_{IN}) + \frac{\kappa_{7M}}{c_{3M}-1} (x_M^{c_{3M}-1} - x_{IN}^{c_{3M}-1}) \right. \\
& \quad \left. + \frac{\kappa_{9M}}{c_{3M}+2} (x_M^{c_{3M}+2} - x_{IN}^{c_{3M}+2}) + \kappa_{10M} \left(\frac{1}{x_{IN}} - \frac{1}{x_M} \right) \right] d\varphi dv, \\
\sigma_{nB} &= -\frac{\rho_{2B} P_n \zeta_{2M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{2B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) + \rho_{2B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \right] \\
& \quad - \frac{\rho_{3B} P_n \zeta_{3M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{3B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) + \rho_{3B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right] \\
& \quad - \frac{\rho_{4B} P_n \zeta_{4M}}{\zeta_M} - \frac{1}{s_{44M}} \left[\rho_{4B}^{(\varphi)} \frac{\partial}{\partial \varphi} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) + \rho_{4B}^{(v)} \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{4M}}{\zeta_M} \right) \right], \quad (7.24)
\end{aligned}$$

where Θ ; x_{IN} , x_M ; s_{44M} ; c_{iM} ; ρ_{jB} , $\rho_{jB}^{(\tau)}$ ($i=1,2,3$; $j=2,3,4$; $\tau = \varphi, v$) are given by

Equations (1.8); (1.9); (2.13); (2.18); (6.9), (7.10); respectively. The coefficients ζ_{iM} ($i=2,3,4$), ζ_M , κ_{7M} have the forms

$$\begin{aligned}\zeta_{2M} &= \frac{2}{x_M^3}, \quad \zeta_{3M} = c_{3M} x_M^{c_{3M}-1}, \quad \zeta_{4M} = - (2 + c_{3M}) x_M^{c_{3M}-3}, \\ \zeta_M &= \frac{2[(c_{1M} + c_{2M}) c_{3M} - 2 c_{2M}] x_{IN}^{c_{3M}-1}}{x_M^3} - \frac{2(c_{1M} + 2 c_{3M}) c_{3M} x_M^{c_{3M}-1}}{x_{IN}^3} \\ &\quad + \frac{2(c_{1M} + c_{3M}) c_{2M} x_M^{c_{3M}-3}}{x_{IN}}, \\ \kappa_{7M} &= \zeta_{2M} \zeta_{3M} [2 c_{2M} (1 - c_{3M}) - c_{1M}] \left(\frac{p_n}{\zeta_M} \right)^2 \\ &\quad + \frac{1}{s_{44M}} \left[\frac{\partial}{\partial \phi} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial \phi} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \Theta^2 \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{2M}}{\zeta_M} \right) \frac{\partial}{\partial v} \left(\frac{p_n \zeta_{3M}}{\zeta_M} \right) \right]. \quad (7.25)\end{aligned}$$

The coefficients η_{iM} , κ_{iM} ($i=2,3$); η_{4M} , κ_{4M} , κ_{9M} ; κ_{120M} ; are given by Equations (6.18); (7.19); (7.22), respectively, where ζ_{jM} ($j=1,3,4$), ζ_M in Equations (6.18), (7.19), (7.22) are given by Equation (7.25). The normal stress p_n is given by Equation (2.33). With regard to Equation (7.24), the coefficient ρ_M in Equation (2.33) is derived as

$$\rho_M = \frac{1}{\zeta_M} \left(\zeta_{2M} x_{IN}^{c_{3M}-1} + \frac{\zeta_{3M}}{x_{IN}^3} + \frac{\zeta_{4M}}{x_{IN}} \right), \quad (7.26)$$

Strengthening

The analytical model of the micro-strengthening $\sigma_{st} = \sigma_{st}(x_1)$ and the macro-strengthening $\overline{\sigma_{st}}$ results from the following analysis [3, 4, 12, 13, 21]. Figures 8.1 and 8.2 shows the plane $x'_2x'_3$ in the cubic cell (see Figure 1.2) for $x_1 \in \langle 0, a_1 \rangle$ and $x_1 \in \langle a_1, d/2 \rangle$, respectively, where $[x_1, x_2, x_3]$ are coordinates of the point $P \subset x'_2x'_3$. The plane $O'P_1P_2$ with the ellipse E_{23} (see Figure 8.2) represents a cross section of the ellipsoid inclusion in the plane $x'_2x'_3$. With regard to Figures (8.1), (8.2), the goniometric functions in Equations (1.8), (1.9) have the forms

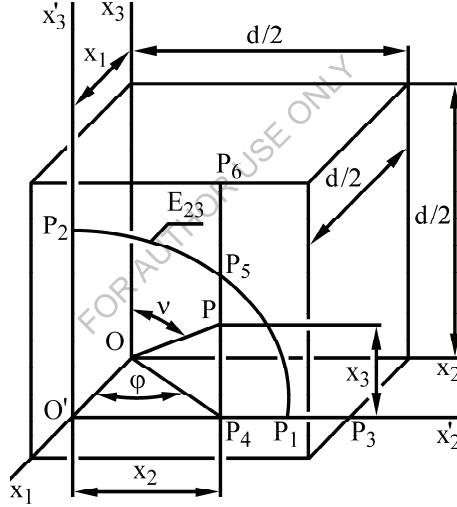


Figure 8.1: The plane $x'_2x'_3$ in the cubic cell (see Figure 1.2) for $x_1 \in \langle 0, a_1 \rangle$, where $[x_1, x_2, x_3]$ are coordinates of the point $P \subset x'_2x'_3$. The plane $O'P_1P_2$ with the ellipse E_{23} represents a cross section of the ellipsoid inclusion in the plane $x'_2x'_3$ (see Figure 1.2).

$$\sin \varphi = \frac{x_2}{\sqrt{x_1^2 + x_2^2}}, \quad \cos \varphi = \frac{x_1}{\sqrt{x_1^2 + x_2^2}}, \quad \tan \varphi = \frac{1}{\cot} = \frac{x_2}{x_1},$$

If $x_1 \in \langle 0, a_1 \rangle$, then the elastic energy surface density W_{st} , which is induced by σ_{st} and accumulated within the area $S_{IN} = \pi b_2 b_3 / 4$ of the plane $O'P_1P_2$ and within the area $S_M = (d/2)^2 - S_{IN}$ of the plane $x'_2x'_3$ (see Figure 8.1), has the form

$$W_{st} = \omega \sigma_{1st}^2, \quad (8.4)$$

where σ_{1st} is related to $x_1 \in \langle 0, a_1 \rangle$. The coefficient ω is derived as

$$\omega = \frac{1}{8} \left[\pi b_2 b_3 \left(\frac{1}{E_{IN}} - \frac{1}{E_M} \right) + \frac{d^2}{E_M} \right], \quad (8.5)$$

where E_{IN} and E_M is Young's modulus for the ellipsoidal inclusion and the matrix, respectively. The elastic energy surface density W_{1S} , which is induced by the stresses $\sigma_{1M} = \sigma_{1M}(x_1)$, $\sigma_{1MB} = \sigma_{1MB}(x_1)$ (see Equations (3.10), (4.10), (4.13), (4.16), (4.19), (5.9), (5.12), (5.15), (5.18), (6.8), (6.11), (6.14), (6.17), (7.9), (7.12), (7.15), (7.18), (7.21), (7.24)) and $\sigma_{1M} = \sigma_{1IN}(x_1)$, $\sigma_{1MB} = \sigma_{1INB}(x_1)$ (see Equations (3.14), (6.21)) has the form

$$\begin{aligned} W_{1S} &= \frac{1}{2} \left(\frac{W_{INS}}{E_{IN}} + \frac{W_{1MS}}{E_M} \right), \\ W_{INS} &= \int_0^{b_2} \left[\int_0^{b_4} \left(\sigma_{1IN}^2 + \sigma_{1INB}^2 \right) dx_3 \right] dx_2, \\ W_{1MS} &= \int_0^{b_2} \left[\int_{b_4}^{d/2} \left(\sigma_{1M}^2 + \sigma_{1MB}^2 \right) dx_3 \right] dx_2 \\ &\quad + \int_{b_2}^{d/2} \left[\int_0^{d/2} \left(\sigma_{1M}^2 + \sigma_{1MB}^2 \right) dx_3 \right] dx_2, \\ x_1 &\in \langle 0, a_1 \rangle. \end{aligned} \quad (8.6)$$

The micro-strengthening $\sigma_{1st} = \sigma_{1st}(x_1)$ for $x_1 \in \langle 0, a_1 \rangle$, which results from the condition $W_{st} = W_{1S}$ [3, 4, 12, 13, 21], is derived as

$$\sigma_{1st} = \sqrt{\frac{1}{2\omega} \left(\frac{W_{INS}}{E_{IN}} + \frac{W_{1MS}}{E_M} \right)}, \quad x_1 \in \langle 0, a_1 \rangle. \quad (8.7)$$

If $x_1 \in \langle a_1, d/2 \rangle$, then the elastic energy surface density W_{st} , which is induced by σ_{st} and accumulated within the area $S_M = d^2/4$ of the plane $x'_2x'_3$ (see Figure 8.2), has the form

$$W_{st} = \frac{\sigma_{2st}^2 d^2}{8 E_M}, \quad (8.8)$$

where σ_{2st} is related to $x_1 \in \langle a_1, d/2 \rangle$. Similarly, we get

$$W_{2S} = \frac{W_{2MS}}{2 E_M}, \quad W_{2MS} = \int_0^{d/2} \int_0^{d/2} (\sigma_{1M}^2 + \sigma_{1MB}^2) dx_2 dx_3, \quad x_1 \in \left\langle a_1, \frac{d}{2} \right\rangle. \quad (8.9)$$

With regard to the condition $W_{st} = W_{2S}$ [3, 4, 12, 13, 21], we get

$$\sigma_{2st} = \frac{2\sqrt{W_{2S}}}{d}. \quad (8.10)$$

Finally, the macro-strengthening $\overline{\sigma_{st}}$ is derived as [3, 4, 12, 13, 21]

$$\overline{\sigma_{st}} = \frac{2}{d} \left(\int_0^{a_1} \sigma_{1st} dx_1 + \int_{a_1}^{d/2} \sigma_{2st} dx_1 \right). \quad (8.11)$$

If $\alpha_{IN} < \alpha_M$ or $\alpha_{IN} > \alpha_M$, the strengthening exhibits a resistive effect against compressive or tensile mechanical loading, respectively.

The macro-strengthening $\overline{\sigma_{st}} = \overline{\sigma_{st}}(v, a_1, a_2, a_3)$ is a function of the inclusion volume fraction v_{IN} and the dimensions a_1, a_2, a_3 of the ellipsoidal inclusion. In case of a real inclusion-matrix composite, such values of the microstructural parameters v_{IN}, a_1, a_2, a_3 can be numerically determined to result in a maximum value of $|\overline{\sigma_{st}}|$.

Crack Formation

The analytical model of the crack formation in the matrix results from the following analysis [3, 4, 5, 19]–[22]. Figures 9.1, 9.3 show the ellipse E_{123} in the plane $x_{12}x_3$ of the cubic cell (see Figures (1.4), (1.5)), where $a_{12} = O4$, $x_{122} = O5$ are given by Equations (1.9), and $a_3 = O3$.

With regard to the plane $x_{12}x_3$ for $\varphi \in \langle 0, \pi/2 \rangle$ (see Figures 1.4, 1.5), the elastic energy density $w_Q = w_Q(x_n, \varphi, v)$ ($Q = IN, INB, M, MB$; see Equations (3.10), (3.14), (4.10), (4.13), (4.16), (4.19), (5.9), (5.12), (5.15), (5.18), (6.8), (6.11), (6.14), (6.17), (6.21), (7.9), (7.12), (7.15), (7.18), (7.21), (7.24)) is determined as a function of the coordinates $x_n, v \in \langle 0, \pi/2 \rangle$.

The elastic energy density $w_Q = w_Q(x_{12}, \varphi, x_3, a_1, a_2, a_3, v_{IN})$ ($Q = IN, INB, M, MB$) as a function of the coordinates x_{12}, x_3 is determined by the following transformations

$$x_n = \frac{x_3}{\cos \theta}, \quad \sin v = \frac{x_{12}}{\sqrt{x_{12}^2 + x_3^2}}, \quad \cos v = \frac{x_3}{\sqrt{x_{12}^2 + x_3^2}}, \quad \tan v = \frac{1}{\cot v} = \frac{x_{12}}{x_3}, \quad (9.1)$$

where $\cos \theta$ is given by Equation (1.6).

Matrix. The curve integral W_{cM} of $w_Q = w_Q(x_{12}, \varphi, x_3, a_1, a_2, a_3, v_{IN})$ ($Q = M, MB$) along the abscissa P_1P_2 (see Figure 9.1) in the plane $x_{12}x_3$ of the matrix (see Figures 1.4, 1.5) has the form

$$W_{cM} = \int_{P_1P_2} (w_M + w_{MB}) dx_3 = \int_0^{d/2} (w_M + w_{MB}) dx_3. \quad (9.2)$$

Let $f_{12M} = f_{12M}(x_{12}, \varphi, a_1, a_2, a_3, v_{IN})$ represent a decreasing function of the variable $x_{12} \in \langle a_{12}, x_{0M} \rangle$, which describe a shape of the matrix crack in the plane $x_{12}x_3$ (see Figure 1.4), where $\varphi \in \langle 0, \pi/2 \rangle$, a_1, a_2, a_3, v_{IN} are parameters of this decreasing function. As presented in [3, 4, 5, 19]–[22], we get

$$\frac{\partial f_{12M}}{\partial x_{12}} = - \frac{\sqrt{W_{cM}^2 - \vartheta_M^2}}{\vartheta_M}, \quad (9.3)$$

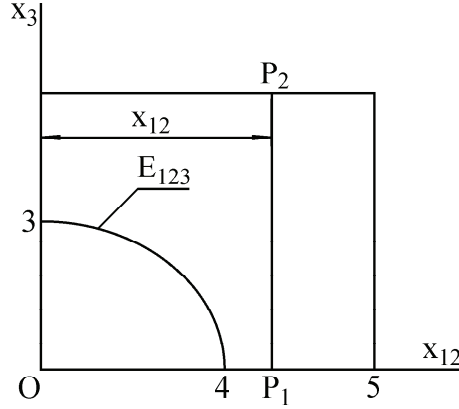


Figure 9.1: The ellipse E_{123} and the abscissa P_1P_2 in the plane $x_{12}x_3$ of the cubic cell (see Figures (1.4), (1.5)), where $a_{12} = O4$, $x_{122} = O5$ are given by Equation (1.9), and $a_3 = O3$.

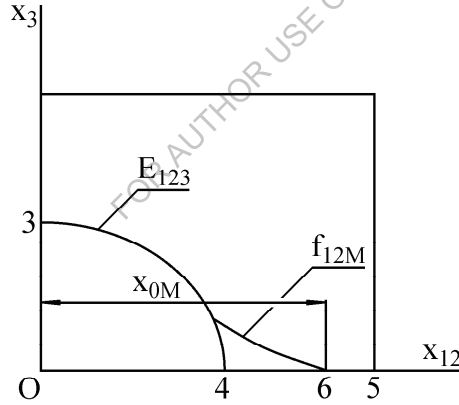


Figure 9.2: The decreasing function $f_{12M} = f_{12M}(x_{12}, \varphi, a_1, a_2, a_3, v_{IN})$ of the variable $x_{12} \in \langle a_{12}, x_{0M} \rangle$, which describes a shape of the matrix crack in the plane $x_{12}x_3$ (see Figure 1.4) for $a_{12} > a_{12M}^{(IC)}$ or $a_{12} > a_{12M}^{(TC)}$ (see Equations (9.8), (9.9)), where $x_{0M} = x_{0M}(\varphi)$ defines a position of the crack tip in the matrix, and $\varphi \in \langle 0, \pi/2 \rangle$, a_1 , a_2 , a_3 , v_{IN} are parameters of this decreasing function.

where ϑ_M is energy per unit length in the matrix. In case of intercrystalline crack formation, we get

$$\vartheta_M = \frac{K_{ICM}^2}{E_M}, \quad (9.4)$$

where K_{ICM} is fracture toughness of the matrix. In case of transcrystalline crack formation, we get

$$\vartheta_M = \vartheta_{gbM}, \quad (9.5)$$

where the energy ϑ_{gbM} per unit length is related to the inter-atomic bonding of boundaries of crystalline grain in the matrix.

As presented in [3, 4, 5, 19]–[22], the condition

$$(W_{cM})_{x_{12}=a_{12}} - \vartheta_M = 0, \quad (9.6)$$

is a transcendental equation with the variable a_{12} and the parameters $\varphi \in \langle 0, \pi/2 \rangle$, a_1, a_2, a_3, v_{IN} (see Figure 1.4).

The roots $a_{12M}^{(IC)} = a_{12M}^{(IC)}(\varphi, a_1, a_2, a_3, v_{IN})$ and $a_{12M}^{(TC)} = a_{12M}^{(TC)}(\varphi, a_1, a_2, a_3, v_{IN})$ (see Equation (1.7)) of Equation (9.3) for ϑ_M , which is given by Equations (9.4) and (9.5), represents such a dimension of the ellipsoidal inclusion along the axis $x_{12} \subset x_1x_2$ (see Figures 1.4, 1.5), which is critical with respect to the intercrystalline and transcrystalline crack formation in the plane x_1x_2 , respectively. Accordingly, if $a_{12M}^{(IC)} > a_{12M}^{(TC)}$ or $a_{12M}^{(IC)} < a_{12M}^{(TC)}$, then the intercrystalline or transcrystalline matrix crack is formed in the plane x_1x_2 , respectively.

Let the function $a_{12M}^{(X)} = a_{12M}^{(X)}(\varphi, a_1, a_2, a_3, v_{IN})$ ($X=IC, TC$) of the variable $\varphi \in \langle 0, \pi/2 \rangle$ exhibit the minimum $a_{minM}^{(X)}$ for $\varphi = \varphi_{minM}^{(X)}$. The critical dimension $a_{minM}^{(X)} = a_{minM}^{(X)}(a_1, a_2, a_3, v_{IN})$ ($X=IC, TC$) along the axis $x_{12} \subset x_1x_2$ (see Figures 1.4, 1.5) defines a limit state with respect to the formation of the intercrystalline matrix crack ($X=IC$) and the transcrystalline matrix crack ($X=TC$) in the plane x_1x_2 at the microstructural parameters a_1, a_2, a_3, v_{IN} (see Equation (1.1)). Accordingly, if $a_{12} > a_{12M}^{(X)}$ ($X=IC, TC$), the condition [3, 4, 5, 19]–[22]

$$W_{cM} - \vartheta_M = 0, \quad a_{12} > a_{12M}^{(X)}, \quad X = IC, TC \quad (9.7)$$

represents a transcendental equation with the variable x_{12} and with the root $x_{0M} = x_{0M}(\varphi, a_2, a_3, v_{IN})$, which defines a position of the crack tip in the matrix (see Figure 9.2). Consequently, the decreasing function $f_{12M} = f_{12M}(x_{12}, \varphi, a_1, a_2, a_3, v_{IN})$ with the variable $x_{12} \in \langle a_{12}, x_{0M} \rangle$ and with the parameters $\varphi \in \langle 0, \pi/2 \rangle$, a_1, a_2, a_3, v_{IN} (see Figures 1.4, 1.5), which describes a shape of the matrix crack in the plane $x_{12}x_3$ for $a_{12} > a_{12M}^{(X)}$ ($X=IC, TC$)), has the form [3, 4, 5, 19]–[22]

$$f_{12M} = \frac{1}{\vartheta_M} \left[C_M - \int \left(\sqrt{W_{cM}^2 - \vartheta_M^2} \right) dx_{12} \right], \quad x_{12} \in \langle a_{12}, x_{0M} \rangle, \quad (9.8)$$

where $C_M = C_M(\varphi, a_1, a_2, a_3, v_{IN})$ is derived as [3, 4, 5, 19]–[22]

$$C_M = \left[\int \left(\sqrt{W_{cM}^2 - \vartheta_M^2} \right) dx_{12} \right]_{x_{12}=x_{0M}}. \quad (9.9)$$

Inclusion. The curve integral W_{cIN} of $w_Q = w_Q(x_{12}, \varphi, x_3, a_1, a_2, a_3, v_{IN})$ ($Q = IN, INB$) along the abscissa P_1P_2 (see Figure 9.3) in the plane $x_{12}x_3$ of the ellipsoidal inclusion (see Figures 1.4, 1.5) has the form

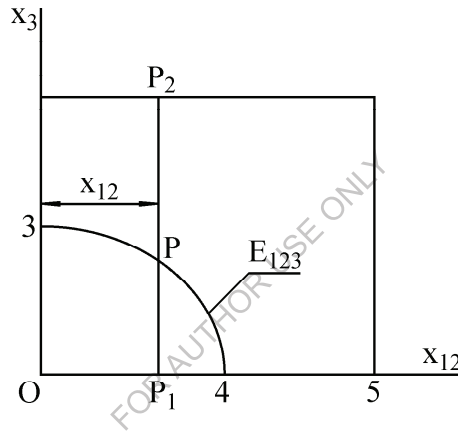


Figure 9.3: The ellipse E_{123} and the abscissa P_1PP_2 in the plane $x_{12}x_3$ of the cubic cell (see Figures (1.4), (1.5)), where $a_{12} = O4, x_{122} = O5$ are given by Equation (1.9), and $a_3 = O3$.

$$\begin{aligned} W_{cIN} &= \int_{P_1P} (w_{IN} + w_{INB}) dx_3 + \int_{PP_2} (w_M + w_{MB}) dx_3 \\ &= \int_0^{b_1} (w_{IN} + w_{INB}) dx_3 + \int_{b_1}^{d/2} (w_M + w_{MB}) dx_3, \end{aligned} \quad (9.10)$$

where $a_{12} = O4$ (see Equation (1.7)), $a_3 = O3$, and b_1 is derived as (see Equation (1.2))

$$b_1 = P_1 P = \frac{a_3 \sqrt{a_{12}^2 - x_{12}^2}}{a_{12}}, \quad x_{12} \in \langle 0, a_{12} \rangle. \quad (9.11)$$

With regard to the intercrystalline and transcrystalline inclusion cracks (see Figure 9.4), the sign '-' and the subscript M in Equations (9.3) and (9.3)–(9.7) are replaced by the sign '+' and the subscript IN , respectively.

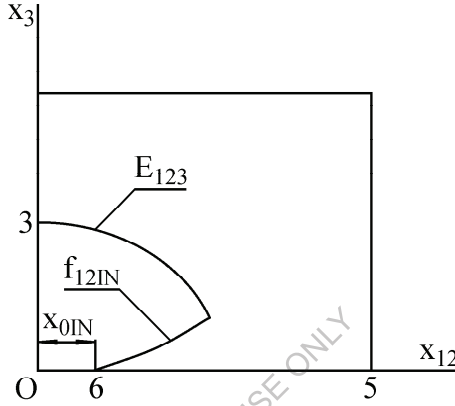


Figure 9.4: The increasing function $f_{12IN} = f_{12IN}(x_{12}, \varphi, a_1, a_2, a_3, v_{IN})$ of the variable $x_{12} \in \langle a_{12}, x_{0IN} \rangle$, which describes a shape of the inclusion crack in the plane $x_{12}x_3$ (see Figure 1.4) for $a_{12} > a_{12IN}^{(IC)}$ or $a_{12} > a_{12IN}^{(TC)}$ (see Equations (9.8), (9.9)), where $x_{0IN} = x_{0IN}(\varphi)$ defines a position of the crack tip in the inclusion, and $\varphi \in \langle 0, \pi/2 \rangle$ is a parameter of this increasing function.

Consequently, the increasing function $f_{12IN} = f_{12IN}(x_{12}, \varphi, a_1, a_2, a_3, v_{IN})$ with the variable $x_{12} \in \langle a_{12}, x_{0IN} \rangle$ and with the parameters $\varphi \in \langle 0, \pi/2 \rangle$, a_1 , a_2 , a_3 , v_{IN} (see Figures 1.4, 1.5), which describes a shape of the inclusion crack in the plane $x_{12}x_3$ for $a_{12} > a_{12IN}^{(IC)}$ or $a_{12} > a_{12IN}^{(TC)}$, has the form [3, 4, 5, 19]–[22]

$$f_{12IN} = \frac{1}{\vartheta_{IN}} \left[\int \left(\sqrt{W_{cIN}^2 - \vartheta_{IN}^2} \right) dx_{12} - C_{IN} \right], \quad x_{12} \in \langle a_{12}, x_{0IN} \rangle, \quad (9.12)$$

where $C_{IN} = C_{IN}(\varphi, a_1, a_2, a_3, v_{IN})$ is derived as [3, 4, 5, 19]–[22]

$$C_{IN} = \left[\int \left(\sqrt{W_{cIN}^2 - \vartheta_{IN}^2} \right) dx_{12} \right]_{x_{12}=x_{0IN}}. \quad (9.13)$$

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Appendix

Cramer's Rule. The system of n linear algebraic equations is derived as

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n &= b_1, \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n &= b_2, \\ \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \quad \quad \quad \vdots \\ a_{n1}x_1 + a_{n2}x_2 + \dots + a_{nn}x_n &= b_n. \end{aligned} \quad (10.1)$$

The root x_i ($i = 1, \dots, n$) is determined by Cramer's rule [23]

$$x_i = \frac{D_i^{(n)}}{D^{(n)}}, \quad i = 1, \dots, n, \quad (10.2)$$

where the determinant $D^{(n)}$ with n rows and n columns has the form

$$\begin{aligned} D^{(n)} &= \begin{vmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{vmatrix} \\ &= \sum_{i=1}^n (-1)^{1+i} a_{1i} D_{1i}^{(n-1)} = \sum_{i=1}^n (-1)^{1+i} a_{i1} D_{i1}^{(n-1)}. \end{aligned} \quad (10.3)$$

The subdeterminant $D_i^{(n)}$ is created from $D^{(n)}$, i.e., the i -th column of $D^{(n)}$ is replaced by

$$\left. \begin{matrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{matrix} \right\} n \text{ rows.} \quad (10.4)$$

Similarly, the subdeterminant $D_{ij}^{(n-1)}$ ($i, j = 1, \dots, n$) with $(n-1)$ rows and $(n-1)$ columns is created from $D^{(n)}$, i.e., the i -th row and the j -th column of $D^{(n)}$ are omitted. If $n = 2$, then we get

$$D^{(2)} = \begin{vmatrix} a_{11}, & a_{12} \\ a_{21}, & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21}. \quad (10.5)$$

Consequently, if $n = 3$, then we get

$$\begin{aligned} D^{(4)} &= \begin{vmatrix} a_{11}, & a_{12}, & a_{13} \\ a_{21}, & a_{22}, & a_{23} \\ a_{31}, & a_{32}, & a_{33} \end{vmatrix} \\ &= a_{11} \begin{vmatrix} a_{22}, & a_{23} \\ a_{32}, & a_{33} \end{vmatrix} - a_{12} \begin{vmatrix} a_{21}, & a_{23} \\ a_{31}, & a_{33} \end{vmatrix} + a_{13} \begin{vmatrix} a_{21}, & a_{22} \\ a_{31}, & a_{32} \end{vmatrix}. \end{aligned} \quad (10.6)$$

Integrals. The derivatives of the functions $f = x^\lambda$, $f = \ln x$ and the constant C are derived as [23]

$$\left(x^\lambda\right)' = \lambda x^{\lambda-1}, \quad (\ln x)' = \frac{1}{x}, \quad C' = 0, \quad (10.7)$$

The indefinite integrals of $f = x^\lambda$, $f = \ln x$ and the constant C have the forms [23]

$$\int x^\lambda dx = \frac{x^{\lambda+1}}{\lambda+1}, \quad \lambda \neq -1; \quad \int \frac{dx}{x} = \ln x, \quad \int C dx = Cx. \quad (10.8)$$

In case of the product fg of the functions $f = f(x)$, $g = g(x)$, we get [23]

$$(fg)' = f'g + fg'. \quad (10.9)$$

and then the integral of fg has the form [23]

$$\int f'g dx = fg - \int fg' dx. \quad (10.10)$$

With regard to Equation (10.17), the following integrals are derived as [23]

$$\begin{aligned} \int x^\lambda \ln x dx &= \frac{x^{\lambda+1}}{\lambda+1} \ln x - \int \frac{x^{\lambda+1}}{\lambda+1} \times \frac{1}{x} dx = \frac{x^{\lambda+1}}{\lambda+1} \ln x - \frac{1}{\lambda+1} \int x^\lambda dx \\ &= \frac{x^{\lambda+1}}{\lambda+1} \left(\ln x - \frac{1}{\lambda+1} \right), \quad \lambda \neq -1, \\ \int \ln x dx &= \int 1 \times \ln x dx = x \ln x - \int x \times \frac{1}{x} dx = x \ln x - \int 1 \times dx = x(\ln x - 1), \\ \int x^\lambda \ln^2 x dx &= \frac{1}{\lambda+1} \left[x^{\lambda+1} \ln^2 x - 2 \int x^\lambda \ln x dx \right] \end{aligned}$$

$$= \frac{x^{\lambda+1}}{\lambda+1} \left[\left(\ln x - \frac{1}{\lambda+1} \right)^2 + \frac{1}{(\lambda+1)^2} \right], \quad \lambda \neq -1. \quad (10.11)$$

Let $F = F(x)$ be a primitive function of $f = f(x)$ in the interval $x \in \langle a, b \rangle$, i.e., $f = dF/dx$. The definite integral $\int_a^b f dx$ is defined by Newton-Leibniz's formula [23], which has the form

$$\int_a^b f dx = F(b) - F(a). \quad (10.12)$$

Wronskian's Method. The differential equation (4.3) with a non-zero right-hand side [23] is derived as

$$\frac{\partial^2 u_n}{\partial x^2} + \frac{2}{x_n} \frac{\partial u_n}{\partial x_n} - \frac{2u_n}{x_n^2} = g, \quad g = \sum_{i=1}^3 C_i x^{\kappa_i-2}, \quad (10.13)$$

where the integration constants C_1, C_2, C_3 are determined by the boundary conditions in Section 2.3. If $g = 0$, we get

$$\frac{\partial^2 u_n}{\partial x^2} + \frac{2}{x_n} \frac{\partial u_n}{\partial x_n} - \frac{2u_n}{x_n^2} = 0. \quad (10.14)$$

If $u_n = x^\lambda$, then the solutions u_{1n}, u_{2n} of Equation (10.24) have the forms

$$u_{1n} = x_n, \quad u_{2n} = \frac{1}{x_n^2}. \quad (10.15)$$

The solution u_n of Equation (10.22) is derived as [23]

$$u_n = \sum_{i=1}^2 a_i u_{in}, \quad a_i = \int \frac{W_i^{(2)}}{W^{(2)}} dx_n, \quad i = 1, 2. \quad (10.16)$$

Wronskian's determinants $W^{(2)}, W_i^{(2)}$ ($i=1,2$) with 2 rows and 2 columns are have the forms [23]

$$W^{(2)} = \begin{vmatrix} u_{1n} & u_{2n} \\ \frac{\partial u_{1n}}{\partial x_n} & \frac{\partial u_{2n}}{\partial x_n} \end{vmatrix}, \quad W_1^{(2)} = \begin{vmatrix} 0 & u_{2n} \\ g & \frac{\partial u_{2n}}{\partial x_n} \end{vmatrix}, \quad W_2^{(2)} = \begin{vmatrix} u_{1n} & 0 \\ \frac{\partial u_{1n}}{\partial x_n} & g \end{vmatrix}. \quad (10.17)$$

The determinant $W_i^{(2)}$ ($i=1,2$) is created from $W^{(2)}$, i.e., the i -th column of $W^{(2)}$ is replaced by the following one [23]

$$\left. \begin{array}{c} 0 \\ g \end{array} \right\} 2 \text{ rows.} \quad (10.18)$$

Let f_1, \dots, f_n represent n solutions of a differential equation of the n -th rank with zero right-hand side. Let the functions f_1, \dots, f_n of the variable x exhibit continuous derivatives to the $(n-1)$ -th degree. The solution of this differential equation with a non-zero right-hand side (i.e., $g \neq 0$) is derived as [23]

$$f = \sum_{i=1}^n a_i f_i, \quad a_i = \int \frac{W_i^{(n)}}{W^{(n)}} dx. \quad (10.19)$$

With respect to f_1, \dots, f_n , Wronskian's determinant $W^{(n)}$ ($i = 1, \dots, n$) with n rows and n columns have the form [23]

$$W^{(n)} = \begin{vmatrix} f_1, & f_2, & \dots & f_n \\ \frac{\partial f_1}{\partial x}, & \frac{\partial f_2}{\partial x}, & \dots & \frac{\partial f_n}{\partial x} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^{n-1} f_1}{\partial x^{n-1}}, & \frac{\partial^{n-1} f_2}{\partial x^{n-1}}, & \dots & \frac{\partial^{n-1} f_n}{\partial x^{n-1}} \end{vmatrix}, \quad (10.20)$$

where $W_i^{(n)}$ ($i = 1, \dots, n$) with n rows and n columns is created from $W^{(n)}$, i.e., the i -th column of $W^{(n)}$ is replaced by the following one [23]

$$\left. \begin{array}{c} 0 \\ 0 \\ \vdots \\ g \end{array} \right\} n \text{ rows.} \quad (10.21)$$

Numerical Determination. Numerical values of the thermal stresses in a real matrix-inclusion composite include integrals and derivatives, which are determined by a programming language. If $f = f(x)$, then a numerical value of the derivative $\partial f / \partial x$ is determined by [23]

$$\frac{\partial f}{\partial x} \approx \frac{f(x + \Delta x) - f(x)}{\Delta x}. \quad (10.22)$$

In case of the angles φ, ν (see Figure 1.4), the step $\Delta x = \Delta \varphi = \Delta \nu = 10^{-6}$ [deg] is sufficient [3, 4, 5, 19]–[22].

Let F represent a definite integral of the function $f = f(\varphi, \nu)$ with the variables $\varphi, \nu \in \langle 0, \pi/2 \rangle$. Let n, m be integral parts of the real numbers $\pi / (2\Delta\varphi), \pi / (2\Delta\nu)$

[3, 4, 5, 19]–[22], respectively. Numerical values of the definite integral F are determined by the following formula [23], [3, 4, 5, 19]–[22]

$$F = \int_0^{\pi/2} \int_0^{\pi/2} f(\varphi, \nu) d\varphi d\nu \approx \sum_{j=0}^m \left(\sum_{i=0}^n f(i \times \Delta\varphi; j \times \Delta\nu) \Delta\varphi \right) \Delta\nu, \quad (10.23)$$

where the steps $\Delta\varphi = \Delta\nu = 0.1$ [deg] are sufficient. Finally, the average numerical value \bar{f} of the function $f = f(\varphi, \nu)$ with the variables $\varphi, \nu \in \langle 0, \pi/2 \rangle$ is determined by the following formula [23]

$$\bar{f} = \left(\frac{2}{\pi} \right)^2 \int_0^{\pi/2} \int_0^{\pi/2} f(\varphi, \nu) d\varphi d\nu \approx \left(\frac{2}{\pi} \right)^2 \sum_{j=0}^m \left(\sum_{i=0}^n f(i \times \Delta\varphi; j \times \Delta\nu) \Delta\varphi \right) \Delta\nu. \quad (10.24)$$

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Index

- analytical model, 11, 77, 81
- boundary conditions, 12, 13, 17, 23, 26, 37, 40, 53, 55, 65, 67, 89
- Cartesian system, 3–7, 9
- Cauchy's equations, 9
- cell matrix, 8, 10, 12, 13
- coordinate system, 1
- coordinates, 4, 5, 8, 77, 78
- crack formation, 1, 2, 81
- derivative, 90
- differential equation, 12, 53, 89, 90
- dual-phase steel, 1
- elastic continuum, 1
- elastic energy, 1, 12, 15, 26, 40, 55, 67
- elastic energy density, 12
- ellipse, 4–6, 77, 78
- equilibrium equations, 9
- Hooke's law, 9, 10
- inclusion, 1, 3–6, 8, 10, 12, 13, 15, 21, 25, 40, 62, 66, 67
- integral, 25, 40, 88–90
- integration constant, 12, 17, 23, 26, 37, 40, 53, 54, 65, 67, 89
- martensitic steel, 1
- mathematical boundary conditions, 14
- mathematical model, 1
- mathematical procedure, 2, 12, 15, 17, 23, 37, 65
- mathematical solution, 1, 12, 15, 17, 23, 26, 37, 40, 67, 89, 90
- matrix, 1, 3, 7, 8, 13, 15, 26, 40, 54, 67
- matrix-inclusion boundary, 7, 13, 91
- matrix-inclusion composite, 1–3, 90
- model system, 1, 3, 5, 7
- normal strain, 9
- normal stress, 13, 15, 20, 22, 29, 31, 33, 35, 43, 49, 52, 56, 58, 60, 62, 63, 68, 70, 71, 73, 74, 76
- Poisson's ratio, 10
- radial displacement, 14
- shear strain, 9
- shear stress, 10
- strengthening, 1, 2, 77, 80
- superposition method, 1, 14
- tangential strain, 9
- tangential stress, 10
- thermal stress, 1, 3–5, 7, 9, 15, 90
- thermal-stress-field interaction, 1
- Wronskian's determinant, 89, 90
- Wronskian's method, 17, 23, 37, 89
- Young's modulus, 10

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