Electronic Supplementary Information

Elastic/viscoelastic polymer bilayers: A model-based approach to intelligent stretchable constructs

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Supporting Movie S1. Bilayer cross grasping and lifting a foam piece following tensioning and release.
Supporting Movie S2. Bilayer curvature testing for a 20 mm extension at an extension rate of 2 mm/s and a 60 s hold.

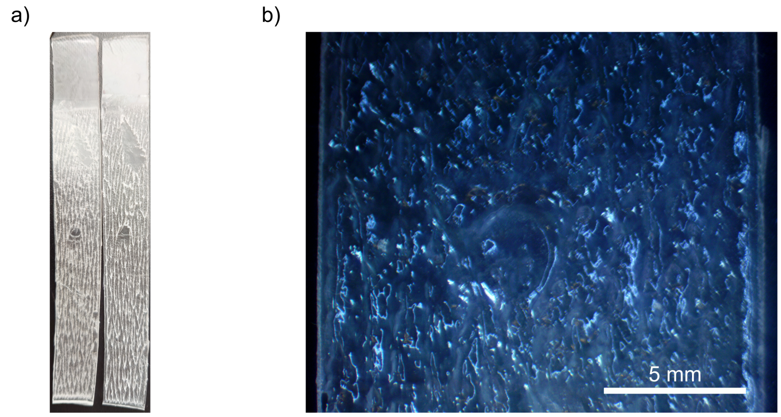

Fig. S1 SEPS-butyl trilayer post adhesion testing photographs. a) Two halves of the SEPS-butyl trilayer shortly following T-peel test described in Subsection 2.5. b) Microscope imaging of one half of the SEPS-butyl trilayer (magnification factor 4x). Note that the raised bumps are the butyl after undergoing cohesive failure. An air pocket can also be observed.

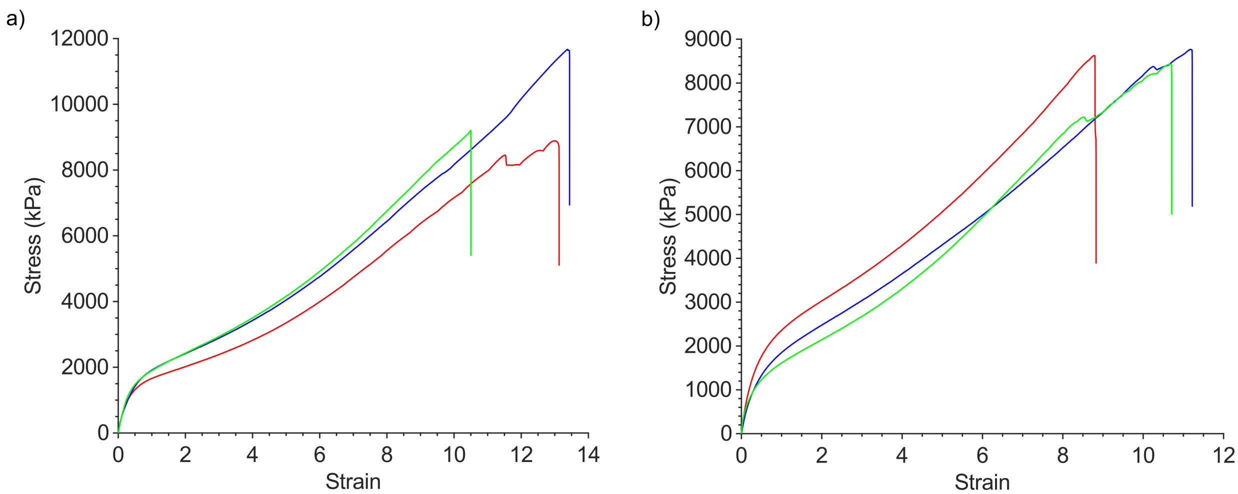

Fig. S2 a) SEPS 2002 and b) SEPS 2004 tensile engineering stresses as a function of engineering strain until failure at 0.50 mm/s extension rate ($\dot{\varepsilon}$ = 0.037 1/s).

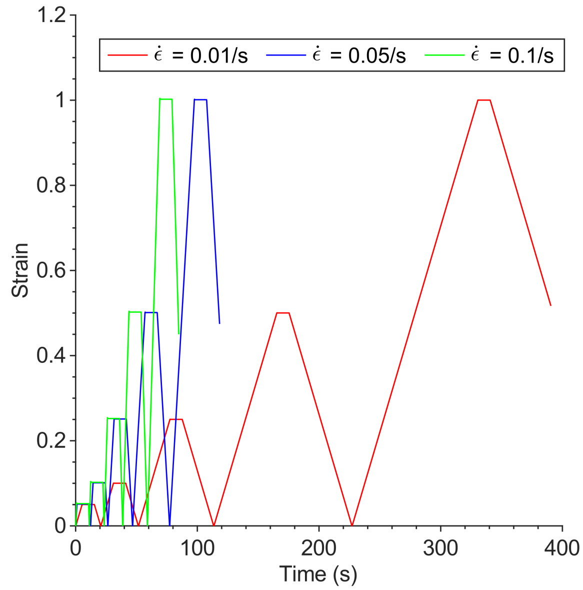

Fig. S3 butyl cyclic uniaxial tension controlled engineering strain over time at varying engineering strain rates $\dot{\varepsilon}$.

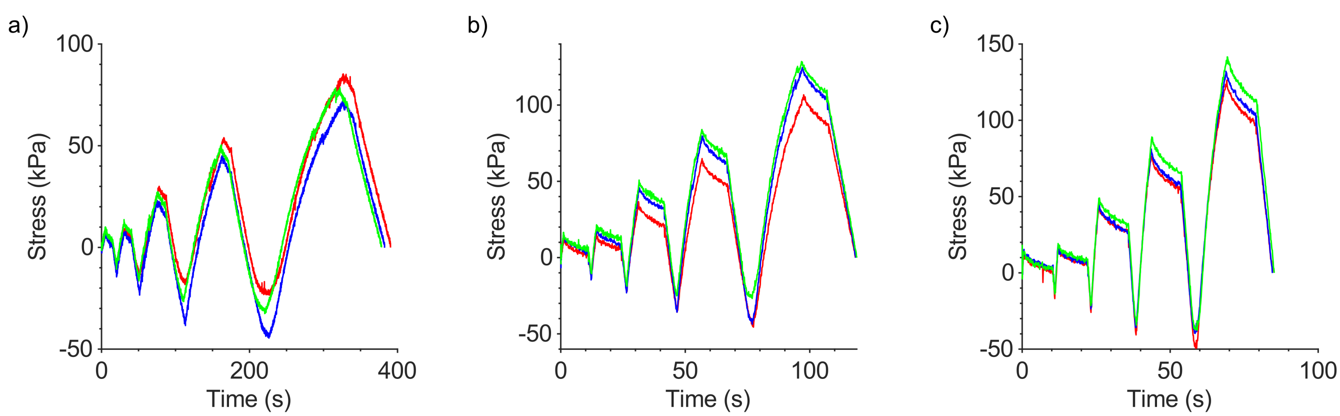

Fig. S4 butyl cyclic uniaxial tension engineering stresses over time at a) 0.01 1/s, b) 0.05 1/s, and c) 0.1 1/s engineering strain rates, $\dot{\varepsilon}$.

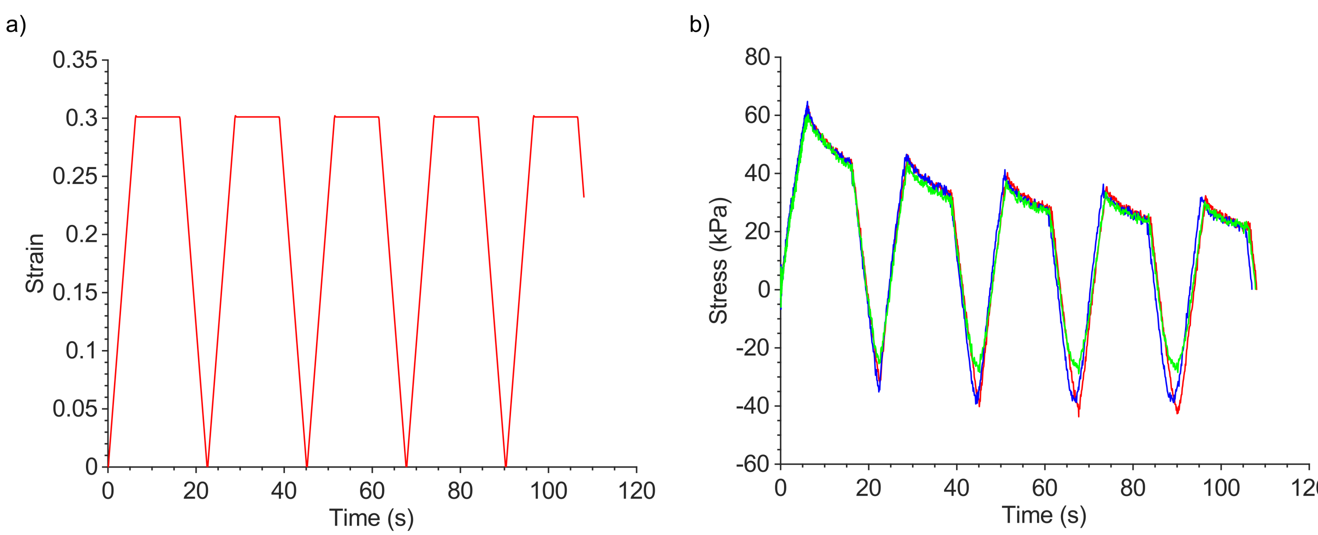

Fig. S5 butyl cyclic uniaxial tension Mullins damage testing. a) Controlled engineering strain over time with a constant engineering strain rate, $\dot{\varepsilon}$ of 0.05 1/s. b) Mullins damage test engineering stresses over time.

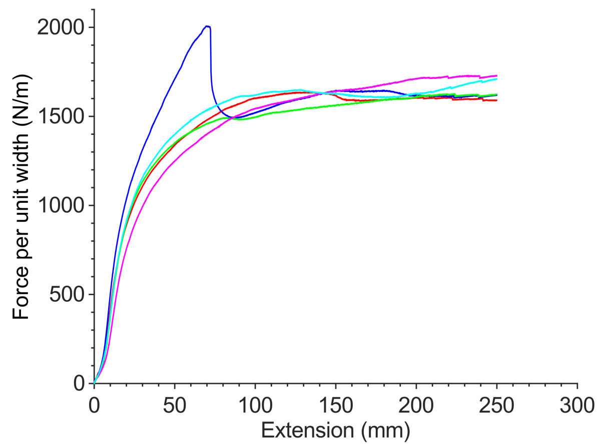

Fig. S6 SIBS-butyl adhesive testing results. Each coloured line corresponds to a different sample trial adhesive test.

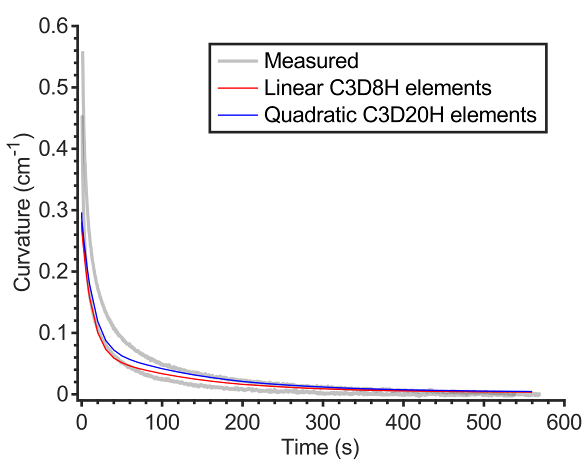

Fig. S7 Shifted measured curvatures and model predicted curvatures using 8-node linear brick and 20-node quadratic brick elements both fully integrated with a constant pressure hybrid formulation. The Generalized Maxwell model with 30 mm extension at an extension rate of 2 mm/s and a 5 s hold is shown for both element types.

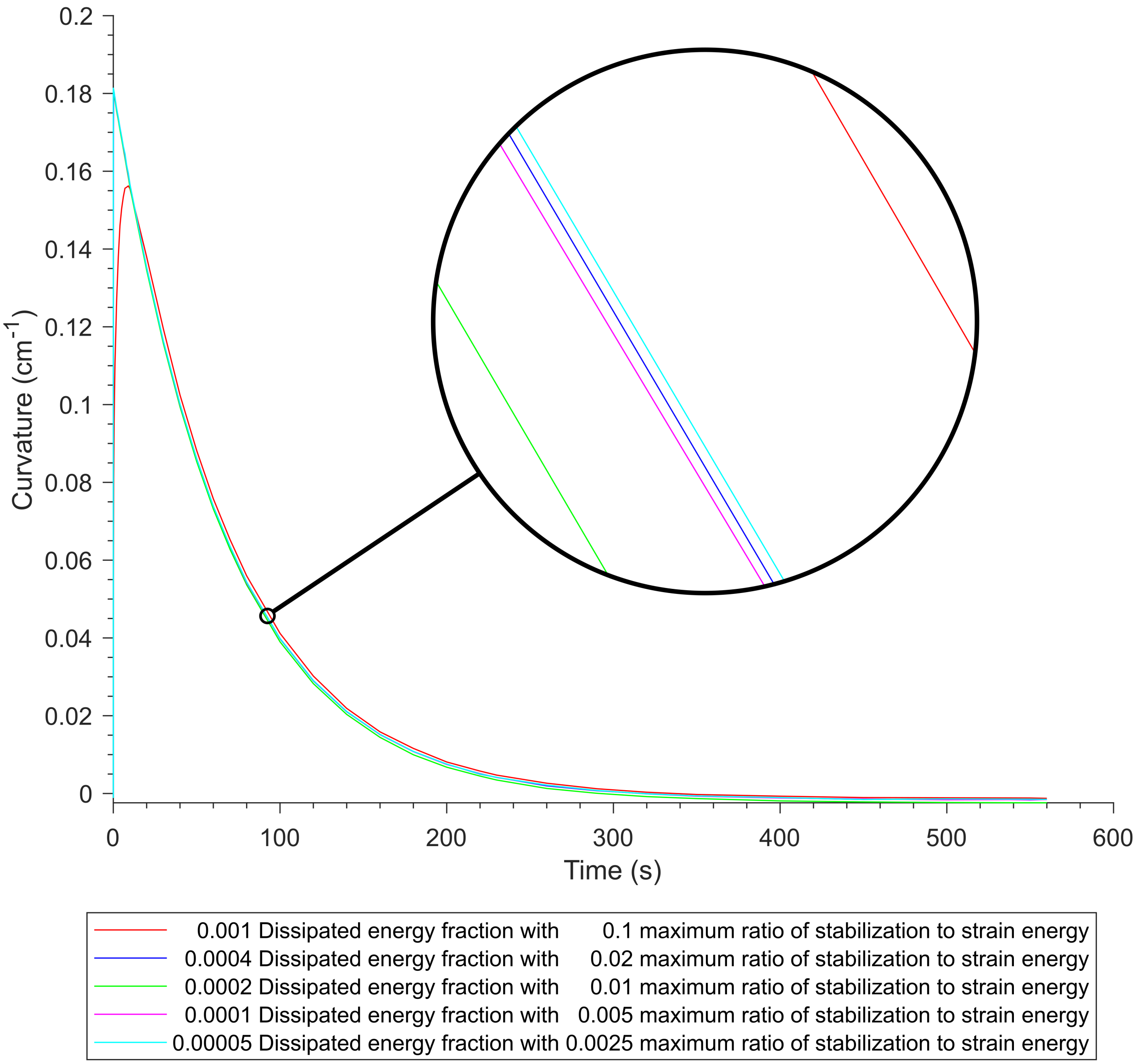

Fig. S8 Converging model predicted curvatures at varying stabilization amounts. The Maxwell model with 30 mm extension at an extension rate of 2 mm/s and a 5 s hold is shown. A 0.0001 dissipated energy fraction with a 0.005 maximum ratio of stabilization to strain energy is utilized in this work.

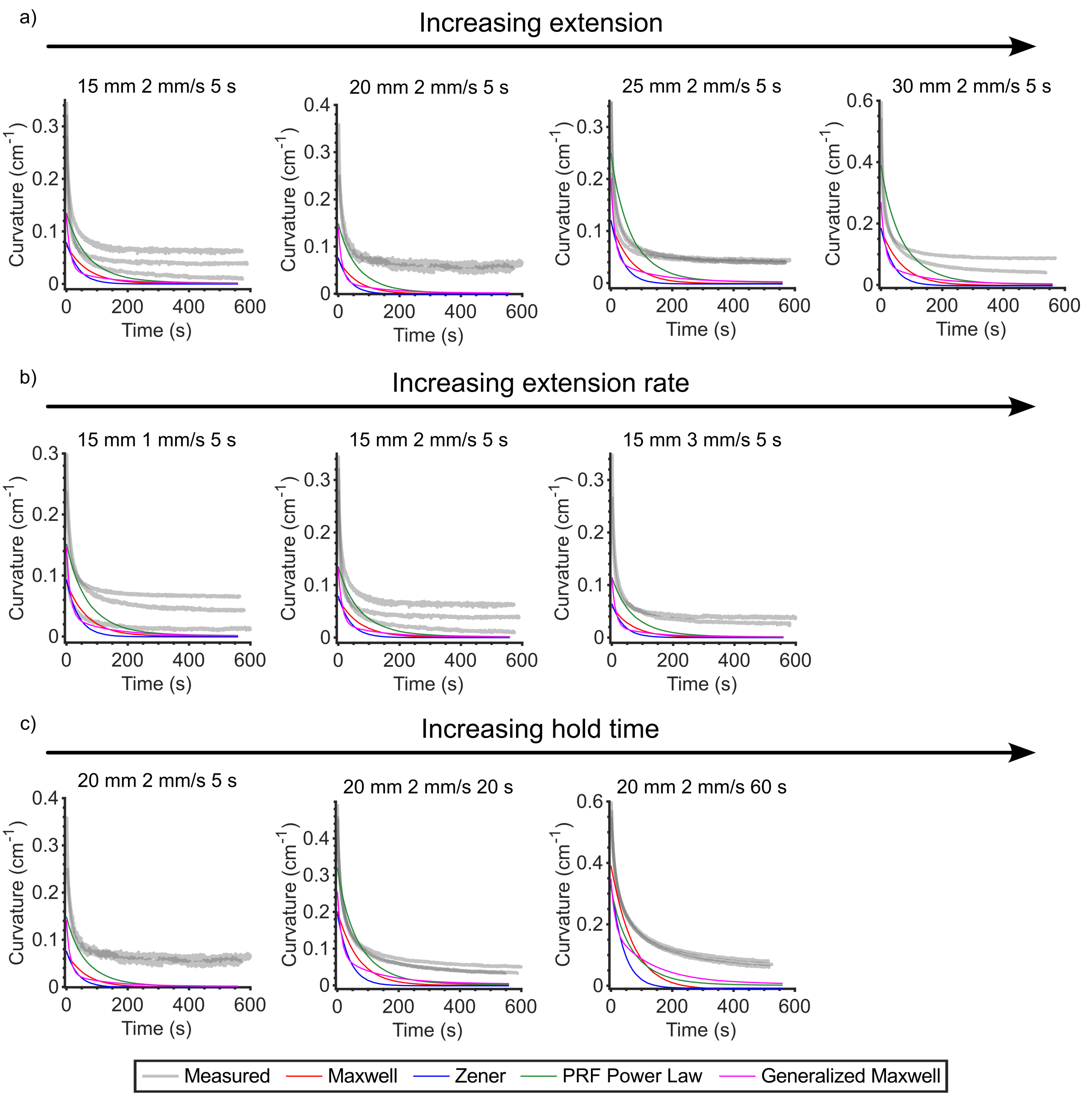

Fig. S9 Unshifted measured curvatures and model predicted curvatures at varying extensions (a), extension rates (b), and hold times (c).

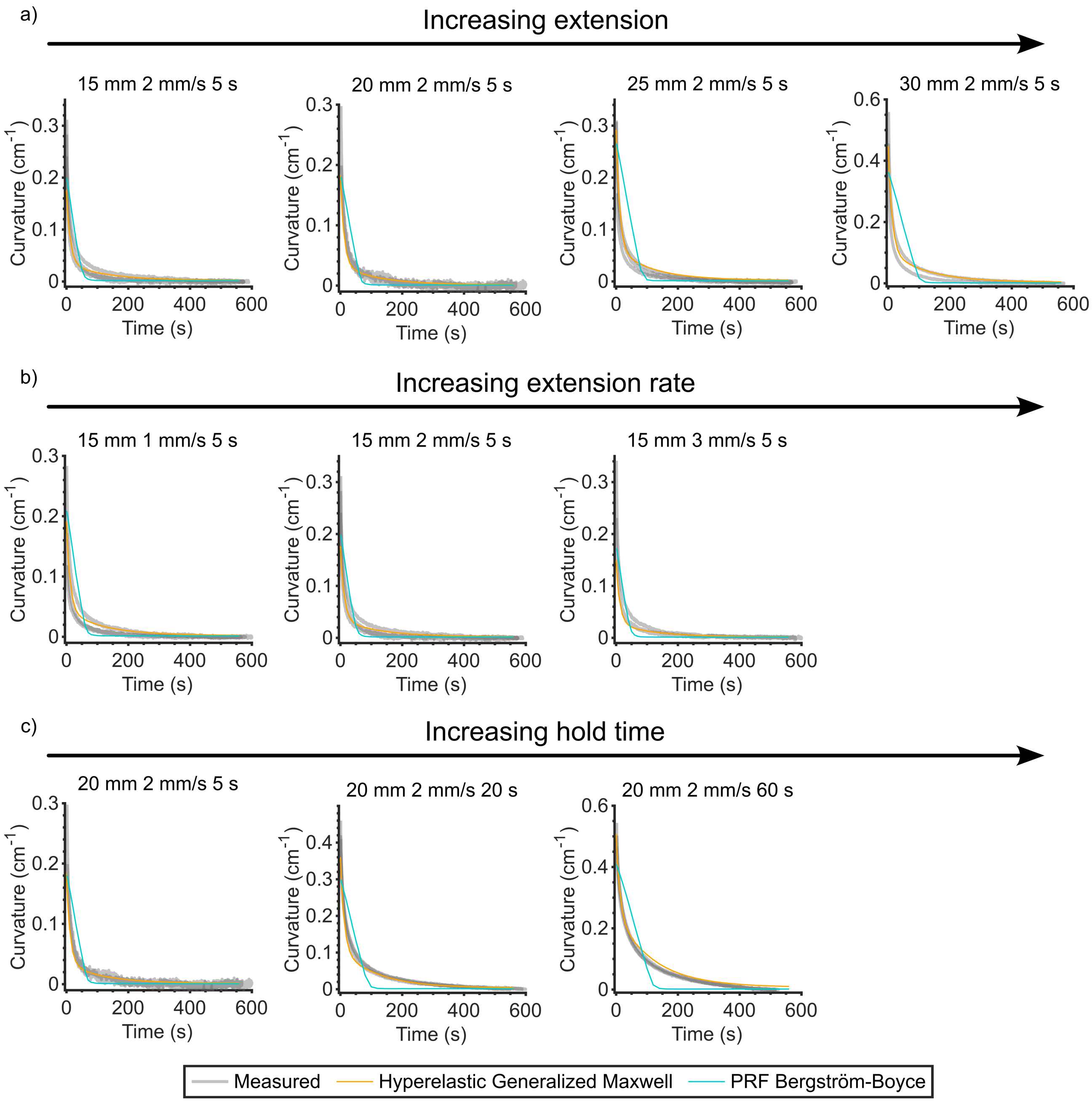

Fig. S10 Shifted measured curvatures and model predicted curvatures for hyperelastic Generalized Maxwell and PRF Bergström-Boyce models at varying extensions (a), extension rates (b), and hold times (c).

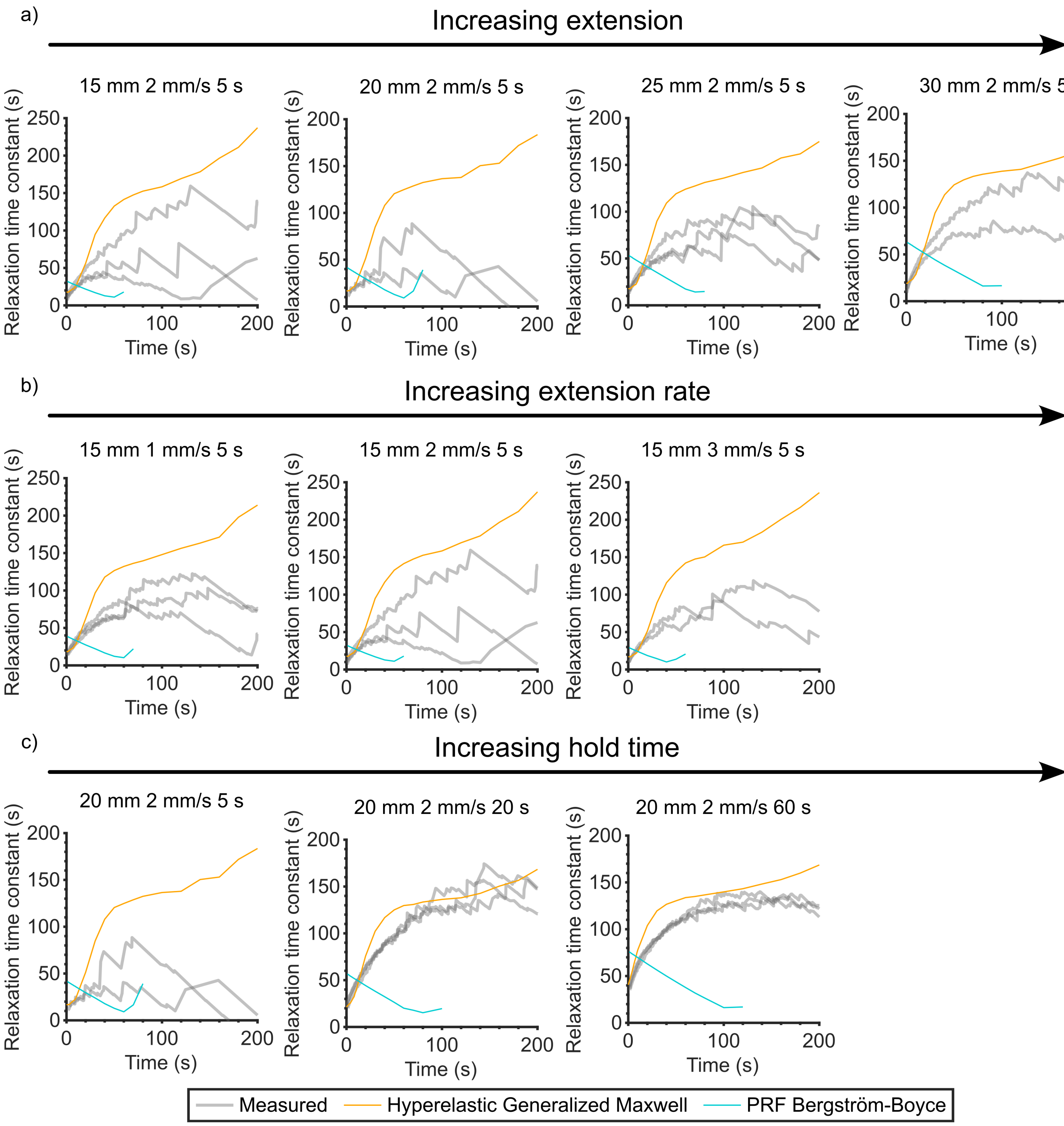

Fig. S11 Curvature relaxation time constant results for shifted measured data and hyperelastic Generalized Maxwell and PRF Bergström-Boyce models at varying extensions (a), extension rates (b), and hold times (c).

Table S1 Average MASE fitnesses of predicted model curvatures to measured bilayer curvatures.

Test Description	Maxwell	Zener	PRF Power Law	Generalized Maxwell	Hyperelastic Generalized Maxwell	PRF Bergström-Boyce
15 mm 1 mm/s 5 s	0.461	0.388	1.246	0.409	0.617	0.886
15 mm 2 mm/s 5 s	0.419	0.442	0.835	0.397	0.427	0.568
15 mm 3 mm/s 5 s	0.373	0.571	0.485	0.399	0.318	0.472
20 mm 1 mm/s 5 s	0.376	0.532	0.717	0.436	0.368	0.576
20 mm 2 mm/s 20 s	0.329	0.665	0.386	0.314	0.150	0.580
20 mm 2 mm/s 60 s	0.450	0.751	0.333	0.206	0.221	0.576
25 mm 2 mm/s 5 s	0.338	0.423	1.364	0.380	0.505	0.986
30 mm 2 mm/s 5 s	0.374	0.508	1.122	0.342	0.417	0.889
Averaged	0.390	0.535	0.811	0.360	0.378	0.692

Table S2 Bilayer curvature testing specimen measurements.

Extension (mm)	Extension rate (mm/s)	Hold time (s)	Total thickness (mm)	SEPS Relative Thickness (%)	Butyl Relative Thickness (%)
15	1	5	2.3	70-80	30-20
15	1	5	2.3	70	30
15	1	5	2.3	60-70	40-30
15	2	5	2.2	70	30
15	2	5	2.2	70	30
15	2	5	2.2	60-70	40-30
15	3	5	2.2	65-70	35-30
15	3	5	2.2	70-80	30-20
20	2	5	1.85	75	25
20	2	5	1.83	80	20
20	2	20	1.87	75	25
20	2	20	1.91	75	25
20	2	20	1.91	65	35
20	2	60	1.82	75	25
20	2	60	1.85	70	30
20	2	60	1.84	65	35
25	2	5	1.85	80	20
25	2	5	1.88	70	30
25	2	5	1.90	70	30
30	2	5	1.78	70-80	30-20
30	2	5	1.80	60-70	40-30

Table S3 FEA mass densities used for SEPS and butyl

SEPS Mass Density (kg/m^3)	Butyl Mass Density (kg/m^3)
910[a]	910[b]

[a] Data from supplier (SEPTON® S2002, Kuraray Co., Ltd.).
[b] Data from supplier (Exxon™ Butyl 268, ExxonMobil).

Table S4 FEA linear elastic model parameters used for SEPS.

Young's Modulus (Pa)	Poisson's Ratio
4696279.36	0.475[a]

[a] Assumed to match Abaqus hyperelastic default.

Table S5 FEA yeoh hyperelastic model parameters used for SEPS.

C_{10}	C_{20}	C_{30}	D_1	D_2	D_3
374152.379	-2509.948	25.7846875	2.53304e-08	0	0

Table S6 FEA maxwell model parameters used for butyl.

Young's Modulus (Pa)	Poisson's Ratio	G_i Prony	K_i Prony	τ_i Prony
399.918534	0.475[a]	0.999	0.999	54.0175253

[a] Assumed to match Abaqus hyperelastic default.

Table S7 FEA zener model parameters used for butyl.

Young's Modulus (Pa)	Poisson's Ratio	G_i Prony	K_i Prony	τ_i Prony
94253.697	0.475[a]	0.760068952	-0.000284331369	31.3700981

[a] Assumed to match Abaqus hyperelastic default.

Table S8 FEA generalized maxwell model parameters used for butyl.

Young's Modulus (Pa)	Poisson's Ratio	G_i Prony	K_i Prony	τ_i Prony
4005.38	0.475[a]	0.0373474	0	0.001
-	-	1.54909E-08	0	0.01
-	-	0.00413878	0	0.1
-	-	0.000230934	0	1.0
-	-	0.374465	0	10
-	-	0.456017	0	100
-	-	0.118548	0	1000

[a] Assumed to match Abaqus hyperelastic default.

Table S9 FEA PRF model Yeoh hyperelastic coefficients used for butyl.

C_{10}	C_{20}	C_{30}	D_1	D_2	D_3
41942.3	23530.2	0.0671298	1.34635e-08	0	0

Table S10 FEA PRF model viscoelastic coefficients used for butyl.

NETWORKID	SRATIO	LAW	q_0	n	m	a	$\dot{\varepsilon}_0$
1	0.887179	Power Law	574044	1	-0.0612589	0	0.0576929

Table S11 FEA Hyperelastic generalized maxwell model Yeoh hyperelastic coefficients used for butyl.

C_{10}	C_{20}	C_{30}	D_1	D_2	D_3
54087.5985	-385.649086	610.455863	1.34635046E-08	0	0

Table S12 FEA Hyperelastic generalized maxwell model parameters used for butyl.

G_i Prony	K_i Prony	τ_i Prony
0.0373474	0	0.001
1.54909E-08	0	0.01
0.00413878	0	0.1
0.000230934	0	1.0
0.374465	0	10
0.456017	0	100
0.118548	0	1000

Table S13 FEA PRF Bergström-Boyce model Yeoh hyperelastic coefficients used for butyl.

C_{10}	C_{20}	C_{30}	D_1	D_2	D_3
51879.31999	12423.400575	2.9190714574	1.34635e-08	0	0

Table S14 FEA PRF Bergström-Boyce model viscoelastic coefficients used for butyl.

NETWORKID	SRATIO	LAW	q_0	m	C	E	$\dot{\varepsilon}_0$
1	0.9999948493	BB Power Law	182772223.14	1.0503379324	-0.567767851	5.312947e-05	1

Table S15 Anova test input parameters. The mean shifting amount refers to the average of how much the unshifted curvature plots were uniformly shifted along the curvature axis for all tests with the same extension, extension rate, and time held.

Extension (mm)	Extension rate (mm/s)	Time held (s)	Mean shifting amount
15	1	5	0.0409
15	2	5	0.0378
15	3	5	0.0321
20	2	5	0.0187
20	2	20	0.0391
20	2	60	0.0714
25	2	5	0.0424
30	2	5	0.0634

Table S16 Anova test results for separated extension, extension rate, and time held.

	Degrees of freedom	Sum of squares	Mean squares	F-statistic	P-value
Extension (mm)	3	0.001070	0.0003568	1.092	0.3850
Extension rate (mm/s)	2	0.000092	0.000458	0.140	0.8705
Time held (s)	2	0.004223	0.0021116	6.462	0.0103
Residuals	14	0.004575	0.0003268		

Table S17 Anova test results for the total time under tension, including during the extension process.

	Degrees of freedom	Sum of squares	Mean squares	F-statistic	P-value
Total time (s)	6	0.004777	0.0007961	2.304	0.0889
Residuals	15	0.005183	0.0003455		