Supporting Information

Investigating Multiaxial Mullins Effect of Carbon Black Reinforced Elastomers using Electrical Resistivity Measurements

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1. The resistivity measurement under biaxial deformation

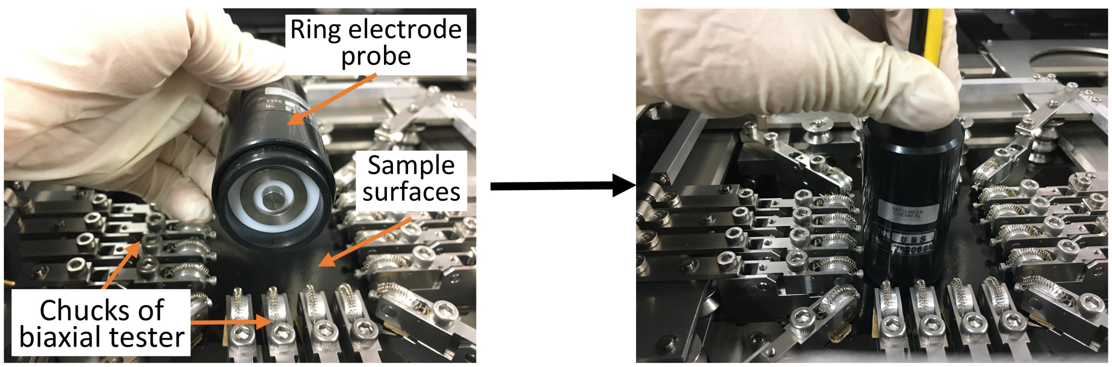

Figure S1. The illustration of resistivity measurement under biaxial deformation by using the ring electrode probe.

2. Loading-unloading cycles under various deformation types for SBR/CB and NR/CB with ϕ = 0.14

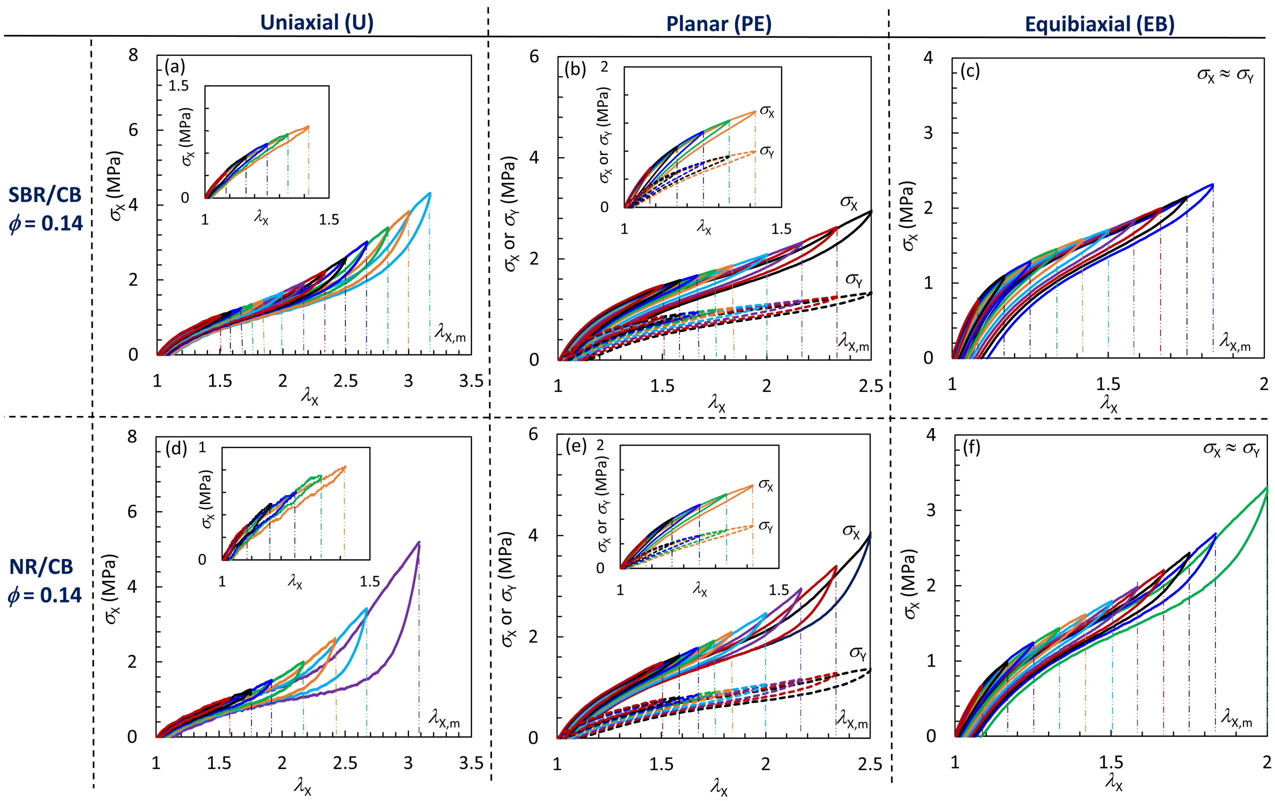

Figure S2. Nominal σ–λ_x relation in loading–unloading cycles with uniaxial, planar, equibiaxial extensions in the x- and y-directions for (a-c) SBR/CB and (d-f) NR/CB with ϕ = 0.14. The vertical dashed lines point out the $\lambda_{x,m}$ values in each cycle. The insets in figures are the magnifications of the small λ_x region.

3. Loading-unloading cycles under various deformation types for SBR/CB and NR/CB with ϕ = 0.05

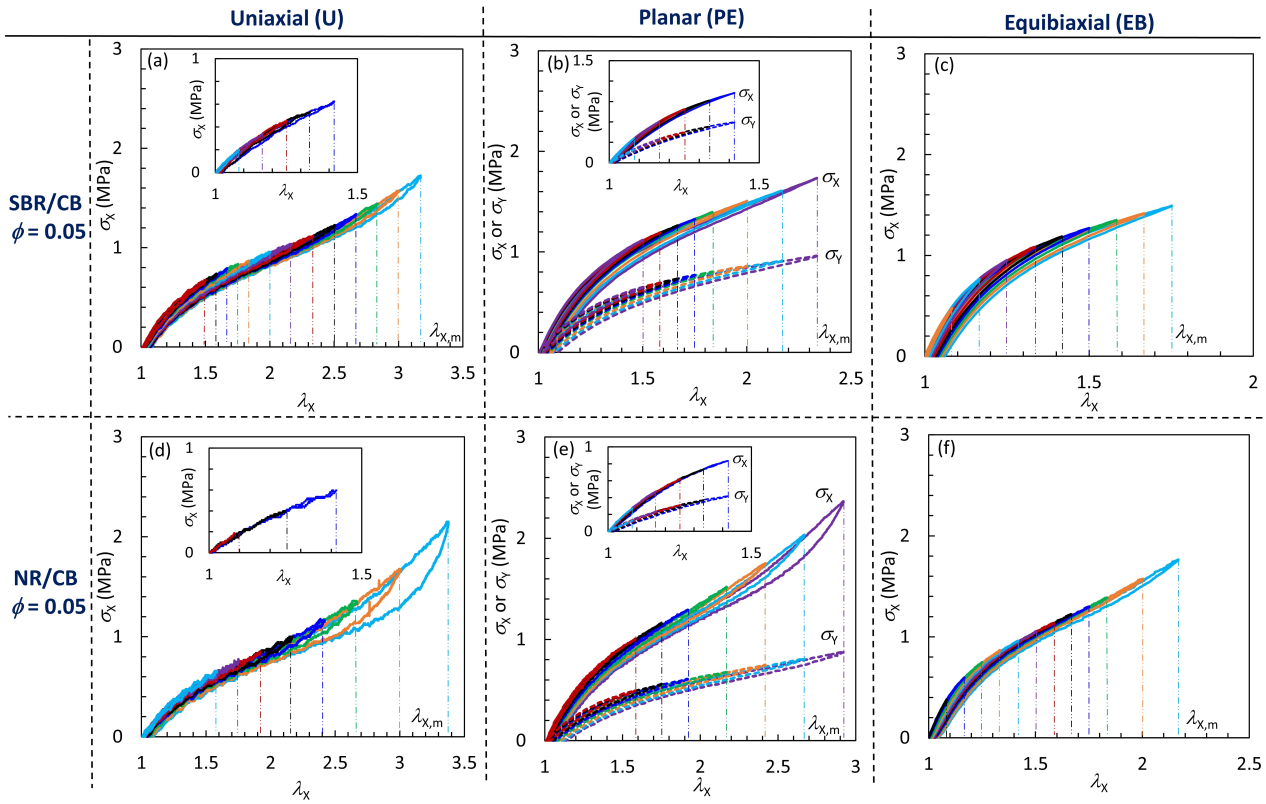

Figure S3. Nominal σ–λ_x relation in loading–unloading cycles with uniaxial, planar, equibiaxial extensions in the x- and y-directions for (a-c) SBR/CB and (d-f) NR/CB with ϕ = 0.05. The vertical dashed lines point out the $\lambda_{x,m}$ values in each cycle. The insets in figures are the magnifications of the small λ_x region.

4. Loading-unloading cycles under various deformation types for unfilled SBR and NR

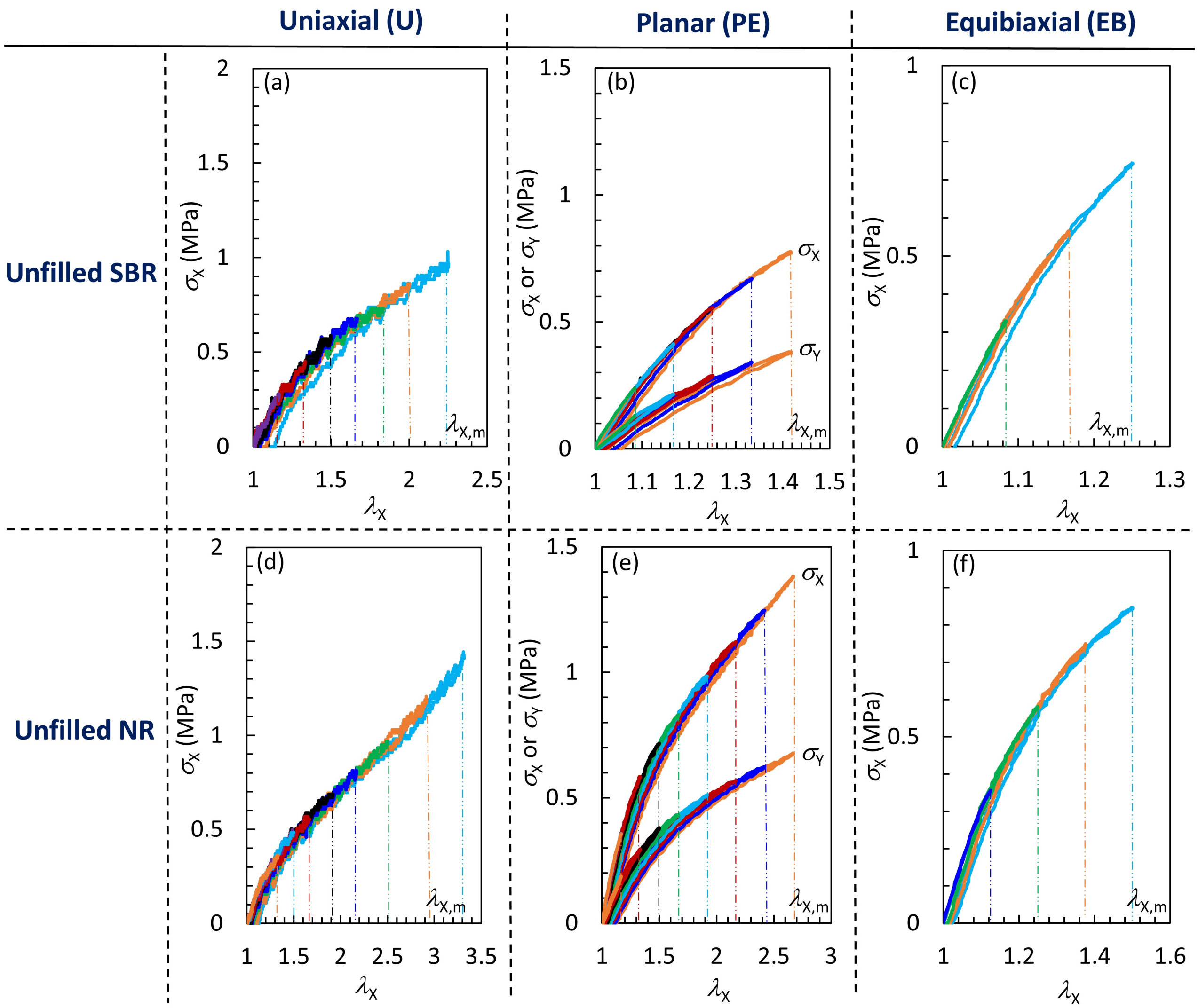

Figure S4. Nominal σ–λ_x relation in loading–unloading cycles with uniaxial, planar, equibiaxial extensions in the x- and y-directions for unfilled (a-c) SBR and (d-f) NR. The vertical dashed lines point out the $\lambda_{x,m}$ values in each cycle.

5. Loading-unloading cycles under unequal biaxial extension for SBR/CB with $\phi = 0.14$ and 0.05.

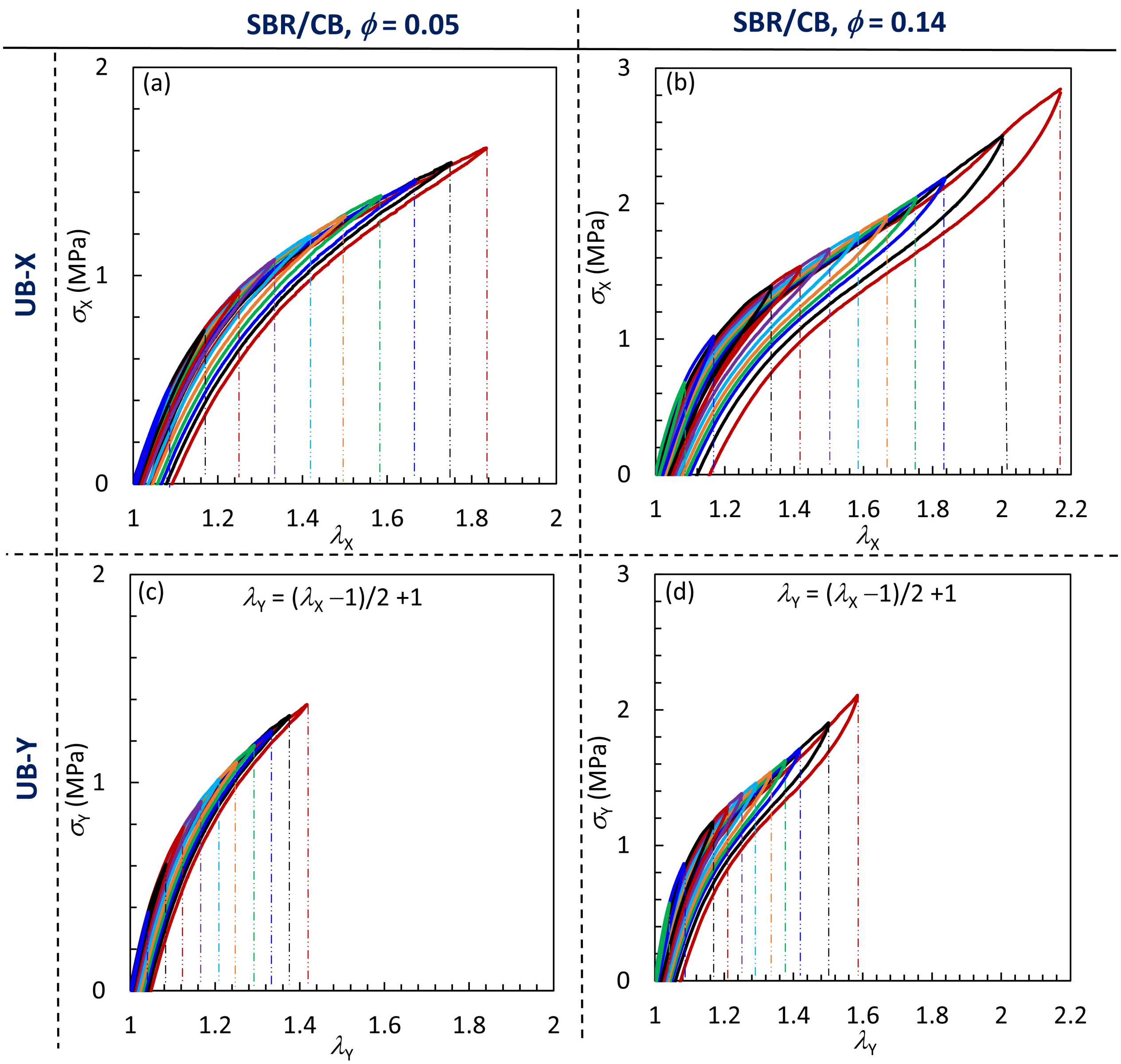

Figure S5. Nominal σ_x–λ_x and σ_y–λ_y relations in loading–unloading cycles with unequal biaxial extensions in the (a-b) x- and (c-d) y-directions for SBR/CB with $\phi = 0.05$ and 0.14. The vertical dashed lines point out the $\lambda_{x,m}$ values in each cycle.

6. Pristine loading under various deformation types for SBR/CB with various ϕ

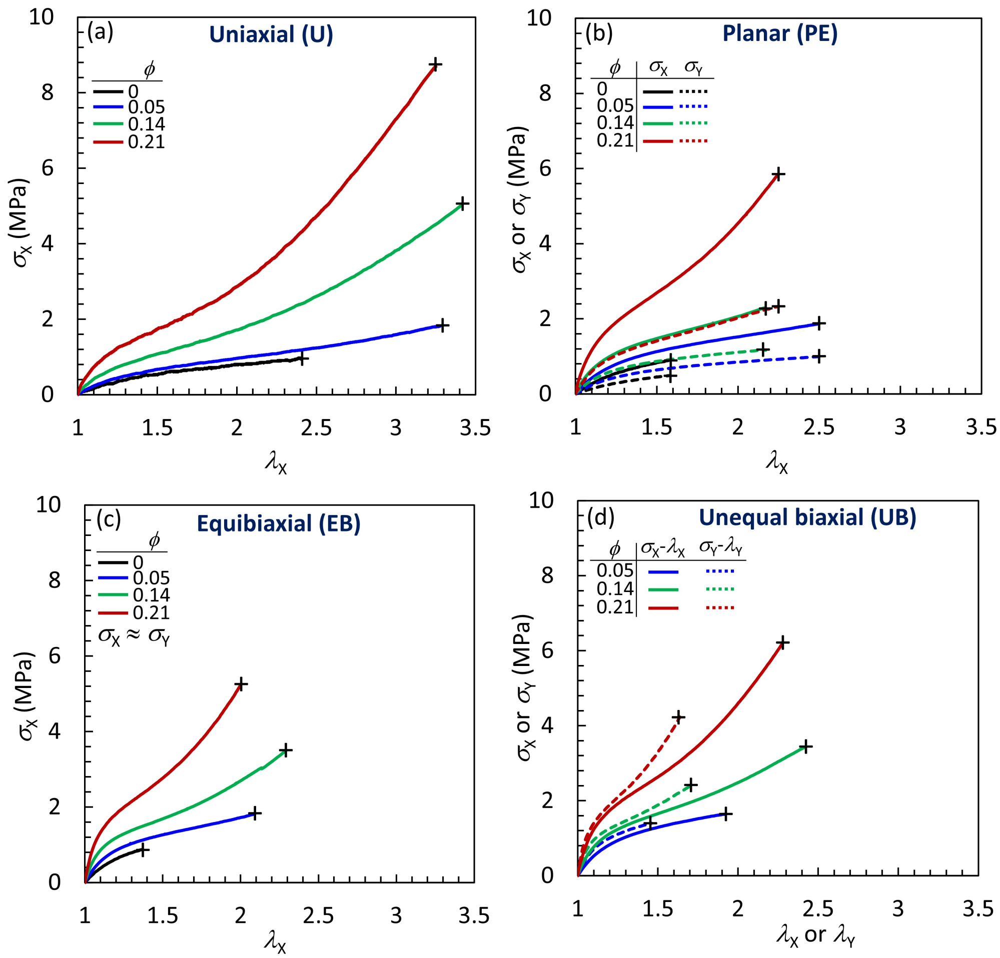

Figure S6. Nominal stress (σ_x or σ_y) elongation (λ_x or λ_y) curves under pristine loading with (a) uniaxial, (b) planar, (c) equibiaxial, and (d) unequal biaxial extensions for SBR/CB with various volume fractions of CB (ϕ). The cross symbols denote the rupture points.

7. Pristine loading under various deformation types for NR/CB with various ϕ

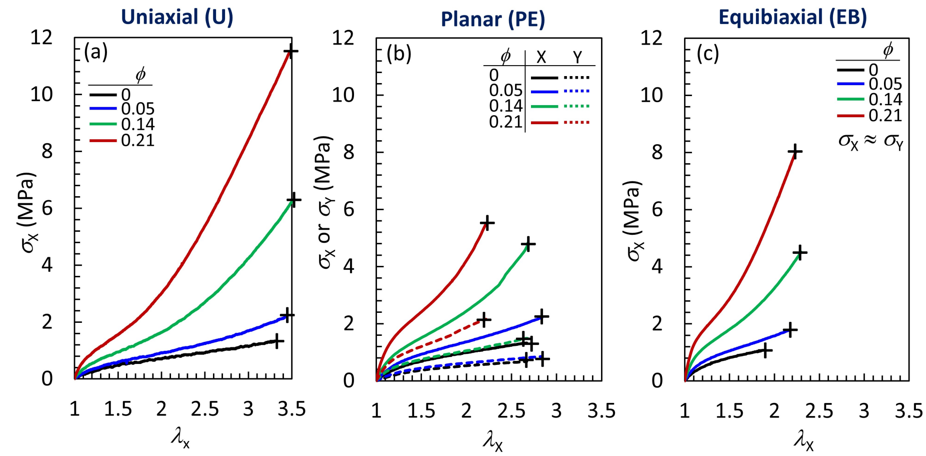

Figure S7. Nominal σ_x–λ_x curves under pristine loading with (a) uniaxial, (b) planar, and (c) equibiaxial extensions for NR/CB with various values of ϕ. The cross symbols denote the rupture points.

8. Energy dissipation per unit volume (D) under various deformation types for SBR/CB and NR/CB with various ϕ

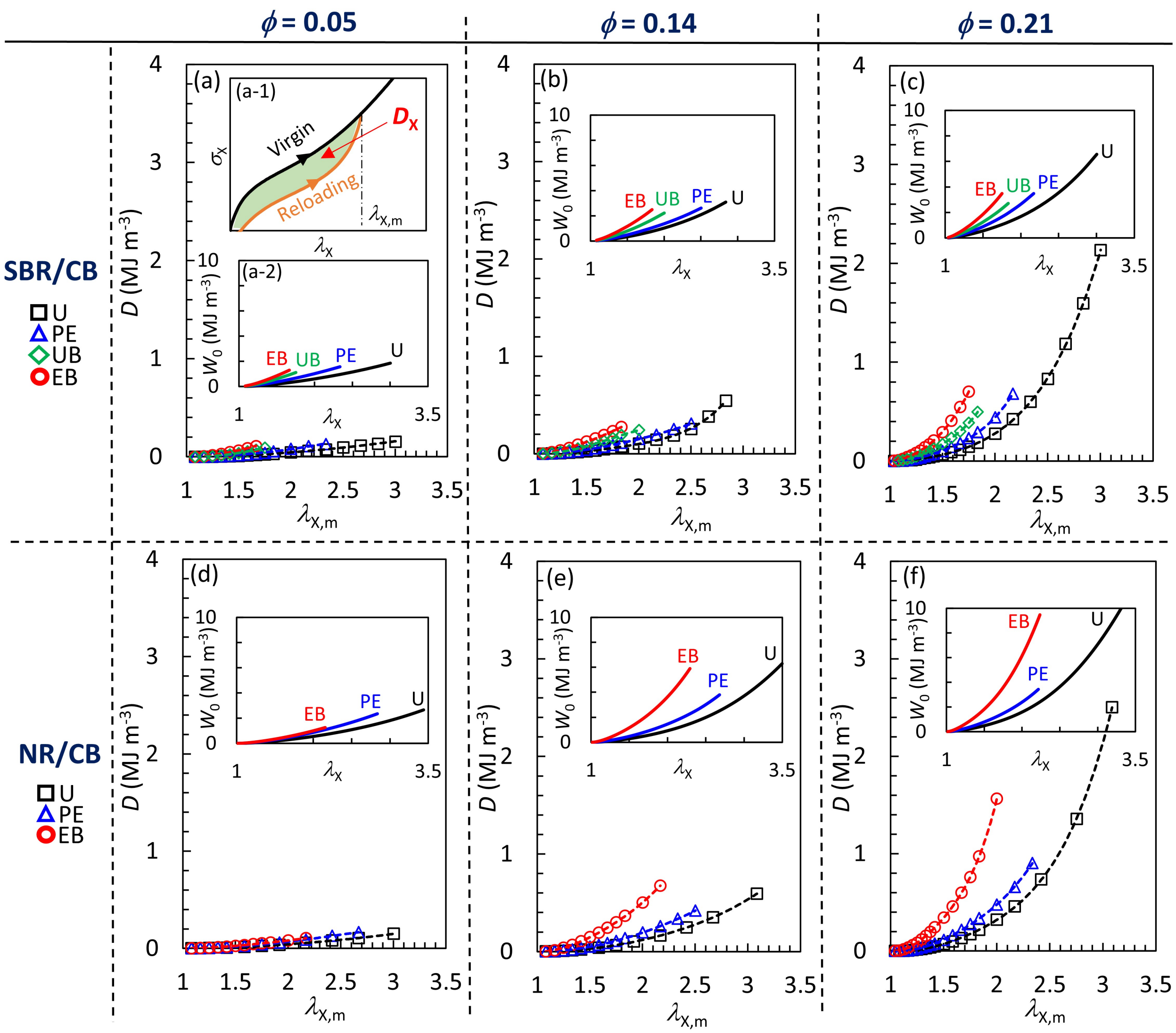

Figure S8. Energy dissipation (D) as a function of $\lambda_{x,m}$ under various deformation types for (a–c) SBR/CB and (d–f) NR/CB with ϕ = 0.05, 0.14, and 0.21. The inset in (a) illustrates the estimation of $D(\lambda_{x,m})$ from the pristine loading and reloading curves. The insets in (a)–(f) show the mechanical work per unit volume in pristine loading (W_0) as a function of λ_x. The dashed lines in each figure represent guides for the eyes.

9. Mechanical and electrical recoveries by thermal annealing of SBR/CB with $\phi = 0.14$

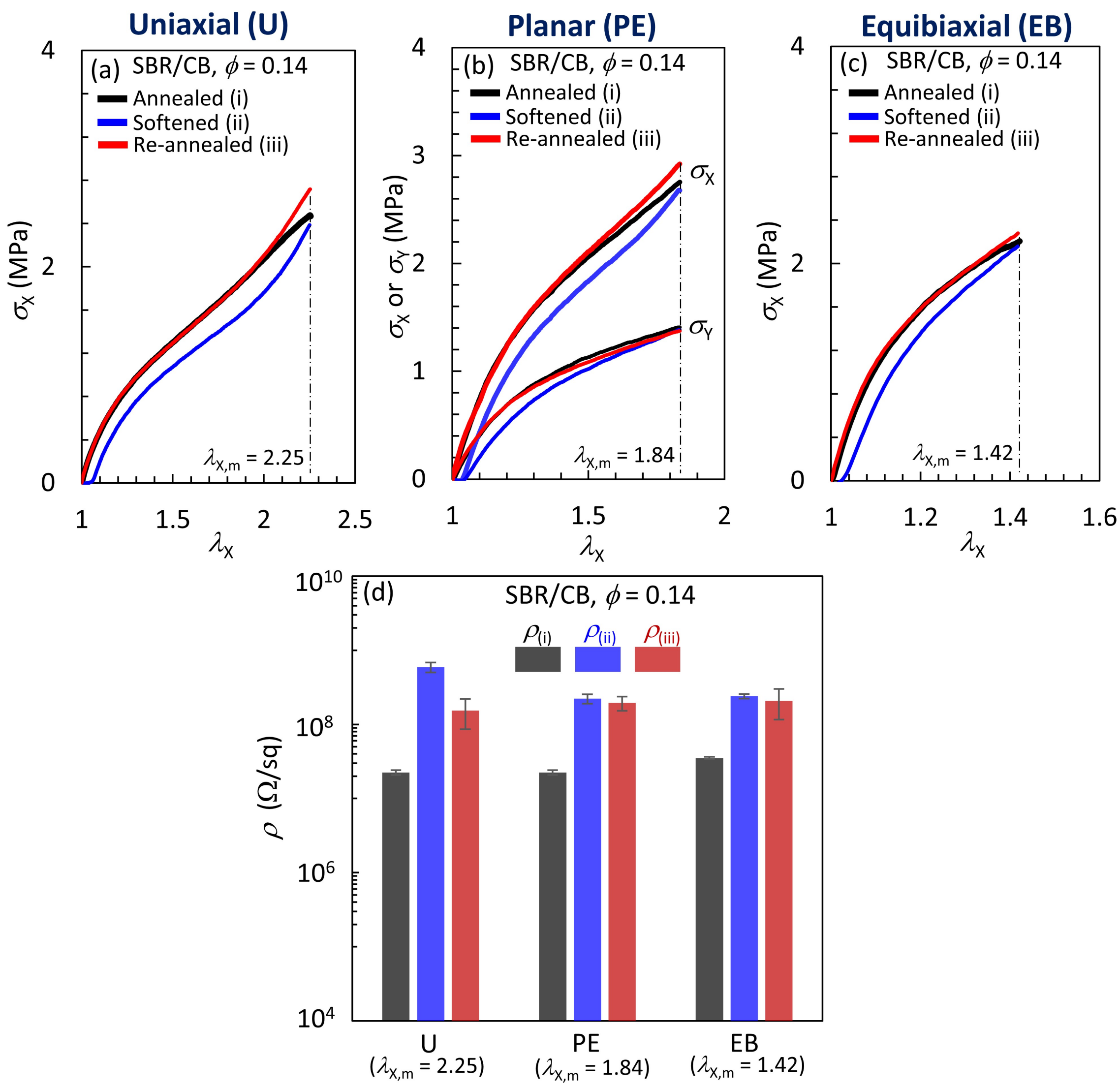

Figure S9. Comparison of (a-c) nominal σ–λ_X relation under a single loading–unloading cycle and (d) surface electrical resistivity (ρ) among the three specimens (i), (ii), and (iii) for SBR/CB with $\phi = 0.14$ in each of uniaxial (U), planar (PE), and equibiaxial (EB) extensions. The error bar in each column chart indicates the standard deviation.

10. Stresses as a function of the first invariant (I_1) under various deformation types

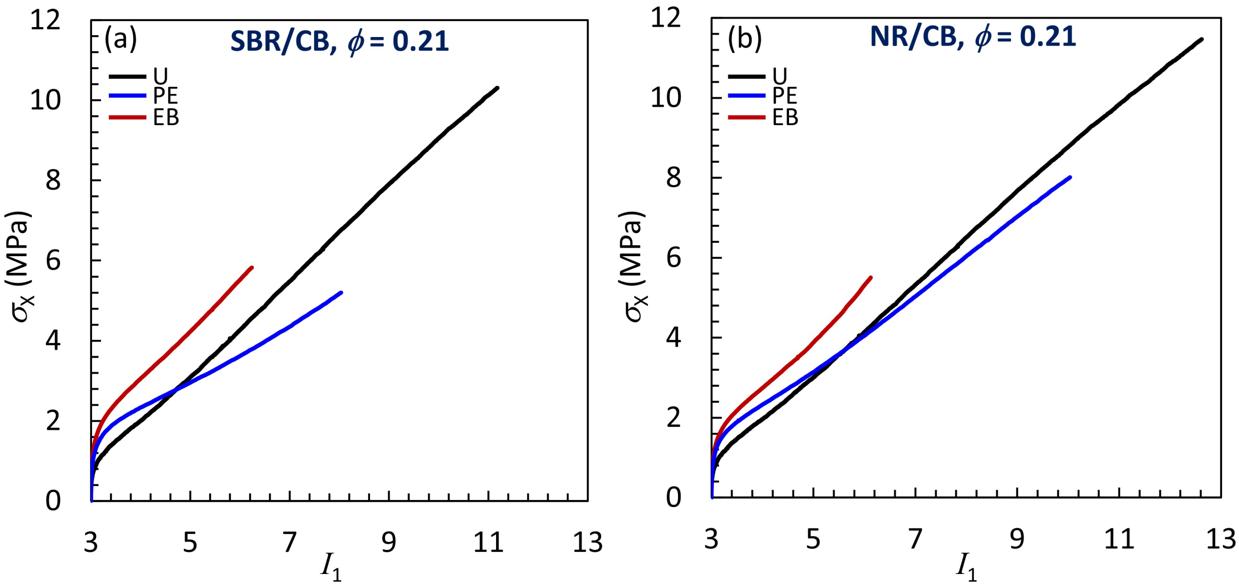

Figure S10. Nominal σ_x–I_1 relation under various deformation types for (a) SBR/CB and (b) NR/CB with ϕ = 0.21. The σ_x values were reproduced from Figures S2-S3.