

Building a Constitutive Relation for Fiber Bundle Model with Plasticity (breakable fibers)

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September 14, 2024

I. Introduction

Consider a fiber bundle model with breakable fibers subjected to an external strain ε . The average yielding threshold of all fibers is $\langle \varepsilon_y \rangle$, and the average breaking threshold of all fibers is $\langle \varepsilon_b \rangle$.

The probability density function of ε_y is $p_y(\varepsilon_y)$ for $\varepsilon_y \in [\langle \varepsilon_y \rangle - \Delta \varepsilon_y, \langle \varepsilon_y \rangle + \Delta \varepsilon_y]$, and the probability density function of ε_b is $p_b(\varepsilon_b)$ for $\varepsilon_b \in [\langle \varepsilon_b \rangle - \Delta \varepsilon_b, \langle \varepsilon_b \rangle + \Delta \varepsilon_b]$. Assume both are uniformly distributed:

$$p_y(\varepsilon_y) = \begin{cases} \frac{1}{2\Delta \varepsilon_y} & \text{if } \langle \varepsilon_y \rangle - \Delta \varepsilon_y \leq \varepsilon_y \leq \langle \varepsilon_y \rangle + \Delta \varepsilon_y \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

$$p_b(\varepsilon_b) = \begin{cases} \frac{1}{2\Delta \varepsilon_b} & \text{if } \langle \varepsilon_b \rangle - \Delta \varepsilon_b \leq \varepsilon_b \leq \langle \varepsilon_b \rangle + \Delta \varepsilon_b \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Their cumulative distribution functions are:

$$P_y(\varepsilon_y) = \begin{cases} 0 & \text{if } \varepsilon_y < \langle \varepsilon_y \rangle - \Delta \varepsilon_y \\ \frac{\varepsilon_y - (\langle \varepsilon_y \rangle - \Delta \varepsilon_y)}{2\Delta \varepsilon_y} & \text{if } \langle \varepsilon_y \rangle - \Delta \varepsilon_y \leq \varepsilon_y \leq \langle \varepsilon_y \rangle + \Delta \varepsilon_y \\ 1 & \text{if } \varepsilon_y > \langle \varepsilon_y \rangle + \Delta \varepsilon_y \end{cases} \quad (3)$$

$$P_b(\varepsilon_b) = \begin{cases} 0 & \text{if } \varepsilon_b < \langle \varepsilon_b \rangle - \Delta \varepsilon_b \\ \frac{\varepsilon_b - (\langle \varepsilon_b \rangle - \Delta \varepsilon_b)}{2\Delta \varepsilon_b} & \text{if } \langle \varepsilon_b \rangle - \Delta \varepsilon_b \leq \varepsilon_b \leq \langle \varepsilon_b \rangle + \Delta \varepsilon_b \\ 1 & \text{if } \varepsilon_b > \langle \varepsilon_b \rangle + \Delta \varepsilon_b \end{cases} \quad (4)$$

There are 3 types of fibers: intact, yielding, and broken. The stress-strain function is:

$$\sigma(\varepsilon) = E\varepsilon[1 - P_y(\varepsilon)] + \left(\int_0^\varepsilon [\alpha E(\varepsilon - \varepsilon_y) + E\varepsilon_y] \cdot p_y(\varepsilon_y) d\varepsilon_y \right) \cdot [1 - P_b(\varepsilon)] \quad (5)$$

$$= E\varepsilon[1 - P_y(\varepsilon)] + \left[\int_0^\varepsilon [(\alpha + 1)E\varepsilon_y + \alpha E\varepsilon] \cdot p_y(\varepsilon_y) d\varepsilon_y \right] \cdot [1 - P_b(\varepsilon)] \quad (6)$$

where α is the ratio of the elastic modulus of yielding fibers to that of intact fibers, and E is the elastic modulus of intact fibers.

II. Mathematical Formulation

Since the behavior of the uniform distribution varies across different intervals, we need to break the process down and consider each interval separately. For the sake of simplicity¹, consider the two intervals $[\langle \varepsilon_y \rangle - \Delta \varepsilon_y, \langle \varepsilon_y \rangle + \Delta \varepsilon_y]$ and $[\langle \varepsilon_b \rangle - \Delta \varepsilon_b, \langle \varepsilon_b \rangle + \Delta \varepsilon_b]$ do not overlap, i.e., $\langle \varepsilon_y \rangle + \Delta \varepsilon_y < \langle \varepsilon_b \rangle - \Delta \varepsilon_b$.

1. For $0 \leq \varepsilon < \langle \varepsilon_y \rangle - \Delta \varepsilon_y$

In this interval, all fibers are intact, i.e., no fiber has yielded yet. The stress-strain function is:

$$\sigma(\varepsilon) = E\varepsilon \quad (7)$$

2. For $\langle \varepsilon_y \rangle - \Delta \varepsilon_y \leq \varepsilon \leq \langle \varepsilon_y \rangle + \Delta \varepsilon_y$

In this interval, some fibers are yielding, some still are intact. Substitute (3), (1), and (4) in (6). The stress-strain function is:

$$\sigma(\varepsilon) = E\varepsilon \left[1 - \frac{\varepsilon - (\langle \varepsilon_y \rangle - \Delta \varepsilon_y)}{2\Delta \varepsilon_y} \right] + \left[\int_0^{\langle \varepsilon_y \rangle - \Delta \varepsilon_y} [\alpha E(\varepsilon - \varepsilon_y) + E\varepsilon_y] \cdot 0 \, d\varepsilon_y + \int_{\langle \varepsilon_y \rangle - \Delta \varepsilon_y}^{\varepsilon} [\alpha E(\varepsilon - \varepsilon_y) + E\varepsilon_y] \cdot \frac{1}{2\Delta \varepsilon_y} \, d\varepsilon_y \right] \quad (8)$$

3. For $\langle \varepsilon_y \rangle + \Delta \varepsilon_y < \varepsilon < \langle \varepsilon_b \rangle - \Delta \varepsilon_b$

In this interval, all fibers are yielding, i.e., no fiber is intact anymore, and no fiber is broken yet. Substitute (3), (1), and (4) into (6). The stress-strain function is:

¹Is it just for the sake of simplicity or is it actually cannot overlap?

$$\begin{aligned}
\sigma(\varepsilon) &= E\varepsilon[1 - 1] + \left[\int_0^\varepsilon \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot p_y(\varepsilon_y) d\varepsilon_y \right] \cdot [1 - 0] \\
&= \int_0^{\langle \varepsilon_y \rangle + \Delta \varepsilon_y} \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot \frac{1}{2\Delta \varepsilon_y} d\varepsilon_y + \int_{\langle \varepsilon_y \rangle + \Delta \varepsilon_y}^{\langle \varepsilon_b \rangle - \Delta \varepsilon_b} \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot 0 d\varepsilon_y \\
&= -\frac{\alpha E}{2\Delta \varepsilon_y} \int_0^{\langle \varepsilon_y \rangle + \Delta \varepsilon_y} (\varepsilon - \varepsilon_y) d(\varepsilon - \varepsilon_y) \\
&= -\frac{\alpha E}{2\Delta \varepsilon_y} \cdot \frac{(\varepsilon - \varepsilon_y)^2}{2} \Big|_0^{\langle \varepsilon_y \rangle + \Delta \varepsilon_y} \\
&= -\frac{\alpha E}{4\Delta \varepsilon_y} \cdot \left((\varepsilon - (\langle \varepsilon_y \rangle + \Delta \varepsilon_y))^2 - \varepsilon^2 \right) \\
\sigma(\varepsilon) &= -\frac{\alpha E}{4\Delta \varepsilon_y} \cdot \left[(\langle \varepsilon_y \rangle + \Delta \varepsilon_y)^2 - 2\varepsilon(\langle \varepsilon_y \rangle + \Delta \varepsilon_y) \right] \tag{9}
\end{aligned}$$

4. For $\langle \varepsilon_b \rangle - \Delta \varepsilon_b \leq \varepsilon \leq \langle \varepsilon_b \rangle + \Delta \varepsilon_b$

In this interval, some fibers are broken, some still are yielding but no fiber is intact. Substitute (3), (1), and (4) into (6). The stress-strain function is:

$$\begin{aligned}
\sigma(\varepsilon) &= E\varepsilon(1 - 1) + \left[\int_0^\varepsilon \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot p_y(\varepsilon_y) d\varepsilon_y \right] \cdot \left[1 - \frac{\varepsilon - (\langle \varepsilon_b \rangle - \Delta \varepsilon_b)}{2\Delta \varepsilon_b} \right] \\
&= \left[\int_0^{\langle \varepsilon_y \rangle + \Delta \varepsilon_y} \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot \frac{1}{2\Delta \varepsilon_y} d\varepsilon_y + \int_{\langle \varepsilon_y \rangle + \Delta \varepsilon_y}^\varepsilon \alpha E \cdot (\varepsilon - \varepsilon_y) \cdot 0 d\varepsilon_y \right] \cdot \left[1 - \frac{\varepsilon - (\langle \varepsilon_b \rangle - \Delta \varepsilon_b)}{2\Delta \varepsilon_b} \right] \\
&= -\frac{\alpha E}{4\Delta \varepsilon_y} \cdot \left[(\langle \varepsilon_y \rangle + \Delta \varepsilon_y)^2 - 2\varepsilon(\langle \varepsilon_y \rangle + \Delta \varepsilon_y) \right] \cdot \left[1 - \frac{\varepsilon - \langle \varepsilon_b \rangle}{2\Delta \varepsilon_b} - \frac{\Delta \varepsilon_b}{2\Delta \varepsilon_b} \right] \\
\sigma &= -\frac{\alpha E}{4\Delta \varepsilon_y} \cdot \left[(\langle \varepsilon_y \rangle + \Delta \varepsilon_y)^2 - 2\varepsilon(\langle \varepsilon_y \rangle + \Delta \varepsilon_y) \right] \cdot \left(\frac{1}{2} - \frac{\varepsilon - \langle \varepsilon_b \rangle}{2\Delta \varepsilon_b} \right) \tag{10}
\end{aligned}$$

5. For $\langle \varepsilon_b \rangle + \Delta \varepsilon_b < \varepsilon \leq 1$

In this interval, all fibers are broken. The stress-strain function is:

$$\sigma(\varepsilon) = 0 \tag{11}$$

III. Results

Now, we have the stress-strain function for each interval. We can combine them to get the final stress-strain function for the entire process:

$$\sigma(\varepsilon) = \begin{cases} E\varepsilon & \text{if } 0 \leq \varepsilon < \langle \varepsilon_y \rangle - \Delta\varepsilon_y \\ E\varepsilon \cdot \frac{1}{2} \left[1 - \frac{\varepsilon - \langle \varepsilon_y \rangle}{\Delta\varepsilon_y} + \frac{\alpha\varepsilon}{2\Delta\varepsilon_y} \right] & \text{if } \langle \varepsilon_y \rangle - \Delta\varepsilon_y \leq \varepsilon \leq \langle \varepsilon_y \rangle + \Delta\varepsilon_y \\ \frac{\alpha E}{4\Delta\varepsilon_y} \cdot \left[2\varepsilon(\langle \varepsilon_y \rangle + \Delta\varepsilon_y) - (\langle \varepsilon_y \rangle + \Delta\varepsilon_y)^2 \right] & \text{if } \langle \varepsilon_y \rangle + \Delta\varepsilon_y < \varepsilon < \langle \varepsilon_b \rangle - \Delta\varepsilon_b \\ \frac{\alpha E}{4\Delta\varepsilon_y} \cdot \left[2\varepsilon(\langle \varepsilon_y \rangle + \Delta\varepsilon_y) - (\langle \varepsilon_y \rangle + \Delta\varepsilon_y)^2 \right] \cdot \left(\frac{1}{2} - \frac{\varepsilon - \langle \varepsilon_b \rangle}{2\Delta\varepsilon_b} \right) & \text{if } \langle \varepsilon_b \rangle - \Delta\varepsilon_b \leq \varepsilon \leq \langle \varepsilon_b \rangle + \Delta\varepsilon_b \\ 0 & \text{if } \langle \varepsilon_b \rangle + \Delta\varepsilon_b < \varepsilon \leq 1 \end{cases}$$

Using GLE, we can obtain the constitutive relation for fiber bundle model with plasticity (breakable fibers): constit4.gle

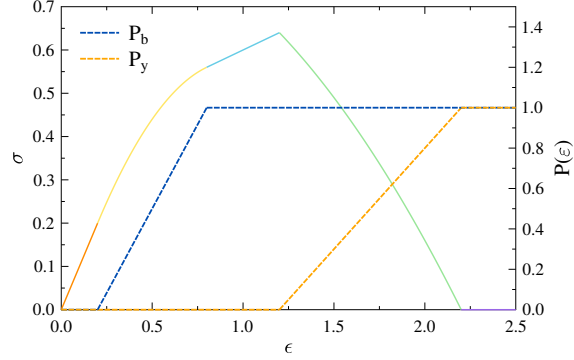


Figure 1: Inset: mass fraction of non-shattered fragments $S = 1 - s$ in the final state of the breakup process as a function of strain rate $\dot{\varepsilon}$ for several ring thicknesses $\Delta R/R$. Main panel: Rescaling the curves of the inset by an appropriate power ν of the ring thickness ΔR , the curves of different ΔR can be collapsed on a master curve. The black continuous line represents a fit with Eq. (??).