

Constitutive modeling for laminates with fiber/matrix interface cracks under transverse loading

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Abstract

Keywords: Fiber Reinforced Polymer Composite (FRPC), Debonding, Constitutive modeling, Finite element analysis (FEA)

1. Introduction

Review damage characterization [1, 2, 3]

Shear-lag [4]

Stress-transfer [5, 6]

5 Stress-based variational [7, 8, 9]+angle ply [9]

Displacement-based variational [10]

Self-consistent approach [11]

Finite strip approach [12]

Continuum damage mechanics [13, 14, 15]

10 Discrete damage mechanics [16]

Cylindrical model [17]

Reissner mixed variational principle [18]

Development of glob-loc model [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]

2. Derivation of constitutive relations

15 *2.1. Reference frames*

Local reference frame of k -th layer: index 1 is the in-plane longitudinal or fiber or 0° -direction; index 2 is the in-plane transverse or 90° -direction; index 3 is the out-of-plane or through-the-thickness direction.

Global reference frame of laminate: index x is the in-plane longitudinal
 20 or laminate 0° direction; index y is the in-plane transverse direction; index
 z is the out-of-plane or through-the-thickness direction.

2.2. Crack density

Scalar and tensor crack density [33, 34, 35, 36]

Scalar density Normalized volume of cracks V_{an} is the ratio of cracked volume
 25 V_a to material volume V

$$V_{an} = \frac{V_a}{V} \quad (1)$$

V_a is equal to the product of total crack surface S_C and average crack
 opening u_a

$$V_{an} = \frac{S_C u_a}{V} = \frac{S_C}{V} u_a = \rho_C u_a \quad (2)$$

The ratio $\frac{S_C}{V}$ has a size of $\frac{1}{length}$ and correspond to the crack density ρ_C .
 It means: product of crack density and average crack opening is equal to
 30 normalized volume of cracks.

Applying the previous Principle to debonds, we have:

$$\begin{aligned} \rho_D &= \frac{\text{total area of debonds}}{\text{total layer volume}} = \frac{n_D w R_f \Delta \theta}{L_{lam} w t_{90^\circ}} = \frac{n_D \cancel{w} R_f \Delta \theta}{L_{lam} \cancel{w} t_{90^\circ}} = \frac{1}{n 2L} \frac{1}{k 2L} R_f \Delta \theta = \\ &= \frac{1}{nk 4L^2} R_f \Delta \theta = \frac{V_f}{nk \pi R_f^2} R_f \Delta \theta = \frac{V_f}{nk R_f} \frac{\Delta \theta}{\pi} \end{aligned} \quad (3)$$

Second-order tensor density

Fourth-order tensor density

2.3. Homogenization

$$\sigma_{ij}^{avg} = \frac{1}{V} \int_V \sigma_{ij} dV \quad \varepsilon_{ij}^{avg} = \frac{1}{V} \int_V \varepsilon_{ij} dV \quad (4)$$

$$\underline{\tilde{\sigma}}_k^{avg} = \underline{\tilde{Q}}_k (\underline{\tilde{\varepsilon}}_k^{avg} - \underline{\tilde{\alpha}}_k \Delta T) \quad (5)$$

$$\underline{\tilde{\sigma}}_{LAM} = \underline{\tilde{\sigma}}^{avg} = \frac{1}{V} \int_V \underline{\tilde{\sigma}} dV = \frac{1}{V} \sum_{k=1}^N \int_{V_k} \underline{\tilde{\sigma}} dV_k = \sum_{k=1}^N \underline{\tilde{\sigma}}_k^{avg} \frac{t_k}{h} \quad (6)$$

$$\varepsilon_{ij}^{avg} = \frac{1}{V} \int_V \varepsilon_{ij} dV = \frac{1}{V} \int_V \frac{1}{2} (u_{i,j} + u_{j,i}) dV = \frac{1}{V} \int_S \frac{1}{2} (u_i n_j + u_j n_i) dS \quad (7)$$

$$\begin{aligned} \varepsilon_{ij}^{avg} &= \frac{1}{V} \int_S \frac{1}{2} (u_i n_j + u_j n_i) dS = \\ &= \frac{1}{V} \int_{S_B} \frac{1}{2} (u_i n_j + u_j n_i) dS + \frac{1}{V} \int_{S_C} \frac{1}{2} (u_i n_j + u_j n_i) dS = \\ &= \varepsilon_{ij}^{applied} + \beta_{ij} \end{aligned} \quad (8)$$

$$\underline{\tilde{\varepsilon}}_k^{avg} = \underline{\tilde{\varepsilon}}_k^{applied} + \underline{\tilde{\beta}}_k = \underline{\tilde{\varepsilon}}_k^{LAM} + \underline{\tilde{\beta}}_k \quad (9)$$

$$\underline{\tilde{\sigma}}_{LAM} = \frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \left(\underline{\tilde{\varepsilon}}_k^{LAM} - \underline{\tilde{\alpha}}_k \Delta T + \underline{\tilde{\beta}}_k \right) \quad (10)$$

$$\underline{\tilde{\sigma}}_{LAM} = \underline{Q}_{eff}^{LAM} \underline{\tilde{\varepsilon}}^{LAM} \quad (11)$$

$$\underline{Q}_{eff}^{LAM} \underline{\tilde{\varepsilon}}^{LAM} = \left(\frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \right) \underline{\tilde{\varepsilon}}^{LAM} + \frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \underline{\tilde{\beta}}_k \quad (12)$$

$$\underline{Q}_{eff}^{LAM} \underline{\tilde{\varepsilon}}^{LAM} \cdot \frac{\underline{\tilde{\varepsilon}}^{LAM}}{\underline{\tilde{\varepsilon}}^{LAM} \cdot \underline{\tilde{\varepsilon}}^{LAM}} = \left(\frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \right) \underline{\tilde{\varepsilon}}^{LAM} \cdot \frac{\underline{\tilde{\varepsilon}}^{LAM}}{\underline{\tilde{\varepsilon}}^{LAM} \cdot \underline{\tilde{\varepsilon}}^{LAM}} + \left(\frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \underline{\tilde{\beta}}_k \right) \cdot \frac{\underline{\tilde{\varepsilon}}^{LAM}}{\underline{\tilde{\varepsilon}}^{LAM} \cdot \underline{\tilde{\varepsilon}}^{LAM}} \quad (13)$$

$$\underline{Q}_{eff}^{LAM} = \left(\frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \right) + \frac{1}{h} \sum_{k=1}^N t_k \underline{\tilde{Q}}_k \frac{\underline{\tilde{\beta}}_k \cdot \underline{\tilde{\varepsilon}}^{LAM}}{\underline{\tilde{\varepsilon}}^{LAM} \cdot \underline{\tilde{\varepsilon}}^{LAM}} \quad (14)$$

$$\underline{T}_k = \begin{bmatrix} \cos^2(\theta_k) & \sin^2(\theta_k) & 2\cos(\theta_k)\sin(\theta_k) \\ \sin^2(\theta_k) & \cos^2(\theta_k) & -2\cos(\theta_k)\sin(\theta_k) \\ -\cos(\theta_k)\sin(\theta_k) & \cos(\theta_k)\sin(\theta_k) & \cos^2(\theta_k) - \sin^2(\theta_k) \end{bmatrix} \quad (15)$$

$$\tilde{Q}_{\underline{k}} = \underline{T}_k^{-1} Q_{\underline{k}} \left(\underline{T}_k^{-1} \right)^T \quad (16)$$

$$\begin{aligned} Q_{eff}^{LAM} &= \left(\frac{1}{h} \sum_{k=1}^N t_k \underline{T}_k^{-1} Q_{\underline{k}} \left(\underline{T}_k^{-1} \right)^T \right) + \frac{1}{h} \sum_{k=1}^N t_k \underline{T}_k^{-1} Q_{\underline{k}} \left(\underline{T}_k^{-1} \right)^T \frac{\underline{T}_k^{-1} \tilde{\beta}_k \left(\underline{T}_k^{-1} \right)^T \cdot \tilde{\varepsilon}^{LAM}}{\tilde{\varepsilon}^{LAM} \cdot \tilde{\varepsilon}^{LAM}} = \\ &= \frac{1}{h} \sum_{k=1}^N t_k \underline{T}_k^{-1} Q_{\underline{k}} \left(\underline{T}_k^{-1} \right)^T \left(1 + \frac{\underline{T}_k^{-1} \tilde{\beta}_k \left(\underline{T}_k^{-1} \right)^T \cdot \tilde{\varepsilon}^{LAM}}{\tilde{\varepsilon}^{LAM} \cdot \tilde{\varepsilon}^{LAM}} \right) \end{aligned} \quad (17)$$

$$Q_{eff,lmij}^{LAM} \tilde{\varepsilon}_{ij}^{LAM} = \left(\frac{1}{h} \sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \right) \tilde{\varepsilon}_{ij}^{LAM} + \frac{1}{h} \sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \tilde{\beta}_{k,ij} \quad (18)$$

$$Q_{eff,lmij}^{LAM} \tilde{\varepsilon}_{ij}^{LAM} \left(\tilde{\varepsilon}_{ij}^{LAM} \right)^{-1} = \left(\frac{1}{h} \sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \right) \tilde{\varepsilon}_{ij}^{LAM} \left(\tilde{\varepsilon}_{ij}^{LAM} \right)^{-1} + \frac{1}{h} \left(\sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \tilde{\beta}_{k,ij} \right) \left(\tilde{\varepsilon}_{ij}^{LAM} \right)^{-1} \quad (19)$$

$$Q_{eff,lmij}^{LAM} = \left(\frac{1}{h} \sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \right) + \frac{1}{h} \sum_{k=1}^N t_k \left(\tilde{Q}_{k,lmij} \tilde{\beta}_{k,ij} \left(\tilde{\varepsilon}_{ij}^{LAM} \right)^{-1} \right) \quad (20)$$

$$Q_{eff,lmij}^{LAM} = \frac{1}{h} \sum_{k=1}^N t_k \tilde{Q}_{k,lmij} \left(\frac{1}{2} (\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk}) + \tilde{\beta}_{k,ij} \left(\tilde{\varepsilon}_{ij}^{LAM} \right)^{-1} \right) \quad (21)$$

$$\begin{aligned} Q_{eff,lmij}^{LAM} &= \\ &= \frac{1}{h} \sum_{k=1}^N t_k \underline{T}_{k,l m r s}^{-1} Q_{k,r s p q} \left(\underline{T}_k^{-1} \right)_{p q i j}^T \left(\frac{1}{2} (\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk}) + \underline{T}_{k,i p}^{-1} \tilde{\beta}_{k,p q} \left(\underline{T}_k^{-1} \right)_{q j}^T \underline{T}_{k,l m r s}^{-1} \left(\tilde{\varepsilon}_{p q}^{LAM} \right)^{-1} \left(\underline{T}_k^{-1} \right)_{q j}^T \right) \end{aligned} \quad (22)$$

35 *2.4. Exact expression of the Vakulenko-Kachanov tensor*

In the local reference frame of k -th layer, the outer normal at crack faces has components:

$$n_1 = 0 \quad n_2 \neq 0 \quad n_3 \neq 0 \quad (23)$$

while crack face displacement has components:

$$u_1 = 0 \quad u_2 \neq 0 \quad u_3 \neq 0 \quad (24)$$

Definition of Vakulenko-Kachanov tensor:

$$\beta_{ij} = \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_i n_j + u_j n_i) dS \quad (25)$$

40 Expand the expression for each component and simplify based on the fact that $u_1 = 0$:

$$\begin{aligned} \beta_{11} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_1 n_1 + u_1 n_1) dS = \frac{1}{V_k} \int_{S_C} \mathbf{u}_1^0 n_1 dS = 0 \\ \beta_{22} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_2 n_2 + u_2 n_2) dS = \frac{1}{V_k} \int_{S_C} u_2 n_2 dS \\ \beta_{33} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_3 n_3 + u_3 n_3) dS = \frac{1}{V_k} \int_{S_C} u_3 n_3 dS \\ \beta_{12} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (\mathbf{u}_1^0 n_2 + u_2 \mathbf{u}_1^0) dS = 0 \\ \beta_{13} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (\mathbf{u}_1^0 n_3 + u_3 \mathbf{u}_1^0) dS = 0 \\ \beta_{23} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_2 n_3 + u_3 n_2) dS \\ \beta_{21} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_2 \mathbf{u}_1^0 + \mathbf{u}_1^0 n_2) dS = 0 \\ \beta_{31} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_3 \mathbf{u}_1^0 + \mathbf{u}_1^0 n_3) dS = 0 \\ \beta_{32} &= \frac{1}{V_k} \int_{S_C} \frac{1}{2} (u_3 n_2 + u_2 n_3) dS = \beta_{23} \end{aligned} \quad (26)$$

Only 3 independent components of the tensor β_{ij} remain: β_{22} , β_{33} and β_{23} . Split total crack surface S_C into total matrix crack surface S_C^m and total fiber

crack surface S_C^f and remember that $n_i^f = -n_i^m$ for $i = 2, 3$

$$\begin{aligned}
\beta_{22} &= \frac{1}{V_k} \int_{S_C} u_2 n_2 dS = \frac{1}{V_k} \left[\int_{S_C^m} u_2^m n_2^m dS + \int_{S_C^f} u_2^f n_2^f dS \right] = \\
&= \frac{1}{V_k} \left[\int_{S_C^m} u_2^m n_2^m dS + \int_{S_C^f} u_2^f (-n_2^m) dS \right] \\
\beta_{33} &= \frac{1}{V_k} \int_{S_C} u_3 n_3 dS = \frac{1}{V_k} \left[\int_{S_C^m} u_3^m n_3^m dS + \int_{S_C^f} u_3^f n_3^f dS \right] = \\
&= \frac{1}{V_k} \left[\int_{S_C^m} u_3^m n_3^m dS + \int_{S_C^f} u_3^f (-n_3^m) dS \right] \\
\beta_{23} &= \frac{1}{V_k} \int_{S_C} (u_2 n_3 + u_3 n_2) dS = \\
&= \frac{1}{V_k} \left[\int_{S_C^m} (u_2^m n_3^m + u_3^m n_2^m) dS + \int_{S_C^f} (u_2^f n_3^f + u_3^f n_2^f) dS \right] = \\
&= \frac{1}{V_k} \left[\int_{S_C^m} u_2^m n_3^m dS + \int_{S_C^f} u_2^f (-n_3^m) dS + \int_{S_C^m} u_3^m n_2^m dS + \int_{S_C^f} u_3^f (-n_2^m) dS \right] \\
&\hspace{15em} (27)
\end{aligned}$$

45 The total matrix debonded surface S_C^m is equal to the total fiber debonded surface S_C^f and equal to:

$$S_C^m = S_C^f = n_D R_f \Delta \theta \quad (28)$$

With Eq. 28, we can recast Eq. 27 as

$$\begin{aligned}
\beta_{22} &= \frac{1}{V_k} \left[n_D R_f w \int_0^{\Delta\theta} (u_2^m - u_2^f) n_2^m d\theta \right] = \\
&= \frac{1}{L_{lam} w t_{90^\circ}} \left[n_D R_f w \int_0^{\Delta\theta} (u_2^m - u_2^f) n_2^m d\theta \right] = \\
&= \frac{1}{L_{lam}} \frac{n_D R_f}{t_{90^\circ}} \left[\int_0^{\Delta\theta} (u_2^m - u_2^f) n_2^m d\theta \right] = \\
&= \rho_D \left[\frac{1}{\Delta\theta} \int_0^{\Delta\theta} (u_2^m - u_2^f) n_2^m d\theta \right] \\
\beta_{33} &= \rho_D \left[\frac{1}{\Delta\theta} \int_0^{\Delta\theta} (u_3^m - u_3^f) n_3^m d\theta \right] \\
\beta_{23} &= \rho_D \left[\frac{1}{\Delta\theta} \int_0^{\Delta\theta} (u_2^m - u_2^f) n_3^m d\theta + \frac{1}{\Delta\theta} \int_0^{\Delta\theta} (u_3^m - u_3^f) n_2^m d\theta \right]
\end{aligned} \tag{29}$$

We can express the displacement jumps at the interface as a function of the local Crack Opening Displacement (COD) and Crack Sliding Displacement
50 (CSD) as

$$\begin{aligned}
u_2^m - u_2^f &= (u_r^m - u_r^f) \cos(\theta) - (u_\theta^m - u_\theta^f) \sin(\theta) = \\
&= COD(\theta) \cos(\theta) - CSD(\theta) \sin(\theta) \\
u_3^m - u_3^f &= (u_r^m - u_r^f) \sin(\theta) + (u_\theta^m - u_\theta^f) \cos(\theta) = \\
&= COD(\theta) \sin(\theta) + CSD(\theta) \cos(\theta)
\end{aligned} \tag{30}$$

where θ is the local angular coordinate at the interface. We can similarly express n_2^m and n_3^m as a function of θ :

$$\begin{aligned}
n_2^m &= \cos(\theta) - \sin(\theta) \\
n_3^m &= \sin(\theta) + \cos(\theta)
\end{aligned} \tag{31}$$

Thus, Eq. 29 becomes

$$\begin{aligned}
\beta_{22} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} [COD(\theta) (\cos^2(\theta) - \cos(\theta) \sin(\theta)) - CSD(\theta) (\sin(\theta) \cos(\theta) - \sin^2(\theta))] d\theta = \\
&= \rho_D \frac{1}{2\Delta\theta} \int_0^{\Delta\theta} [COD(\theta) (1 + \cos(2\theta) - \sin(2\theta)) + CSD(\theta) (1 - \cos(2\theta) - \sin(2\theta))] d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 - \sin(2\theta)) + \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta \\
\beta_{33} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} [COD(\theta) (\sin(\theta) \cos(\theta) + \sin^2(\theta)) + CSD(\theta) (\cos^2(\theta) + \cos(\theta) \sin(\theta))] d\theta = \\
&= \rho_D \frac{1}{2\Delta\theta} \int_0^{\Delta\theta} [COD(\theta) (1 + \sin(2\theta) - \cos(2\theta)) + CSD(\theta) (1 + \sin(2\theta) + \cos(2\theta))] d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 + \sin(2\theta)) - \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta \\
\beta_{23} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD(\theta) (2 \sin(\theta) \cos(\theta) + \cos^2(\theta) - \sin^2(\theta)) + \\
&\quad - \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} CSD(\theta) (\sin^2(\theta) - \cos^2(\theta) + 2 \cos(\theta) \sin(\theta)) d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} 2 \left[\frac{COD(\theta) + CSD(\theta)}{2} \cos(2\theta) + \frac{COD(\theta) - CSD(\theta)}{2} \sin(2\theta) \right] d\theta \\
&\quad (32)
\end{aligned}$$

2.5. Analytical modeling of $COD(\theta)$ and $CSD(\theta)$

55 The Crack Opening Displacement (COD) and Crack Sliding Displacement (CSD) are in general a function of θ , the angular coordinate along the crack which varies between 0 and $\Delta\theta$. Without making any approximation, the Crack Opening Displacement (COD) and Crack Sliding Displacement (CSD) can be expressed as the sum of their average value and a term, respectively $\delta COD(\theta)$

60 and $\delta CSD(\theta)$, that represents the variation of the function from its average:

$$\begin{aligned} COD(\theta) &= COD_{avg} + \delta COD(\theta) \\ CSD(\theta) &= CSD_{avg} + \delta CSD(\theta). \end{aligned} \quad (33)$$

By defining $\Delta\Psi$

$$\Delta\Psi = \min(\Delta\theta, \Delta\Phi), \quad (34)$$

we introduce at this point an approximation and assume that the functions $\delta COD(\theta)$ and $\delta CSD(\theta)$ can be expressed as the product of the maximum value of the displacement and a function, respectively $f\left(\theta - \frac{\Delta\Psi}{2}\right)$ and $g\left(\theta - \frac{\Delta\theta}{2}\right)$:

$$\begin{aligned} COD(\theta) &= COD_{avg} + \delta COD(\theta) = COD_{avg} + COD_{max} f\left(\theta - \frac{\Delta\Psi}{2}\right) \\ CSD(\theta) &= CSD_{avg} + \delta CSD(\theta) = CSD_{avg} + CSD_{max} g\left(\theta - \frac{\Delta\theta}{2}\right), \end{aligned} \quad (35)$$

65 where $f\left(\theta - \frac{\Delta\Psi}{2}\right)$ and $g\left(\theta - \frac{\Delta\theta}{2}\right)$ are assumed to be odd functions over their respective integration domain $[0, \Delta\Psi]$ and $[0, \Delta\theta]$

$$\int_0^{\Delta\theta} f\left(\theta - \frac{\Delta\Psi}{2}\right) d\theta = 0 \quad \int_0^{\Delta\theta} g\left(\theta - \frac{\Delta\theta}{2}\right) d\theta = 0. \quad (36)$$

We assume the two functions $f\left(\theta - \frac{\Delta\Psi}{2}\right)$ and $g\left(\theta - \frac{\Delta\theta}{2}\right)$ to be two odd polynomials of degree $2n - 1$:

$$\begin{aligned} f\left(\theta - \frac{\Delta\Psi}{2}\right) &= \begin{cases} \sum_{k=0}^{n-1} a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2}\right)^{2k+1} & 0 \leq \theta \leq \Delta\Psi \\ 0 & otherwise \end{cases} \\ g\left(\theta - \frac{\Delta\theta}{2}\right) &= \begin{cases} \sum_{k=0}^{n-1} b_{2k+1} \left(\theta - \frac{\Delta\theta}{2}\right)^{2k+1} & 0 \leq \theta \leq \Delta\theta \\ 0 & otherwise \end{cases} \end{aligned} \quad (37)$$

which satisfy by construction the conditions expressed in Equation 36. The
70 coefficients a_{2k+1} and b_{2k+1} are determined by imposing that

$$\begin{aligned} COD(\Delta\Psi) &= 0 \\ CSD(\Delta\theta) &= 0. \end{aligned} \quad (38)$$

The explicit construction of the polynomials $f\left(\theta - \frac{\Delta\Psi}{2}\right)$ and $g\left(\theta - \frac{\Delta\theta}{2}\right)$ for $n = 1, 2, 3$ (or degree $2n - 1 = 1, 3, 5$) is reported in Appendix A.

We recall the expressions of the non-zero components of the Vakulenko-Kachanov tensor

$$\begin{aligned}
\beta_{22} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 - \sin(2\theta)) + \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta \\
\beta_{33} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 + \sin(2\theta)) - \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta \\
\beta_{23} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} 2 \left[\frac{COD(\theta) + CSD(\theta)}{2} \cos(2\theta) + \frac{COD(\theta) - CSD(\theta)}{2} \sin(2\theta) \right] d\theta
\end{aligned} \tag{39}$$

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and proceed to the integration of the different summands:

1.

$$\begin{aligned}
& \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD(\theta) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left(COD_{avg} + COD_{max} \sum_{k=0}^{n-1} a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2} \right)^{2k+1} \right) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD_{avg} d\theta + \\
& + \frac{1}{\Delta\theta} \int_0^{\Delta\Psi} COD_{max} \sum_{k=0}^{n-1} a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2} \right)^{2k+1} d\theta + \\
& + \frac{1}{\Delta\theta} \int_{\Delta\Psi}^{\Delta\theta} COD_{max} \sum_{k=0}^{n-1} a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2} \right)^{2k+1} d\theta = \\
& = \frac{1}{\Delta\theta} [COD_{avg}\theta] \Big|_0^{\Delta\theta} + \frac{1}{\Delta\theta} \left[COD_{max} \sum_{k=0}^{n-1} \frac{a_{2k+1}}{2(k+1)} \left(\theta - \frac{\Delta\Psi}{2} \right)^{2(k+1)} \right] \Big|_0^{\Delta\Psi} = \\
& = COD_{avg} + COD_{max} \sum_{k=0}^{n-1} \frac{a_{2k+1}}{2(k+1)\Delta\theta} \left(\left(\frac{\Delta\Psi}{2} \right)^{2(k+1)} - \left(-\frac{\Delta\Psi}{2} \right)^{2(k+1)} \right) = \\
& = COD_{avg}
\end{aligned} \tag{40}$$

2.

$$\frac{1}{\Delta\theta} \int_0^{\Delta\theta} CSD(\theta) d\theta = CSD_{avg} \tag{41}$$

3.

$$\begin{aligned}
& \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD(\theta) \sin(2\theta) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left(COD_{avg} + COD_{max} \sum_{k=0}^{n-1} a_{2k+1} \theta^{2k+1} \right) \sin(2\theta) d\theta = \\
& = -\frac{1}{2\Delta\theta} COD_{avg} [\cos(2\theta)] \Big|_0^{\Delta\theta} + \\
& + \frac{1}{\Delta\theta} \left[COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^{i+1} \sin\left(\frac{1+\text{mod}(i,2)}{2} \pi - 2\theta \right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \theta^{k-i} \right) \right] \Big|_0^{\Delta\Psi} = \\
& = \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \\
& + \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^{i+1} \sin\left(\frac{1+\text{mod}(i,2)}{2} \pi - 2\Delta\Psi \right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i} \right)
\end{aligned} \tag{42}$$

4.

$$\begin{aligned}
& \frac{1}{\Delta\theta} \int_0^{\Delta\theta} CSD(\theta) \sin(2\theta) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left(CSD_{avg} + CSD_{max} \sum_{k=0}^{n-1} b_{2k+1} \theta^{2k+1} \right) \sin(2\theta) d\theta = \\
& = -\frac{1}{2\Delta\theta} CSD_{avg} [\cos(2\theta)] \Big|_0^{\Delta\theta} + \\
& + \frac{1}{\Delta\theta} \left[CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^{i+1} \sin\left(\frac{1+\text{mod}(i,2)}{2}\pi - 2\theta\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \theta^{k-i} \right) \right] \Big|_0^{\Delta\theta} = \\
& = \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
& + \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^{i+1} \sin\left(\frac{1+\text{mod}(i,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i} \right) \quad (43)
\end{aligned}$$

5.

$$\begin{aligned}
& \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD(\theta) \cos(2\theta) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left(COD_{avg} + COD_{max} \sum_{k=0}^{n-1} a_{2k+1} \theta^{2k+1} \right) \cos(2\theta) d\theta = \\
& = \frac{1}{2\Delta\theta} COD_{avg} [\sin(2\theta)] \Big|_0^{\Delta\theta} + \\
& + \frac{1}{\Delta\theta} \left[COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^i \sin\left(\frac{1+\text{mod}(i+1,2)}{2}\pi - 2\theta\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \theta^{k-i} \right) \right] \Big|_0^{\Delta\theta} = \\
& = \frac{\sin(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \\
& + \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^i \sin\left(\frac{1+\text{mod}(i+1,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i} \right) \quad (44)
\end{aligned}$$

6.

$$\begin{aligned}
& \frac{1}{\Delta\theta} \int_0^{\Delta\theta} CSD(\theta) \cos(2\theta) d\theta = \\
& = \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left(CSD_{avg} + CSD_{max} \sum_{k=0}^{n-1} b_{2k+1} \theta^{2k+1} \right) \cos(2\theta) d\theta = \\
& = -\frac{1}{2\Delta\theta} CSD_{avg} [\cos(2\theta)] \Big|_0^{\Delta\theta} + \\
& + \frac{1}{\Delta\theta} \left[CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^i \sin\left(\frac{1+\text{mod}(i+1,2)}{2} \pi - 2\theta\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \theta^{k-i} \right) \right] \Big|_0^{\Delta\theta} = \\
& = \frac{\sin(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
& + \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2} \right)^i \sin\left(\frac{1+\text{mod}(i+1,2)}{2} \pi - 2\Delta\theta\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\theta^{k-i} \right) \\
& \tag{45}
\end{aligned}$$

Finally we can compute the expressions of the components of the Vakulenko-Kachanov tensor:

1. β_{22}

$$\begin{aligned}
\beta_{22} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 - \sin(2\theta)) + \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta \\
&= \frac{\rho_D}{2} (COD_{avg} + CSD_{avg}) + \\
&\quad - \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} COD_{avg} - \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&\quad - \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&\quad - \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&\quad + \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \\
&\quad + \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&\quad - \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&\quad - \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) = \\
&= \frac{\rho_D}{2} COD_{avg} \left(1 - \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} + \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&\quad + \frac{\rho_D}{2} CSD_{avg} \left(1 - \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} - \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&\quad + \frac{\rho_D}{2} COD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) - \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&\quad - \frac{\rho_D}{2} CSD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) + \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right)
\end{aligned} \tag{46}$$

2. β_{33}

$$\begin{aligned}
\beta_{33} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD(\theta) + CSD(\theta)}{2} (1 + \sin(2\theta)) - \frac{COD(\theta) - CSD(\theta)}{2} \cos(2\theta) \right] d\theta = \\
&= \frac{\rho_D}{2} (COD_{avg} + CSD_{avg}) + \\
&+ \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&- \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \\
&- \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) = \\
&= \frac{\rho_D}{2} COD_{avg} \left(1 + \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} - \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&+ \frac{\rho_D}{2} CSD_{avg} \left(1 - \frac{1 + \cos(2\Delta\theta)}{2\Delta\theta} + \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&+ \frac{\rho_D}{2} COD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right) - \left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right)\right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} CSD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^i \sin\left(\frac{1 + \text{mod}(i+1, 2)}{2} \pi - 2\Delta\Psi\right) + \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1 + \text{mod}(i, 2)}{2} \pi - 2\Delta\Psi\right)\right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right)
\end{aligned} \tag{47}$$

$$\begin{aligned}
\beta_{23} &= \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} 2 \left[\frac{COD(\theta) + CSD(\theta)}{2} \cos(2\theta) + \frac{COD(\theta) - CSD(\theta)}{2} \sin(2\theta) \right] d\theta = \\
&= \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} COD_{avg} + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1+mod(i+1,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} \frac{\sin(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^i \sin\left(\frac{1+mod(i+1,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} COD_{avg} - \frac{\rho_D}{2} \frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} CSD_{avg} + \\
&+ \frac{\rho_D}{2} \frac{1}{\Delta\theta} COD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1+mod(i,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&- \frac{\rho_D}{2} \frac{1}{\Delta\theta} CSD_{max} \sum_{i=0}^{2n-1} \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1+mod(i,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) = \\
&= \frac{\rho_D}{2} COD_{avg} \left(\frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} + \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&- \frac{\rho_D}{2} CSD_{avg} \left(\frac{1 - \cos(2\Delta\theta)}{2\Delta\theta} - \frac{\sin(2\Delta\theta)}{2\Delta\theta}\right) + \\
&+ \frac{\rho_D}{2} COD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^i \sin\left(\frac{1+mod(i+1,2)}{2}\pi - 2\Delta\Psi\right) + \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1+mod(i,2)}{2}\pi - 2\Delta\Psi\right)\right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} a_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right) + \\
&+ \frac{\rho_D}{2} CSD_{max} \frac{1}{\Delta\theta} \sum_{i=0}^{2n-1} \left(\left(-\frac{1}{2}\right)^i \sin\left(\frac{1+mod(i+1,2)}{2}\pi - 2\Delta\Psi\right) - \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1+mod(i,2)}{2}\pi - 2\Delta\Psi\right)\right) \cdot \\
&\quad \cdot \left(\sum_{k=i}^{2n-1} b_k \frac{k!}{(k-i)!} \Delta\Psi^{k-i}\right)
\end{aligned} \tag{48}$$

2.6. *Application to UD composite*

2.7. *Application to $[0_{mk}^\circ, 90_k^\circ, 0_{mk}^\circ]$ laminate*

3. Computations with the Finite Element Method (FEM)

3.1. *Models of Representative Volume Element (RVE)*

85 3.2. *Details of FEM implementation*

4. Results and discussion

5. Conclusions

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Appendix A. Explicit expressions for $f(\theta)$ and $g(\theta)$

In the following, recall that

$$\Delta\Psi = \min(\Delta\theta, \Delta\Phi). \quad (\text{A.1})$$

$\mathbf{n} = \mathbf{1}$

$$\begin{aligned} f\left(\theta - \frac{\Delta\Psi}{2}\right) &= \sum_{k=0}^0 a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2}\right)^{2k+1} = a_1 \left(\theta - \frac{\Delta\Psi}{2}\right) \\ g\left(\theta - \frac{\Delta\theta}{2}\right) &= \sum_{k=0}^0 b_{2k+1} \left(\theta - \frac{\Delta\theta}{2}\right)^{2k+1} = b_1 \left(\theta - \frac{\Delta\theta}{2}\right) \end{aligned} \quad (\text{A.2})$$

$$\begin{aligned} \int_0^{\Delta\Psi} f\left(\theta - \frac{\Delta\Psi}{2}\right) d\theta &= \int_0^{\Delta\Psi} a_1 \left(\theta - \frac{\Delta\Psi}{2}\right) d\theta = \left[\frac{a_1}{2} \theta^2 - a_1 \frac{\Delta\Psi}{2} \theta \right] \Big|_0^{\Delta\Psi} = 0 \quad \forall a_1 \\ \int_0^{\Delta\theta} g\left(\theta - \frac{\Delta\theta}{2}\right) d\theta &= \int_0^{\Delta\theta} b_1 \left(\theta - \frac{\Delta\theta}{2}\right) d\theta = \left[\frac{b_1}{2} \theta^2 - b_1 \frac{\Delta\theta}{2} \theta \right] \Big|_0^{\Delta\theta} = 0 \quad \forall b_1 \end{aligned} \quad (\text{A.3})$$

$$\begin{aligned} COD_{avg} + COD_{max} a_1 \left(\Delta\Psi - \frac{\Delta\Psi}{2}\right) &= 0 \rightarrow a_1 = -\frac{2}{\Delta\Psi} \frac{COD_{avg}}{COD_{max}} \\ CSD_{avg} + CSD_{max} b_1 \left(\Delta\theta - \frac{\Delta\theta}{2}\right) &= 0 \rightarrow b_1 = -\frac{2}{\Delta\theta} \frac{CSD_{avg}}{CSD_{max}} \end{aligned} \quad (\text{A.4})$$

$$\begin{aligned}
& \sum_{i=0}^1 \left(-\frac{1}{2}\right)^{i+1} \sin\left(\frac{1+\text{mod}(i,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=0}^{1-i} a_k (1-(k+1))! \Delta\Psi^k\right) = \\
& = \left(-\frac{1}{2}\right)^1 \sin\left(\frac{1+\text{mod}(0,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=0}^1 a_k (1-(k+1))! \Delta\Psi^k\right) + \\
& + \left(-\frac{1}{2}\right)^2 \sin\left(\frac{1+\text{mod}(1,2)}{2}\pi - 2\Delta\Psi\right) \left(\sum_{k=0}^0 a_k (1-(k+1))! \Delta\Psi^k\right) = \\
& = -\frac{1}{2} \cos(2\Delta\Psi) \left(\sum_{k=0}^1 a_k (1-(k+1))! \Delta\Psi^k\right) + \\
& + \frac{1}{4} \sin(2\Delta\Psi) \left(\sum_{k=0}^0 a_k (1-(k+1))! \Delta\Psi^k\right) = \\
& = -\frac{1}{2} \cos(2\Delta\Psi) (a_0 + a_1 (n-(k+1))! \Delta\Psi^k) + \\
& + \frac{1}{4} \sin(2\Delta\Psi) \left(\sum_{k=0}^0 a_k (n-(k+1))! \Delta\Psi^k\right) =
\end{aligned} \tag{A.5}$$

n = 2

$$\begin{aligned}
f\left(\theta - \frac{\Delta\Psi}{2}\right) &= \sum_{k=0}^1 a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2}\right)^{2k+1} = a_1 \left(\theta - \frac{\Delta\Psi}{2}\right) + a_3 \left(\theta - \frac{\Delta\Psi}{2}\right)^3 \\
g\left(\theta - \frac{\Delta\theta}{2}\right) &= \sum_{k=0}^1 b_{2k+1} \left(\theta - \frac{\Delta\theta}{2}\right)^{2k+1} = b_1 \left(\theta - \frac{\Delta\theta}{2}\right) + b_3 \left(\theta - \frac{\Delta\theta}{2}\right)^3
\end{aligned} \tag{A.6}$$

n = 3

$$\begin{aligned}
f\left(\theta - \frac{\Delta\Psi}{2}\right) &= \sum_{k=0}^2 a_{2k+1} \left(\theta - \frac{\Delta\Psi}{2}\right)^{2k+1} = \\
& = a_1 \left(\theta - \frac{\Delta\Psi}{2}\right) + a_3 \left(\theta - \frac{\Delta\Psi}{2}\right)^3 + a_5 \left(\theta - \frac{\Delta\Psi}{2}\right)^5 \\
g\left(\theta - \frac{\Delta\theta}{2}\right) &= \sum_{k=0}^1 b_{2k+1} \left(\theta - \frac{\Delta\theta}{2}\right)^{2k+1} = \\
& = b_1 \left(\theta - \frac{\Delta\theta}{2}\right) + b_3 \left(\theta - \frac{\Delta\theta}{2}\right)^3 + b_5 \left(\theta - \frac{\Delta\theta}{2}\right)^5
\end{aligned} \tag{A.7}$$