Stiffness reduction in UD and cross-ply laminates due to fiber/matrix interface cracks

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Abstract

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1. Introduction

Main ref [1]

2. Derivation of constitutive relations

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 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

Principle 1. Normalized volume of cracks V_{an} is the ratio of cracked volume V_a to material volume V

$$V_{an} = \frac{V_a}{V} \tag{1}$$

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

$$V_{an} = \frac{S_C u_a}{V} = \frac{S_C}{V} u_a = \rho_C u_a \tag{2}$$

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 normalized volume of cracks.

Applying the previous Principle to debonds, we have:

$$\begin{aligned}\rho_D = \frac{\text{total area of debonds}}{\text{total layer volume}} &= \frac{n_D w R_f \Delta\theta}{L_{lam} w t_{90^\circ}} = \frac{n_D \cancel{w}}{L_{lam} \cancel{w} t_{90^\circ}} R_f \Delta\theta = \frac{1}{n2L}\frac{1}{k2L} R_f \Delta\theta = \\ &= \frac{1}{nk4L^2} R_f \Delta\theta = \frac{V_f}{nk\pi R_f^2} R_f \Delta\theta = \frac{V_f}{nkR_f}\frac{\Delta\theta}{\pi}\end{aligned} \tag{3}$$

2.3. Vakulenko-Kachanov tensor

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

$$n_1 = 0 \quad n_2 \neq 0 \quad n_3 \neq 0 \tag{4}$$

while crack face displacement has components:

$$u_1 = 0 \quad u_2 \neq 0 \quad u_3 \neq 0 \tag{5}$$

Definition of Vakulenko-Kachanov tensor:

$$\beta_{ij} = \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_i n_j + u_j n_i\right) dS \tag{6}$$

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

$$
\begin{aligned}
\beta_{11} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_1 n_1 + u_1 n_1 \right) dS = \frac{1}{V_k} \int_{S_C} \cancelto{0}{u_1 n_1} dS = 0 \\
\beta_{22} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_2 n_2 + u_2 n_2 \right) dS = \frac{1}{V_k} \int_{S_C} u_2 n_2 dS \\
\beta_{33} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_3 n_3 + u_3 n_3 \right) dS = \frac{1}{V_k} \int_{S_C} u_3 n_3 dS \\
\beta_{12} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(\cancelto{0}{u_1 n_2} + \cancelto{0}{u_2 n_1} \right) dS = 0 \\
\beta_{13} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(\cancelto{0}{u_1 n_3} + \cancelto{0}{u_3 n_1} \right) dS = 0 \\
\beta_{23} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_2 n_3 + u_3 n_2 \right) dS \\
\beta_{21} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(\cancelto{0}{u_2 n_1} + \cancelto{0}{u_1 n_2} \right) dS = 0 \\
\beta_{31} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(\cancelto{0}{u_3 n_1} + \cancelto{0}{u_1 n_3} \right) dS = 0 \\
\beta_{32} =& \frac{1}{V_k} \int_{S_C} \frac{1}{2} \left(u_3 n_2 + u_2 n_3 \right) dS = \beta_{23}
\end{aligned}
\tag{7}
$$

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 $i = 2, 3$

$$
\begin{aligned}
\beta_{22} =& \frac{1}{V_k}\int_{S_C} u_2 n_2 dS = \frac{1}{V_k}\left[\int_{S_C^m} u_2^m n_2^m dS + \int_{S_C^f} u_2^f n_2^f dS\right] = \\
=& \frac{1}{V_k}\left[\int_{S_C^m} u_2^m n_2^m dS + \int_{S_C^f} u_2^f \left(-n_2^m\right) dS\right] \\
\beta_{33} =& \frac{1}{V_k}\int_{S_C} u_3 n_3 dS = \frac{1}{V_k}\left[\int_{S_C^m} u_3^m n_3^m dS + \int_{S_C^f} u_3^f n_3^f dS\right] = \\
=& \frac{1}{V_k}\left[\int_{S_C^m} u_3^m n_3^m dS + \int_{S_C^f} u_3^f \left(-n_3^m\right) dS\right] \\
\beta_{23} =& \frac{1}{V_k}\int_{S_C} \left(u_2 n_3 + u_3 n_2\right) dS = \\
=& \frac{1}{V_k}\left[\int_{S_C^m} \left(u_2^m n_3^m + u_3^m n_2^m\right) dS + \int_{S_C^f} \left(u_2^f n_3^f + u_3^f n_2^f\right) dS\right] = \\
=& \frac{1}{V_k}\left[\int_{S_C^m} u_2^m n_3^m dS + \int_{S_C^f} u_2^f \left(-n_3^m\right) dS + \int_{S_C^m} u_3^m n_2^m dS + \int_{S_C^f} u_3^f \left(-n_2^m\right) dS\right]
\end{aligned}
\tag{8}
$$

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

$$
S_C^m = S_C^f = n_D R_f \Delta\theta \tag{9}
$$

With Eq. 9, we can recast Eq. 8 as

$$
\begin{aligned}
\beta_{22} =& \frac{1}{V_k}\left[n_D R_f w \int_0^{\Delta\theta}\left(u_2^m - u_2^f\right) n_2^m d\theta\right] = \\
=& \frac{1}{L_{lam} w t_{90^\circ}}\left[n_D R_f w \int_0^{\Delta\theta}\left(u_2^m - u_2^f\right) n_2^m d\theta\right] = \\
=& \frac{1}{L_{lam}}\frac{n_D R_f}{t_{90^\circ}}\left[\int_0^{\Delta\theta}\left(u_2^m - u_2^f\right) n_2^m d\theta\right] = \\
=& \rho_D\left[\frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(u_2^m - u_2^f\right) n_2^m d\theta\right] \\
\beta_{33} =& \rho_D\left[\frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(u_3^m - u_3^f\right) n_3^m d\theta\right] \\
\beta_{23} =& \rho_D\left[\frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(u_2^m - u_2^f\right) n_3^m d\theta + \frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(u_3^m - u_3^f\right) n_2^m d\theta\right]
\end{aligned}
\tag{10}
$$

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

$$
\begin{aligned}
u_2^m - u_2^f =& \left(u_r^m - u_r^f\right)\cos(\theta) - \left(u_\theta^m - u_\theta^f\right)\sin(\theta) = \\
=& COD(\theta)\cos(\theta) - CSD(\theta)\sin(\theta) \\
u_3^m - u_3^f =& \left(u_r^m - u_r^f\right)\sin(\theta) + \left(u_\theta^m - u_\theta^f\right)\cos(\theta) = \\
=& COD(\theta)\sin(\theta) + CSD(\theta)\cos(\theta)
\end{aligned}
\tag{11}
$$

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:

$$
\begin{aligned}
n_2^m &= \cos(\theta) - \sin(\theta) \\
n_3^m &= \sin(\theta) + \cos(\theta)
\end{aligned}
\tag{12}
$$

Thus, Eq. 10 becomes

$$
\begin{aligned}
&\beta_{22} = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[COD\left(\theta\right)\left(\cos^2\left(\theta\right) - \cos\left(\theta\right)\sin\left(\theta\right)\right) - CSD\left(\theta\right)\left(\sin\left(\theta\right)\cos\left(\theta\right) - \sin^2\left(\theta\right)\right)\right] d\theta = \\
&= \rho_D \frac{1}{2\Delta\theta} \int_0^{\Delta\theta} \left[COD\left(\theta\right)\left(1 + \cos\left(2\theta\right) - \sin\left(2\theta\right)\right) + CSD\left(\theta\right)\left(1 - \cos\left(2\theta\right) - \sin\left(2\theta\right)\right)\right] d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\left(1 - \sin\left(2\theta\right)\right) + \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\cos\left(2\theta\right)\right] d\theta \\
&\beta_{33} = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[COD\left(\theta\right)\left(\sin\left(\theta\right)\cos\left(\theta\right) + \sin^2\left(\theta\right)\right) + CSD\left(\theta\right)\left(\cos^2\left(\theta\right) + \cos\left(\theta\right)\sin\left(\theta\right)\right)\right] d\theta = \\
&= \rho_D \frac{1}{2\Delta\theta} \int_0^{\Delta\theta} \left[COD\left(\theta\right)\left(1 + \sin\left(2\theta\right) - \cos\left(2\theta\right)\right) + CSD\left(\theta\right)\left(1 + \sin\left(2\theta\right) + \cos\left(2\theta\right)\right)\right] d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\left(1 + \sin\left(2\theta\right)\right) - \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\cos\left(2\theta\right)\right] d\theta \\
&\beta_{23} = \\
&\quad = \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} COD\left(\theta\right)\left(2\sin\left(\theta\right)\cos\left(\theta\right) + \cos^2\left(\theta\right) - \sin^2\left(\theta\right)\right) + \\
&\qquad - \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} CSD\left(\theta\right)\left(\sin^2\left(\theta\right) - \cos^2\left(\theta\right) + 2\cos\left(\theta\right)\sin\left(\theta\right)\right) d\theta = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} 2\left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\cos\left(2\theta\right) + \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\sin\left(2\theta\right)\right] d\theta
\end{aligned}
\tag{13}
$$

2.4. Analytical modeling of $COD\left(\theta\right)$ and $CSD\left(\theta\right)$

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

$$
\begin{aligned}
COD\left(\theta\right) &= COD_{avg} + \delta COD\left(\theta\right) \\
CSD\left(\theta\right) &= CSD_{avg} + \delta CSD\left(\theta\right).
\end{aligned}
\tag{14}
$$

We introduce at this point an approximation and assume that the functions $\delta COD\left(\theta\right)$ and $\delta CSD\left(\theta\right)$ can be expressed as the product of the maximum value and a function, respectively $f\left(\theta\right)$ and $g\left(\theta\right)$:

$$
\begin{aligned}
COD\left(\theta\right) &= COD_{avg} + \delta COD\left(\theta\right) = COD_{avg} + COD_{max} f\left(\theta\right) \\
CSD\left(\theta\right) &= CSD_{avg} + \delta CSD\left(\theta\right) = CSD_{avg} + CSD_{max} g\left(\theta\right),
\end{aligned}
\tag{15}
$$

where $f\left(\theta\right)$ and $g\left(\theta\right)$ are assumed to be odd functions over the integration domain $[0, \Delta\theta]$

$$
\int_0^{\Delta\theta} f\left(\theta\right) d\theta = 0 \qquad \int_0^{\Delta\theta} g\left(\theta\right) d\theta = 0. \tag{16}
$$

We assume the two functions $f\left(\theta\right)$ and $g\left(\theta\right)$ to two odd polynomials of degree $2k+1$:

$$
f\left(\theta\right) = \sum_{k=0}^{n-1} a_{2k+1}\theta^{2k+1} \qquad g\left(\theta\right) = \sum_{k=0}^{n-1} b_{2k+1}\theta^{2k+1}. \tag{17}
$$

$$
\begin{aligned}
&\beta_{22} = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\left(1 - \sin\left(2\theta\right)\right) + \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\cos\left(2\theta\right)\right] d\theta \\
&\beta_{33} = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} \left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\left(1 + \sin\left(2\theta\right)\right) - \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\cos\left(2\theta\right)\right] d\theta \\
&\beta_{23} = \\
&= \rho_D \frac{1}{\Delta\theta} \int_0^{\Delta\theta} 2\left[\frac{COD\left(\theta\right) + CSD\left(\theta\right)}{2}\cos\left(2\theta\right) + \frac{COD\left(\theta\right) - CSD\left(\theta\right)}{2}\sin\left(2\theta\right)\right] d\theta
\end{aligned}
\tag{18}
$$

$$
\begin{aligned}
&\frac{1}{\Delta\theta}\int_0^{\min(\Delta\theta,\Delta\Phi)} COD\left(\theta\right)d\theta = \\
&=\frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(COD_{avg}+COD_{max}\sum_{k=0}^{n-1}a_{2k+1}\theta^{2k+1}\right)d\theta = \\
&=\frac{1}{\Delta\theta}\left[COD_{avg}\theta+COD_{max}\sum_{k=0}^{n-1}\frac{a_{2k+1}}{2\left(k+1\right)}\theta^{2(k+1)}\right]\Bigg|_0^{\min(\Delta\theta,\Delta\Phi)} = \\
&=COD_{avg}+COD_{max}\sum_{k=0}^{n-1}\frac{a_{2k+1}}{2\left(k+1\right)}\frac{\min\left(\Delta\theta,\Delta\Phi\right)^{2(k+1)}}{\Delta\theta}
\end{aligned}
\tag{19}
$$

$$
\frac{1}{\Delta\theta}\int_0^{\Delta\theta} CSD\left(\theta\right)d\theta = CSD_{avg}+CSD_{max}\sum_{k=0}^{n-1}\frac{b_{2k+1}}{2\left(k+1\right)}\Delta\theta^{2k+1}
\tag{20}
$$

$$
\begin{aligned}
&\frac{1}{\Delta\theta}\int_0^{\min(\Delta\theta,\Delta\Phi)} COD\left(\theta\right)\sin\left(2\theta\right)d\theta = \\
&=\frac{1}{\Delta\theta}\int_0^{\Delta\theta}\left(COD_{avg}+COD_{max}\sum_{k=0}^{n-1}a_{2k+1}\theta^{2k+1}\right)\sin\left(2\theta\right)d\theta = \\
&=\frac{1}{\Delta\theta}\left[-\frac{1}{2}COD_{avg}\cos\left(2\theta\right)+COD_{max}\sum_{k=0}^{n-1}\frac{a_{2k+1}}{2\left(k+1\right)}\theta^{2(k+1)}\right]\Bigg|_0^{\min(\Delta\theta,\Delta\Phi)} =
\end{aligned}
\tag{21}
$$

$$
\begin{aligned}
\int_0^{\Delta\theta}\left(1+\sin\left(2\theta\right)-\cos\left(2\theta\right)\right)d\theta &= \left[\theta-\frac{1}{2}\cos\left(2\theta\right)-\frac{1}{2}\sin\left(2\theta\right)\right]_0^{\Delta\theta} = \\
&= \Delta\theta+\frac{1}{2}\left(1-\cos\left(2\Delta\theta\right)\right)-\frac{1}{2}\sin\left(2\Delta\theta\right) = \\
&= \Delta\theta-\frac{1}{2}\left(\sqrt{2}\sin\left(2\Delta\theta+\frac{\pi}{4}\right)-1\right)
\end{aligned}
\tag{22}
$$

$$\int_0^{\Delta\theta} f(\theta)\left(1+\sin(2\theta)-\cos(2\theta)\right)d\theta =$$
$$= \cancelto{0}{\int_0^{\Delta\theta} f(\theta)\,d\theta} - \sqrt{2}\int_0^{\Delta\theta} f(\theta)\sin\left(\frac{\pi}{4}-2\theta\right)d\theta$$
$$\int_0^{\Delta\theta} g(\theta)\left(1+\sin(2\theta)-\cos(2\theta)\right)d\theta =$$
$$= \cancelto{0}{\int_0^{\Delta\theta} g(\theta)\,d\theta} - \sqrt{2}\int_0^{\Delta\theta} g(\theta)\sin\left(\frac{\pi}{4}-2\theta\right)d\theta \tag{23}$$

$$\int_0^{\Delta\theta} f(\theta)\sin\left(\frac{\pi}{4}-2\theta\right)d\theta =$$
$$= \left[\sum_{i=0}^{n}\left[\left(a_0\left(1-H(i-1)\right)+\sum_{k=0}^{n-1}a_{2k+1}\theta^{2k+1-i}\right)\frac{1}{2}(-1)^i\sin\left(\left(1-\frac{1}{2}\bmod\left(\frac{i+1}{2}\right)\right)\pi-\left(\frac{\pi}{4}-2\theta\right)\right)\right]\right]_0^{\Delta\theta} =$$
$$= \sum_{i=0}^{n}\left[\left(a_0\left(1-H(i-1)\right)+\sum_{k=0}^{n-1}a_{2k+1}\Delta\theta^{2k+1-i}\right)\frac{1}{2}(-1)^i\sin\left(\left(1-\frac{1}{2}\bmod\left(\frac{i+1}{2}\right)\right)\pi-\left(\frac{\pi}{4}-2\Delta\theta\right)\right)\right]+$$
$$+\frac{\sqrt{2}}{4}a_0$$

$$\int_0^{\Delta\theta} g(\theta)\sin\left(\frac{\pi}{4}-2\theta\right)d\theta =$$
$$= \left[\sum_{i=0}^{n}\left[\left(b_0\left(1-H(i-1)\right)+\sum_{k=0}^{n-1}b_{2k+1}\theta^{2k+1-i}\right)\frac{1}{2}(-1)^i\sin\left(\left(1-\frac{1}{2}\bmod\left(\frac{i+1}{2}\right)\right)\pi-\left(\frac{\pi}{4}-2\theta\right)\right)\right]\right]_0^{\Delta\theta} =$$
$$= \sum_{i=0}^{n}\left[\left(b_0\left(1-H(i-1)\right)+\sum_{k=0}^{n-1}b_{2k+1}\Delta\theta^{2k+1-i}\right)\frac{1}{2}(-1)^i\sin\left(\left(1-\frac{1}{2}\bmod\left(\frac{i+1}{2}\right)\right)\pi-\left(\frac{\pi}{4}-2\Delta\theta\right)\right)\right]+$$
$$+\frac{\sqrt{2}}{4}b_0 \tag{24}$$

$$
\begin{aligned}
\beta_{22} = & \rho_D \left[1 - \frac{1}{2\Delta\theta}\left(\sqrt{2}\sin\left(2\Delta\theta + \frac{\pi}{4}\right) - 1\right)\right]\left(COD_{avg} - CSD_{avg}\right) + \\
& - \frac{1}{2}\rho_D \left(a_0 COD_{max} - b_0 CSD_{max}\right) + \\
& -\sqrt{2}\sum_{i=0}^{n}\left(\left(a_0 COD_{max} - b_0 CSD_{max}\right)\left(1 - H\left(i-1\right)\right) + \sum_{k=0}^{n-1}\left(a_{2k+1} COD_{max} - b_{2k+1} CSD_{max}\right)\Delta\theta^{2k+1-i}\right) \times \\
& \times \frac{1}{2}\left(-1\right)^i \sin\left(\left(1 - \frac{1}{2}\bmod\left(\frac{i+1}{2}\right)\right)\pi - \left(\frac{\pi}{4} - 2\Delta\theta\right)\right)
\end{aligned}
\tag{25}
$$

References

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