Direct correlation of single-molecule properties with bulk mechanical performance for the biomimetic design of polymers

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Supporting Information

Part I. Synthesis and characterization of SB-UPy-DCL monomers, oligomer, and polymer

Part II. X-ray crystal structure of SB-UPy-DCL motif

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Part I. Synthesis and characterization of Stack-blocked UPy-DCL monomers, oligomer, and polymer

General Experimental Information: Unless otherwise noted, reactions were carried out with stirring with a magnetic stirbar at room temperature. Anhydrous solvents were purified through a column of alumina according to the method described by Pangborn et al. before use. All commercial reagents were used as received unless otherwise noted. Flash column chromatography was performed by forced flow of indicated solvent systems over 32 – 63 μ silica gel from Dynamic Adsorbents (Norcross, GA). 1H NMR and 13C NMR spectra were recorded at 500 and 125 MHz, respectively, on Bruker GN-500 or CRYO-500 spectrometers. 1H NMR and 13C NMR chemical shifts are reported as δ values in ppm relative to TMS or residual solvent: CDCl3 (7.26 ppm; 77.0 ppm), or CD2Cl2 (5.30 ppm; 54.0 ppm). 1H NMR data are reported as follows: chemical shift in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet), coupling constants in Hz, and relative integration in number of protons. Multiplets (m) are reported over the range of chemical shift at which they appear. For 13C NMR spectra, only chemical shift values are reported. Mass Spectra were obtained on Micromass LCT (ES-MS, low resolution), Micromass Autospec (ES-MS and GC-MS, high resolution), and Perseptive Biosystems DE STR (MALDI-TOF) instruments. Gel Permeation Chromatography (GPC) traces were obtained on an Agilent 1100 SEC system using a PLGel Mixed-C column from Polymer Labs (Amherst, MA). THF was used as eluting solvent at a flow rate of 1.0 mL/min. Number averaged and weight averaged molecular weight distributions (Mn and Mw, respectively) of samples were measured with respect to polystyrene (PS) standards purchased from Aldrich (Milwaukee, WI). Single molecule force spectroscopy experiments were performed on an Asylum MFP-3D atomic force microscope (AFM) with an Olympus Biolever (nominal spring constants ~30 and ~6 pN/nm) and a gold-coated silicon wafer assembled in a closed fluid cell.

Scheme S1: Synthesis of Stack-blocked UPy-DCL monomers
5-(Benzyloxy)pentanoic acid (S1) A solution of freshly distilled δ-valerolactone (88.2 mL; 95.2 g, 0.951 mol), finely ground KOH (350 g, 4.76 mol), and benzyl chloride (391 mL; 430 g, 3.04 mol) in toluene (1.5 L) was prepared in a 3-neck round-bottom flask equipped with a mechanical stirrer in one neck, a reflux condenser in another, and sealed with a septum on the third. The solution was heated to reflux for 18 h, then cooled to room temperature, after which DI-water (1 L) was added, and the mixture stirred for an additional hour. The aqueous layer was collected, washed with Et$_2$O (1 × 1 L), and concentrated HCl (12.1 M) was added until the pH reached 4-5. The resulting mixture was extracted with Et$_2$O (3 × 0.5 L), after which the combined ethereal layers were washed with brine (1 L), then the solvent evaporated in vacuo. The light yellow oily residue was co-distilled with toluene (2 × 150 mL), then dried and purified by vacuum distillation (lit. b.p. ca. 130 °C at 7.5 mtorr). A small amount of white impurity has a tendency to clog the distilling apparatus, and may be brought over by heat gun with no water flow, and the desired distillate collected separately. Yield: 99.1 g (50%) clear oil.

$^1$H NMR (500 MHz, CDCl$_3$) δ 11.09 (br. s, 1H), 7.36–7.25 (m, 5H), 4.50 (s, 2H), 3.49 (t, $J = 6.1$, 2H), 2.39 (t, $J = 7.3$, 2H), 1.76–1.73 (m, 2H), 1.72–1.65 (m, 2H). $^{13}$C NMR (125 MHz, CDCl$_3$) δ 179.1, 138.4, 128.4, 127.65, 127.57, 72.9, 69.7, 33.6, 29.0, 21.5. ES-MS $m/z$ calcd for C$_{12}$H$_{16}$O$_3$ (M+Na)$^+$ 231.0997, found 231.1003.

Ethyl 7-(benzyloxy)-3-oxoheptanoate (S2) To a solution of compound S1 (40.0 g, 192 mmol) in anhydrous toluene (200 mL) was added catalytic DMF (0.15 mL; 1.9 mmol), followed by dropwise addition of oxalyl chloride (23.6 mL; 34.9 g, 275 mmol) over 1.5 h via an addition funnel. The resulting solution was stirred for an additional 30 min, heated to 55 °C for 2 h, then concentrated in vacuo to afford 5-(benzyloxy)pentanoyl chloride, and the light yellow oil was used in the next step without any further purification. Yield: 43.0 g (99% crude).

In a separate flask, a solution of 2,2-dimethyl-1,3-dioxane-4,6-dione (Meldrum’s acid, 23.3 g, 162 mmol) and anhydrous pyridine (30.0 mL; 30.5 g, 386 mmol) in anhydrous DCM (600 mL) was prepared and chilled to 0 °C. A 1:1 v/v solution of 5-(benzyloxy)pentanoyl chloride (43.0 g, 190 mmol) in anhydrous DCM was added dropwise using an addition funnel, and the reaction was allowed to come to room temperature overnight, then transferred to a separatory funnel and washed with 0.1 M HCl (600 mL). The aqueous layer was extracted with DCM (3 × 300 mL), and the organic layers were combined, dried over Na$_2$SO$_4$, filtered, and the solvent evaporated in vacuo to afford a dark red oil. Absolute ethanol (500 mL) was added to the residue, and mixture was heated to reflux for 16 h. The solvent was evaporated in vacuo and the residue purified by flash chromatography (0 to 18% EtOAc in hexanes; product fractions 14–18% EtOAc). Yield: 34.7 g (65% over two steps), light yellow oil.

$^1$H NMR (500 MHz, CDCl$_3$) δ 7.36–7.25 (m, 5H), 4.49 (s, 2H), 4.19 (q, $J = 7.0$, 2H), 3.47 (t, $J = 6.0$, 2H), 3.42 (s, 2H), 2.57 (t, $J = 7.1$, 2H), 1.74–1.66 (m, 2H), 1.66 – 1.60 (m, 2H), 1.27 (t, $J = 7.1$, 3H). $^{13}$C NMR (125 MHz, CDCl$_3$) δ 202.7, 167.2, 138.5, 128.4, 127.65, 127.55, 72.9, 69.9, 61.4, 49.3, 42.7, 29.0, 20.3, 14.1. ES-MS $m/z$ calcd for C$_{16}$H$_{22}$O$_4$ (M+Na)$^+$ 301.1416, found 301.1412.

Ethyl 2-(5-(benzyloxy)pentanoyl)tridec-12-enoate (S3) To a solution of compound S2 (2.00 g, 7.19 mmol) in DMF (24 mL) was added K$_2$CO$_3$ (1.99 g, 14.37 mmol) and 11-bromoundec-1-ene (1.73 mL; 1.84 g, 7.90 mmol), and suspension was stirred for 16 h at room temperature. Following removal of solvent under reduced pressure, the residue was partitioned between Et$_2$O and DI-water (30 mL each). The aqueous layer was extracted with Et$_2$O (1 × 30 mL), after
which the ethereal layers were combined and washed with brine (30 mL), dried with MgSO₄, filtered, and the solvent evaporated in vacuo. The residue thus obtained was purified by flash chromatography (0 to 8% EtOAc in hexanes; product fractions 6–8% EtOAc; dialkylated side-product also elutes at 6%; the desired product elutes slightly later) to obtain the desired compound as a yellow liquid. Yield: 1.22 g (40%).

1H NMR (500 MHz, CDCl₃) δ 7.36–7.25 (m, 5H), 5.81 (ddt, J = 16.8, 10.0, 6.8, 1H), 4.99 (d, J = 17.3, 1H), 4.93 (d, J = 9.9, 1H), 4.49 (s, 2H), 4.17 (q, J = 7.1, 2H), 3.47 (t, J = 6.1, 2H), 3.40 (t, J = 6.8, 2H), 1.24 (m, 15H). 13C NMR (125 MHz, CDCl₃) δ 205.4, 170.0, 139.2, 138.5, 128.4, 127.6, 127.5, 114.1, 72.9, 70.0, 61.2, 59.2, 41.5, 33.8, 29.5, 29.43, 29.36, 29.3, 29.1, 29.0, 28.9, 28.2, 27.5, 20.3, 14.1. ES-MS m/z calced for C₂₇H₄₂O₄ (M+Na)+ 453.2981, found 453.2960.

2-Amino-6-(4-(benzylxy)butyl)-5-(undec-10-enyloxypyrimidin-4(1H)-one (S4) Compound S3 (1.21 g, 2.81 mmol) was dissolved in absolute ethanol (14 mL) in a round-bottom flask equipped with a reflux condenser, to which guanidine carbonate (0.515 g, 2.81 mmol) was added, and the solution was heated to reflux for 24 h. The solvent was removed in vacuo, and the resulting residue was dissolved in a small volume of DCM, loaded onto a silica gel column, followed by purification via flash chromatography (0 to 5% methanol in DCM; product fraction 4–5% methanol). Yield: 0.587 g (49%) white solid.

1H NMR (500 MHz, CDCl₃) δ 7.35–7.25 (m, 5H), 6.71 (br. s, 1H), 5.80 (ddt, J = 17.6, 7.1, 1H), 2.08–1.99 (m, 4H), 1.81–1.77 (m, 2H), 1.70–1.61 (m, 4H), 1.49–1.43 (m, 2H), 1.40–1.15 (m, 17H). 13C NMR (125 MHz, CDCl₃) δ 205.4, 170.0, 139.2, 138.5, 128.4, 127.6, 127.5, 114.1, 72.9, 70.0, 61.2, 59.2, 41.5, 33.8, 29.5, 29.4, 29.3, 29.1, 29.0, 28.9, 28.2, 27.5, 20.3, 14.1. ES-MS m/z calced for C₂₇H₄₂O₄ (M+Na)+ 453.2981, found 453.2960.

4-Iodo-2,6-diisopropylaniline (S5) A solution of 2,6-diisopropyl aniline (12.7 g, 71.8 mmol) was prepared in a 2:1 mixture of DCM and methanol (360 mL / 180 mL) in a round-bottom flask. Benzyltrimethylammonium dichloroiodate (25 g, 71.8 mmol) and CaCO₃ (7.91 g, 79.0 mmol) were added sequentially. The solution was heated to reflux for 24 h. After removal of solvent in vacuo, the residue thus obtained was purified by flash chromatography (0 to 10% EtOAc in hexanes; product fractions 8–10% EtOAc). Yield: 10.1 g (95%) viscous red-orange liquid.

1H NMR (500 MHz, CDCl₃) δ 7.32–7.24 (m, 5H), 6.56 (s, 2H), 5.81 (ddt, J = 17.0, 10.2, 6.1, 1H), 4.97 (d, J = 6.9, 2H), 2.29 (t, J = 7.3, 2H), 2.03 (q, J = 7.0, 2H), 1.71–1.65 (m, 4H), 1.42–1.32 (m, 2H), 1.30–1.20 (m, 14H). 13C NMR (125 MHz, CDCl₃) δ 154.3, 139.2, 138.2, 128.5, 127.8, 127.7, 114.1, 73.1, 70.4, 33.8, 29.9, 29.7, 29.6, 29.5, 29.2, 29.1, 28.9, 25.7, 25.1. ES-MS m/z calced for C₅₀H₇₆N₄O₄ (M+Na)+ 819.5764, found 819.5743. MALDI-TOF calcd for C₅₀H₇₆N₄O₄ (M+H)+ 797.6, found 797.9.

2,6-Diisopropyl-4-(undec-10-enyloxy)aniline (S6) In a round-bottom flask, compound S5 (1.00 g, 3.30 mmol) was dissolved in anhydrous toluene (10 mL) and 10-undecene-1-ol (2.64 mL; 2.24 g, 13.2 mmol), cesium carbonate (2.15 g, 6.60 mmol), anhydrous 1,10-phenanthroline (0.472 g, 2.64 mmol), and copper (I) iodide (0.252 g, 1.32 mmol) were added sequentially. The mixture was stirred (for large scale reactions, a mechanical stirrer was used) for 48 h while heating to reflux. The reaction mixture was cooled to room temperature, and filtered through a 1.5 × 3 cm pad of silica gel, eluting with EtOAc. The filtrate was concentrated in vacuo and...
purified by flash chromatography (0 to 70% DCM in hexanes; product fractions 30–70% DCM). The resulting oil was further purified by vacuum distillation (0.1 torr, 110-130 °C). Yield: 1.00 g (88%) of dark red oil.

1H NMR (500 MHz, CD2Cl2) δ 6.56 (s, 2H), 6.37 (d, J= 17.0, 10.2, 6.1, 1H), 4.97 (d, J= 17.1, 1H), 4.90 (d, J= 10.2, 1H), 3.85 (t, J= 6.6, 2H), 3.41 (br. s, 2H), 2.92 (septet, J= 6.8, 2H), 2.02 (q, J= 7.0, 2H), 1.70 (quintet, J= 7.0, 2H), 1.45–1.39 (m, 2H), 1.38–1.27 (m, 22H). 13C NMR (125 MHz, CDCl3) δ 152.4, 139.3, 134.3, 133.7, 114.1, 109.4, 68.4, 33.8, 29.6, 29.55, 29.46, 29.4, 29.1, 28.9, 28.2, 26.1, 22.5. GC-MS m / z calcd for C23H39NO (M+) 345.3032, found 345.3035.

1-(6-(4-(Benzyloxy)butyl)-4-oxo-5-(undec-10-enyl)-1,4-dihydropyrimidin-2-yl)-3-(2,6-diisopropyl-4-(undec-10-enyloxy)phenyl)urea (S7) In a round-bottom flask, compound S6 (6.94 g, 20.3 mmol) was dissolved in anhydrous DCM (80 mL), and the solution was cooled to 0 °C in an ice bath. Phosgene (13.5 mL, 1.93 M in toluene; 2.58 g, 26.1 mmol) was added, followed by anhydrous pyridine (6.47 mL; 63.6 g, 80.4 mmol), and the reaction was stirred for 2 h at 0 °C. Dry nitrogen gas was then bubbled through the mixture for 10 min to remove unreacted phosgene, after which the reaction mixture was filtered. The solvent was then removed in vacuo, the filtrate re-suspended in benzene, filtered again, and the filtrate once again evaporated in vacuo. The resulting residue was dissolved in anhydrous pyridine (80 mL), then added to a round-bottom flask charged with compound S4 (5.70 g, 13.4 mmol), and allowed to react for 17 h. After removal of solvent in vacuo, the residue was purified by flash chromatography (0 to 10% EtOAc in hexanes; product fractions 8–10% EtOAc). Yield: 10.1 g (95%) viscous red-orange liquid.

1H NMR (500 MHz, CDCl3) δ 13.02 (s, 1H), 12.52 (s, 1H), 11.72 (s, 1H), 7.32–7.24 (m, 5H), 6.73 (s, 2H), 5.82 (ddt, J= 17.1, 10.4, 6.6, 1H), 5.80 (ddt, J= 17.1, 10.5, 6.6, 1H), 5.00 (d, J= 17.1, 1H), 4.98 (d, J= 9.2, 1H), 4.92 (d, J= 8.9, 1H), 4.46 (s, 2H), 3.96 (t, J= 6.5, 2H), 3.44 (t, J= 5.8, 2H), 3.16 (septet, J= 6.8, 2H), 2.49 (t, J= 7.1, 2H), 2.29 (t, J= 7.3, 2H), 2.08–1.99 (m, 4H), 1.81–1.77 (m, 2H), 1.70–1.61 (m, 4H), 1.49–1.43 (m, 2H), 1.40–1.15 (m, 36H). 13C NMR (125 MHz, CDCl3) δ 172.2, 158.7, 156.8, 153.5, 148.1, 146.3, 139.3, 138.3, 128.4, 127.59, 127.55, 124.1, 118.4, 114.11, 114.08, 109.3, 73.0, 69.6, 67.8, 33.8, 31.6, 30.2, 29.6, 29.54, 29.50, 29.47, 29.44, 29.42, 29.3, 29.14, 29.10, 28.94, 28.91, 26.1, 24.7, 24.2, 23.0, 22.7, 14.1. ES-MS m / z calcd for C50H76N4O4 (M+H)+ 797.6, found 797.9. MALDI-TOF m / z calcd for C30H76N4O4 (M+H)+ 797.6, found 797.9.

Stack-blocked UPy-DCL diol (S8) Compound S7 (2.00 g, 5.32 mmol) was dissolved in degassed, anhydrous DCM (140 mL) in a two-neck round-bottom flask equipped with a reflux condenser in one neck and sealed with a septum in the other. Upon heating the solution to reflux, Grubbs generation I catalyst (104.0 mg, 0.12 mmol) was degassed and heated at reflux for 15 min, the reaction mixture was allowed to cool to room temperature, then directly loaded onto a silica gel column for purification by flash chromatography (0 to 4% EtOAc in chloroform; product fraction 4% EtOAc). The product fractions were pooled and evaporated in vacuo to produce light brown solid (1.1 g). This solid was then dissolved in degassed, anhydrous THF (30 mL). After degassing for an additional 5 min, Pd(OH)2 on activated carbon (0.2 g, 0.53 mmol) was added under nitrogen, and the solution was degassed for an additional 10 min, then purged pressurized with H2 to 300 psi. The mixture was stirred at room temperature for 18 h, then filtered with suction over celite, the celite bed washed further with chloroform, and the filtrate evaporated under reduced pressure. The
resulting solid was dissolved in a minimum volume of chloroform, and loaded onto a silica gel column. Flash chromatography (0 to 10% acetone in DCM), and the pure fractions combined and evaporated to afford the product as a white solid. Yield: 0.70 g (37% over two steps).

\[ \text{1H NMR (500 MHz, CDCl}_3\) } \delta 13.01 (s, 2H), 12.51 (s, 2H), 11.74 (s, 2H), 6.75 (s, 4H), 4.00 (t, \text{J} = 6.1, 4H), 3.62 (t, \text{J} = 6.0, 4H), 3.16 (septet, \text{J} = 6.7, 4H), 2.52 (t, \text{J} = 7.4, 4H), 2.32–2.26 (m, 4H), 1.82–1.78 (m, 4H), 1.68–1.63 (m, 4H), 1.59–1.48 (m, 6H), 1.40–1.15 (m, 92H).  

\[ \text{13C NMR (125 MHz, CDCl}_3\) } \delta 173.8, 172.3, 158.8, 156.9, 153.6, 148.2, 146.2, 124.1, 118.6, 109.2, 67.4, 62.1, 31.9, 30.3, 30.0, 29.7, 29.63, 29.60, 29.4, 29.3, 29.2, 29.10, 29.05, 29.0, 28.94, 28.90, 28.6, 28.5, 25.7, 25.5, 24.24, 24.17, 23.0.  \]

MALDI-TOF m/z calcd for C82H136N8O8 (M+H)+ 1362.1, found 1362.5.

**Stack-blocked UPy-DCL ADMET monomer (1)** To a vial charged with compound S8 (328 mg, 0.241 mmol) dissolved in anhydrous toluene (6 mL), 10-undecenoyl chloride (155 µL; 146 mg, 0.722 mmol) was added, followed by anhydrous pyridine (85 µL; 83.8 mg, 1.06 mmol). After stirring for 20 h at room temperature, the mixture was filtered, and the filtrate evaporated in vacuo. The residue was purified via flash chromatography (0 to 2% EtOAc in chloroform; product fractions 1–2% EtOAc) to yield a white solid. Yield: 320 mg (78%) off-white solid.

\[ \text{1H NMR (500 MHz, CDCl}_3\) } \delta 16.9, 10.2, 7.3, 2H), 4.98 (d, \text{J} = 17.1, 2H), 4.92 (d, \text{J} = 10.1, 2H), 4.06–4.03 (m, 4H), 4.00 (t, \text{J} = 6.1, 4H), 3.16 (septet, \text{J} = 6.6, 4H), 2.51–2.47 (m, 4H), 2.32–2.24 (m, 8H), 2.03 (q, \text{J} = 7.0, 4H), 1.80 (quintet, \text{J} = 6.5, 4H), 1.67–1.63 (m, 8H), 1.61–1.43 (m, 8H), 1.39–1.17 (m, 108H).  

\[ \text{13C NMR (125 MHz, CDCl}_3\) } \delta 173.8, 172.2, 158.7, 156.9, 153.5, 148.1, 148.0, 145.8, 139.2, 124.1, 118.6, 114.1, 109.3, 109.2, 76.8, 67.4, 63.4, 34.2, 33.8, 31.9, 30.3, 30.0, 29.7, 29.63, 29.58, 29.44, 29.35, 29.33, 29.29, 29.2, 29.12, 29.06, 28.99, 28.95, 28.89, 28.8, 28.6, 28.5, 28.2, 28.1, 25.7, 25.5, 24.9, 24.5, 24.25, 24.22, 23.0, 22.7, 14.1.  \]

ES-MS m/z calcd for C104H172N8O10 (M+Na)+ 1716.3, found 1717.9.

**Stack-blocked UPy-DCL bis-4-bromo-benzoyl ester (S9)** To a round bottom flask charged with compound S8 (328 mg, 0.241 mmol) dissolved in anhydrous toluene (6 mL), 10-undecenoyl chloride (155 µL; 146 mg, 0.722 mmol) was added, followed by anhydrous pyridine (85 µL; 83.8 mg, 1.06 mmol). After stirring for 20 h at room temperature, the mixture was filtered, and the filtrate evaporated in vacuo. The residue was purified via flash chromatography (0 to 2% EtOAc in chloroform; product fractions 1–2% EtOAc) to yield a white solid. Yield: 320 mg (78%) off-white solid.

\[ \text{1H NMR (500 MHz, CDCl}_3\) } \delta 16.9, 10.2, 7.3, 2H), 4.98 (d, \text{J} = 17.1, 2H), 4.92 (d, \text{J} = 10.1, 2H), 4.06–4.03 (m, 4H), 4.00 (t, \text{J} = 6.1, 4H), 3.16 (septet, \text{J} = 6.6, 4H), 2.51–2.47 (m, 4H), 2.32–2.24 (m, 8H), 2.03 (q, \text{J} = 7.0, 4H), 1.80 (quintet, \text{J} = 6.5, 4H), 1.67–1.63 (m, 8H), 1.61–1.43 (m, 8H), 1.39–1.17 (m, 108H).  

\[ \text{13C NMR (125 MHz, CDCl}_3\) } \delta 173.8, 172.2, 158.7, 156.9, 153.5, 148.1, 148.0, 145.8, 139.2, 124.1, 118.6, 114.1, 109.3, 109.2, 76.8, 67.4, 63.4, 34.2, 33.8, 31.9, 30.3, 30.0, 29.7, 29.63, 29.58, 29.44, 29.35, 29.33, 29.29, 29.2, 29.12, 29.06, 28.99, 28.95, 28.89, 28.8, 28.6, 28.5, 28.2, 28.1, 25.7, 25.5, 24.9, 24.5, 24.25, 24.22, 23.0, 22.7, 14.1.  \]

ES-MS m/z calcd for C104H172N8O10 (M+Na)+ 1716.3, found 1717.9.
**Scheme S2:** Synthesis of bis-thiol-capped SB-UPy-DCL oligomer for SMFS studies

1-(S-trityl)mercaptoundec-10-ene (S10) Triphenylmethanethiol (1.00 g, 3.60 mmol) was suspended in a mixture of 3N aqueous NaOH (1.20 mL, 3.60 mmol) and ethanol (8 mL), and stirred for 10 min. 11-bromoundec-1-ene (800 µL, 844 mg, 3.60 mmol) was added, and mixture stirred for 21 h at room temperature. The reaction was quenched by addition of saturated aqueous NH₄Cl (5 mL), then diluted with DCM (5 mL). The organic layer was separated, and the aqueous layer was extracted with DCM (3 × 5 mL). The organic layers were combined and dried over MgSO₄, filtered, and concentrated in vacuo. The resulting residue was purified by flash chromatography (0 to 2% EtOAc in hexanes; product fractions 1–2% EtOAc) to isolate the pure product as a white, waxy solid. Yield: 1.22 g (78%).

1H NMR (500 MHz, CDCl₃) δ 7.42–7.40 (m, 6H), 7.29–7.27 (m, 6H), 7.22–7.18 (m, 3H), 5.81 (ddt, J = 17.0, 10.2, 6.7, 1H), 4.98 (dd, J = 17.0, 2.0, 1H), 4.92 (dd, J = 10.0, 1.0, 1H), 2.13 (t, J = 7.3, 2H), 2.03 (q, J = 7.0 Hz), 1.37 (septet, J = 7.8, 4H), 1.28–1.10 (m, 10H). 13C NMR (125 MHz, CDCl₃) δ 145.1, 139.2, 129.6, 127.8, 126.5, 114.1, 66.3, 33.8, 32.0, 29.4, 29.3, 29.15, 29.08, 29.0, 28.9, 28.6. ES-MS m/z calcld for C₃₀H₃₆S (M+Na)+ 451.2435, found 451.2425.

Bis-1-(S-trityl)mercaptoundec-10-ene-end-capped SB-UPy-DCL ADMET oligomer (n = 8) (S11) In a round bottom flask, monomer 1 (137 mg, 0.081 mmol) and chain transfer agent 3 (8.6 mg, 0.02 mmol) were dissolved in chloroform (1.5 mL), to which Grubbs generation 2 catalyst (3.40 mg, 0.004 mmol) was added. The mixture was heated to reflux for 1 h, allowed to come to room temperature, and precipitated out of ethanol (~50 mL). After stirring in ethanol for 1 h, the solvent was decanted, and the precipitant re-dissolved in a minimum volume of chloroform, after which the solvent was removed in vacuo. GPC Mₙ: 15.0 kDa; PDI: 2.6.

Bis-undec-10-ene-1-thiol-end-capped SB-UPy-DCL ADMET oligomer (n = 8) (2) In a scintillation vial, oligomer S10 (150 mg) was dissolved in 10% TFA in DCM (220 µL TFA in 2 mL DCM), and stirred for 10 min., followed by addition of trisopropylsilane until the solution was no longer yellow (~100 µL), and stirred for an additional 10 min. The reaction was quenched by addition of saturated aqueous NaHCO₃ solution (2 mL), after which the organic phase was extracted. The aqueous layer was extracted with DCM (3 × 1 mL), and the combined organic phase was dried over MgSO₄, filtered, and concentrated in vacuo. The residue was precipitated out of ethanol (~50 mL), and stirred for 1 h. The solvent was decanted, and the precipitant was re-dissolved in a minimum volume of chloroform. The solvent was then removed in vacuo to afford oligomer 2 as a light brown film. GPC Mₙ: 30.2 kDa; PDI: 1.6.
Scheme S3: Synthesis of modular polymer for bulk mechanical studies

SB-UPy-DCL ADMET polymer (S12). In a round bottom flask, monomer 1 (250 mg, 0.147 mmol) was dissolved in 1,2,4-trichlorobenzene (2 mL) and heated to 70 °C under argon, and Grubbs generation 2 catalyst (16 mg, 0.018 mmol) was added. Vacuum (30 torr) was immediately applied, and fine bubbling due to ethylene evolution was observed. After 10 min, high vacuum (0.1 torr) was applied. After fine bubbling ceased and only large bubbles were observed, the mixture was transferred to a PTFE dish in an argon-purged vacuum oven. Vacuum (30 torr) was applied, and solvent slowly evaporated for 36 h at 80 °C. The resulting film was removed and subjected to bulk mechanical testing. GPC $M_n$: 33.0 kDa; PDI: 2.1.
Scheme S3: Synthesis of modular polymer for bulk mechanical studies SB-UPy-DCL ADMET polymer (S12).

In a round bottom flask, monomer 1 (250 mg, 0.0147 mmol) was dissolved in 1,2,4-trichlorobenzene (2 mL) and heated to 70 °C under argon, and Grubbs generation 2 catalyst (16 mg, 0.018 mmol) was added. Vacuum (30 torr) was immediately applied, and fine bubbling due to ethylene evolution was observed. After 10 min, high vacuum (0.1 torr) was applied. After fine bubbling ceased and only large bubbles were observed, the mixture was transferred to a PTFE dish in an argon-purged vacuum oven. Vacuum (30 torr) was applied, and solvent slowly evaporated for 36 h at 80 °C. The resulting film was removed and subjected to bulk mechanical testing. GPC Mn: 33.0 kDa; PDI: 2.1.

Stack-blocked UPy-DCL ADMET Monomer (1)

1H NMR (500 MHz, CDCl3):
COSY (500MHz, CDCl₃):

ROESY (500 MHz, CDCl₃, 600 ms mixing time):
**Supplementary Information**

**13C NMR (125 MHz, CDCl3):**

![13C NMR spectra](image)

**ES-MS:**

![ES-MS spectrum](image)
Bis-1-(S-trityl)mercaptoundec-10-ene-end-capped SB-UPy-DCL ADMET oligomer (n = 8) (S11)

\(^1\)H NMR (500 MHz, CDCl\(_3\)):
Bis-1-(3-trityl)mercaptoundec-10-ene-end-capped SB-UPy-DCL ADMET oligomer (n = 8) (2)

$^1$H NMR (500 MHz, CDCl$_3$):

![NMR Spectrum]

GPC (THF eluent, 1 mL/min, Polystyrene standard):

![GPC Chart]

Oligomer
Mn: 15.0 kDa
PDI: 2.6

Polymer
Mn: 33.0 kDa
PDI: 2.1
Part II. X-ray crystal structure of SB-UPy-DCL motif

Recrystallization of compound S9 from ethyl acetate produced suitable crystals for X-ray crystallography. A colorless crystal of approximate dimensions 0.16 x 0.26 x 0.38 mm was mounted on a glass fiber and transferred to a Bruker SMART APEX II diffractometer. The APEX2\(^2\) program package was used to determine the unit-cell parameters and for data collection (30 sec/frame scan time for a sphere of diffraction data). The raw frame data was processed using SAINT\(^3\) and SADABS\(^4\) to yield the reflection data file. Subsequent calculations were carried out using the SHELXTL\(^5\) program. There were no systematic absences nor any diffraction symmetry other than the Friedel condition. The centrosymmetric triclinic space group \(\text{P}\bar{1}\) was assigned.

The structure was solved by direct methods and refined on \(F^2\) by full-matrix least-squares techniques. The analytical scattering factors\(^6\) for neutral atoms were used throughout the analysis. Hydrogen atoms were included using a riding model. Carbon atoms C(38)-C(44) showed higher thermal motion than neighboring atoms but a reasonable disorder model could not be determined. It was necessary to restrain the C(42)-C(43) distance during refinement.

Least-squares analysis yielded \(wR2 = 0.1762\) and \(\text{Goof} = 1.047\) for 527 variables refined against 10282 data (0.78 Å), \(R1 = 0.0594\) for those 7783 data with \(I > 2\sigma(I)\).

Definitions:

\[ wR2 = \left[ \Sigma \left[ w(F_o^2 - F_c^2)^2 \right] / \Sigma [w(F_o^2)] \right]^{1/2} \]

\[ R1 = \Sigma ||F_o|-|F_c|| / \Sigma |F_o| \]

\[ \text{Goof} = S = \left( \Sigma [w(F_o^2 - F_c^2)^2] / (n-p) \right)^{1/2} \]

where \(n\) is the number of reflections and \(p\) is the total number of parameters refined.

The thermal ellipsoid plot is shown at the 50% probability level.
Crystal data and structure refinement.

Empirical formula  

\[ \text{C}_{96} \text{H}_{142} \text{Br}_{2} \text{N}_{8} \text{O}_{10} \]

Formula weight  

1728.00

Temperature  

138(2) K

Wavelength  

0.71073 Å

Crystal system  

Triclinic

Space group  

\( P \)

Unit cell dimensions  

\( a = 13.6293(9) \text{ Å} \) \( \alpha = 94.0180(9)^\circ \)
\( b = 13.9079(9) \text{ Å} \) \( \beta = 90.6040(8)^\circ \)
\( c = 14.0595(9) \text{ Å} \) \( \gamma = 117.0209(8)^\circ \)

Volume  

2365.6(3) Å\(^3\)

Z  

1

Density (calculated)  

1.213 Mg/m\(^3\)

Absorption coefficient  

0.916 mm\(^{-1}\)

\( F(000) \)  

924

Crystal color  

colorless

Crystal size  

0.38 x 0.26 x 0.16 mm\(^3\)

Theta range for data collection  

1.65 to 27.10°

Index ranges  

\(-17 \leq h \leq 17, -17 \leq k \leq 17, -17 \leq l \leq 18\)

Reflections collected  

26724

Independent reflections  

10282 [\( R(\text{int}) = 0.0238 \) ]

Completeness to theta = 25.50°  

99.6 %

Absorption correction  

Numerical

Max. and min. transmission  

0.8688 and 0.7239

Refinement method  

Full-matrix least-squares on \( F^2 \)

Data / restraints / parameters  

10282 / 1 / 527

Goodness-of-fit on \( F^2 \)  

1.047

Final R indices [I>2\( \sigma(I) = 7783 \) data]  

\( R_1 = 0.0594, wR_2 = 0.1619 \)

R indices (all data, 0.78Å)  

\( R_1 = 0.0803, wR_2 = 0.1762 \)

Largest diff. peak and hole  

1.310 and -0.650 e.Å\(^{-3}\)
Figure S1: X-ray crystal structure of compound S9 with the SB-UPy-DCL motif.

Hydrogen bond distances and angles [Å and °].

<table>
<thead>
<tr>
<th>D-H...A</th>
<th>d(D-H)</th>
<th>d(H...A)</th>
<th>d(D...A)</th>
<th>(&lt;(DHA))</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1) – H(1) • O(3)'</td>
<td>0.88</td>
<td>1.86</td>
<td>2.720(3)</td>
<td>165.1</td>
</tr>
<tr>
<td>N(2) – H(2) • N(3)'</td>
<td>0.88</td>
<td>2.11</td>
<td>2.989(3)</td>
<td>174.8</td>
</tr>
<tr>
<td>N(4) – H(4) • O(2)</td>
<td>0.88</td>
<td>1.92</td>
<td>2.586(3)</td>
<td>131.7</td>
</tr>
</tbody>
</table>
**Part III. Molecular model of SB-UPy-DCL monomer**

Maestro MacroModel was used in order to generate a reasonable minimum energy conformation of dimerized and ruptured end-to-end distances of SB-UPy-DCL monomer. For both dimerized and ruptured forms, the minimum energy conformation was generated in AMBER* force field with CHCl₃ solvation.

The UPy-dimerization H-bond distance and angle values (N – H ··· N distance and angle: 2.989 Å and 175°, respectively; N – H ··· O distance and angle: 2.720 Å and 165°, respectively) were taken from the X-ray crystal structure of SB-UPy-DCL compound S9 described in Part II, and these values were used for energy minimization constraints with an extremely large force constant (5000 kJ/(mol Å²)) to lock the values in place. Then the ends of the monomer were ‘pulled’ by placing an additional constraint of 150 Å end-to-end distance with a force constant of 5 kJ/(mol Å²). The minimized energy conformation showed an end-to-end distance of 57.4 Å in the dimerized state.

For the ruptured SB-UPy-DCL monomer, a constraint of 150 Å end-to-end distance with a force constant of 5 kJ/(mol Å²) was placed with no additional constraints. This yielded an end-to-end distance of 86.9 Å in the ruptured SB-UPy-DCL monomer.

Therefore the modeled difference in distance between the dimerized and extended forms of SB-UPy-DCL is 2.85 nm.

We also note that the difference in distance between unfolded and folded of 2.85 nm agrees with simple estimate based on bond angle and distance. The 20 carbon-carbon single bonds in the DCL architecture corresponds to 1.54 Å × 20 × sin(109.5°) = 2.5 nm. When we add also the length of the stack-blocking aryl group due to free bond rotation in the direction of pulling, this adds an additional 3-5 angstroms to make 2.8-3.0 nm.

**Figure S2:** Molecular model and end-to-end distances along the pulling axis of dimerized (a.) and ruptured (b.) SB-UPy-DCL monomer generated from MacroModel.
Part IV. SMFS studies and data analysis of SB-UPy-DCL oligomer

Pulling SMFS experiments and data analysis.

A 0.1 mg/ml sample of oligomer 2 in toluene was prepared and injected into a closed fluid cell assembled with a Biolever (Olympus) and a gold-coated silicon wafer as the sample surface. SMFS studies were performed on an Asylum MFP-3D AFM with Igor Pro 6.22A software. The spring constant of each cantilever was found by the thermal tuning method. Over 2000 force curves each were obtained at 10, 25, 60, 125, 250, 500, 1000 and 2000 nm/s pulling speed with Biolever nominal spring constant 30 pN/nm, and at 10, 25, 60, 125 nm/s pulling speed with Biolever nominal spring constant 6 pN/nm. The following parameters were used for the experiment: dwell towards surface, 5.0 s; surface trigger point, 500 pN. The force curves thus obtained were selected for analysis based on the presence and quality of evenly-spaced saw-tooth patterns well-fitted to a single persistence length (0.38 ± 0.08 nm) according to the worm-like chain (WLC) model of polymer elasticity, described by the equation:

\[ F(x) = \frac{k_B T}{l_p} \left[ \frac{1}{4} \left( 1 - \frac{x}{L_c} \right)^2 - \frac{1}{4} \left( 1 + \frac{x}{L_c} \right) \right] \]

where \( l_p \) is the persistence length and \( L_c \) is the contour length. From the WLC fit, the increase in contour length (\( \Delta L_c \)) of the oligomer following each rupture event was binned and fitted to a histogram (Figure S3), and was derived to be 2.95 ± 0.43 nm, which is in excellent agreement with the modeled increase in length between the folded and fully extended states of individual SB-UPy-DCL modules (2.85 nm; Figure S2), confirming that the observed saw-tooth patterns result from the sequential rupture of UPy-DCL modules in oligomer 2. Further, the histogram of \( \Delta L_c \) exhibits a well-defined mono-modal Gaussian shape (Figure S3), confirming a potential energy landscape consisting of a single transition state between folded and unfolded states.

At each loading rate, both rupture force and natural logarithm of loading rate were binned and fitted to a Gaussian (Figures S4 and S5), and plotted as a single data point on a semi-logarithmical plot of rupture force vs. loading rate (Figure 2b). A Bell-Evans model least squares linear fit in the non-equilibrium regime was performed with the five highest loading rate data points. From the linear fit, \( \Delta x_u \) was derived from the slope, while \( k_u \) was derived from the \( x \)-intercept according to the equation:

\[ F_{\text{rupture}} = \left( \frac{k_B T}{\Delta x_u^2} \right) \ln \mu + \left( \frac{k_B T}{\Delta x_u^4} \right) \ln \left( \frac{\Delta x_u^3}{k_u k_B T} \right) \]

where \( \mu \) is the loading rate.
Part IV. SMFS studies and data analysis of SB-UPy-DCL oligomer

Pulling SMFS experiments and data analysis.  A 0.1 mg/ml sample of oligomer in toluene was prepared and injected into in a closed fluid cell assembled with a Biolever (Olympus) and a gold-coated silicon wafer as the sample surface.  SMFS studies were performed on an Asylum MFP-3D AFM with Igor Pro 6.22A software.  The spring constant of each cantilever was found by the thermal tuning method. Over 2000 force curves each were obtained at 10, 25, 60, 125, 250, 500, 1000 and 2000 nm/s pulling speed with Biolever nominal spring constant 30 pN/nm, and at 10, 25, 60, 125 nm/s pulling speed with Biolever nominal spring constant 6 pN/nm.  The following parameters were used for the experiment: dwell towards surface, 5.0 s; surface trigger point, 500 pN.  The force curves thus obtained were selected for analysis based on the presence and quality of evenly-spaced saw-tooth patterns well-fitted to a single persistence length (0.38 ± 0.08 nm) according to the worm-like chain (WLC) model of polymer elasticity, described by the equation:

\[
\ell_p = \frac{L_c}{\pi} \frac{\exp\left(-\frac{\mu}{k_BT} \frac{\mu}{k_BT} \right)}{1 - \frac{\mu}{k_BT} \frac{\mu}{k_BT}}
\]

where \(\ell_p\) is the persistence length and \(L_c\) is the contour length.

From the WLC fit, the increase in contour length (\(\Delta L_c\)) of the oligomer following each rupture event was binned and fitted to a histogram (Figure S3), and was derived to be 2.95 ± 0.43 nm, which is in excellent agreement with the modeled increase in length between the folded and fully extended states of individual SB-UPy-DCL modules (2.85 nm; Figure S2), confirming that the observed saw-tooth patterns result from the sequential rupture of UPy-DCL modules in oligomer 2.  Further, the histogram of \(\Delta L_c\) exhibits a well-defined mono-modal Gaussian shape (Figure S3), confirming a potential energy landscape consisting of a single transition state between folded and unfolded states.

At each loading rate, both rupture force and natural logarithm of loading rate were binned and fitted to a Gaussian (Figures S4 and S5), and plotted as a single data point on a semi-logarithmical plot of rupture force vs. loading rate (Figure 2b).  A Bell-Evans model least squares linear fit in the non-equilibrium regime was performed with the five highest loading rate data points.  From the linear fit, \(\Delta x u \pm \) was derived from the slope, while \(k_u \pm \) was derived from the 

Figure S3: Additional representative force curves at 60(a), 360(b), 7500(c), 15000(d), and 30000(e,f) pN/s loading rates, respectively.  Note that some force curves very high force for final rupture indicative of gold-thiol rupture while others don’t, indicating non-specific adhesion to surface.
**Table S1**: Summary of pulling SMFS experimental data

<table>
<thead>
<tr>
<th>Spring const. (pN/nm)</th>
<th>Ret. Velocity (nm/s)</th>
<th>Gaussian center ln µ</th>
<th>Gaussian width ln µ</th>
<th>Gaussian center Force (pN)</th>
<th>Gaussian width Force (pN)</th>
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<tbody>
<tr>
<td>6</td>
<td>10</td>
<td>3.70</td>
<td>0.17</td>
<td>70.7</td>
<td>14.5</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>4.62</td>
<td>0.18</td>
<td>71.3</td>
<td>17.7</td>
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<td>6</td>
<td>60</td>
<td>5.59</td>
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<td>74.9</td>
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<td>6</td>
<td>125</td>
<td>6.20</td>
<td>0.15</td>
<td>77.1</td>
<td>14.2</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>4.53</td>
<td>0.25</td>
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<td>5.31</td>
<td>0.30</td>
<td>83.9</td>
<td>15.8</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>6.05</td>
<td>0.19</td>
<td>84.3</td>
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<td>30</td>
<td>125</td>
<td>6.99</td>
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<td>30</td>
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<td>500</td>
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<td>116</td>
<td>18.8</td>
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<td>30</td>
<td>1000</td>
<td>9.29</td>
<td>0.18</td>
<td>131</td>
<td>20.2</td>
</tr>
<tr>
<td>30</td>
<td>2000</td>
<td>10.2</td>
<td>0.23</td>
<td>153</td>
<td>19.9</td>
</tr>
</tbody>
</table>

**Figure S4**: Histogram and Gaussian fit of increase in contour length ($\Delta L_c$) per rupture event yields $\Delta L_c = 2.95 \pm 0.43$ nm, close to the dimer separation of 2.85 nm at full extension obtained from modeling (Figure S2).
**Table S1**: Summary of pulling SMFS experimental data

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<tr>
<td>30</td>
<td>2000</td>
<td>10.2</td>
<td>0.23</td>
<td>153</td>
<td></td>
</tr>
</tbody>
</table>

**Figure S5**: a. Histograms and Gaussian fits of rupture force at various out-of-equilibrium loading rates. Gaussian fits for most probable rupture force for pulling SMFS experiments are shown in b. (6 pN/nm cantilever) and in c. (30 pN/nm cantilever).
**Figure S6:** a. Histograms and Gaussian fits for the natural logarithm of loading rate at various out of equilibrium loading rates. b. and c. Gaussian fits for natural logarithm of loading rate for pulling SMFS experiments with 6 pN/nm (b.) and 30 pN/nm cantilevers (c.).

Cyclic SMFS experiments and data analysis. A 0.1 mg/ml solution of oligomer in toluene was injected into a closed fluid cell assembled with a Biolever (Olympus) and a gold-coated silicon wafer as sample surface. All cyclic SMFS studies were performed with Biolever nominal spring constant 6 pN/nm, whose accurate spring constants were measured by the thermal tuning method 9. Cyclic SMFS studies were designed using the ForceRampSimple panel on Igor Pro 6.22A software on an Asylum MFP-3D AFM. The surface trigger was set to 500 pN, and the pull-off distance usually varied somewhere between 100–200 nm and was determined experimentally. Extension and retraction velocities were always set to be equal, and were varied between 125, 200, 250, 400, and 500 nm/s. Pause after retraction was set to 0.5 seconds for all loading rates before the next cycle. Maximum extension before retraction was aimed to be around 60 – 70 nm away from the surface, corresponding to a slightly shorter distance than the fully extended and ruptured distance of an 8-mer according to the MacroModel results. For data analysis, only rejoining forces were examined on the retraction path as described in the text. Manual determination of loading rate on the rejoining path from the force versus time curve was omitted due to low signal-to-noise ratio in the lower pN portion of the force-retraction curve. Instead, the simpler equation of $\mu = k_c \times v$, where $k_c$ is the cantilever spring constant measured by the thermal tuning method and $v$ is the velocity, was used. A semi-logarithmic plot of most probable rejoining force versus loading rate was constructed, from which a least squares linear fit of the data was obtained in a similar manner to the pulling experiments. From the slope of the linear fit was derived $\Delta x_f^{\ddagger}$ according to the equation (Equation 16 in ref.15):

$$F_{\text{rejoin}} = k_f^0 \times \Delta x_f^{\ddagger}$$

where $F_{\text{rejoin}}$ is the most probable rejoining force, $k_f^0$ is the folding rate in the absence of external force, $\Delta x_f^{\ddagger}$ is the distance on the reaction coordinate diagram from the transition state to the unfolded energy well, $\mu$ is the loading rate, and $\gamma = 0.577215$ is the Euler constant. We note the Euler constant only serves to offset the intercepts, and has no effect on the slope from which $\Delta x_f^{\ddagger}$ is derived.

In order to correct for the systematic errors introduced in calculating $\Delta x_f^{\ddagger}$ from simplifying the loading rate to $\mu = k_c \times v$, we employed methods reported by Ray et al. 16 to estimate the error in determining $\Delta x_f^{\ddagger}$ (equation 27 in ref. 16). For $F^*$ (most probable force) the values for Gaussian center force from Table S2 were used, and for $k_c$ the values determined from the thermal tuning method (4.03 pN/nm) was used. $F^{\ddagger}$ and $F_p$ were calculated as described in ref. 16 using the uncorrected $\Delta x_f^{\ddagger}$ (1.05 nm) and $l_p$ (0.38 nm), respectively. $L_c$ was set to be 60 nm on average based on our maximum extension parameter on ForceRampSimple. Errors using equation 27 in ref. 16 were calculated separately for each Gaussian center force, and averaged together to obtain 18.5 % average error for $\Delta x_f^{\ddagger}$. When this error percentage is employed, $\Delta x_f^{\ddagger} = 1.22 \pm 0.65$ nm.
Cyclic SMFS experiments and data analysis.

A 0.1 mg/ml solution of oligomer 2 in toluene was injected into a closed fluid cell assembled with a Biolever (Olympus) and a gold-coated silicon wafer as sample surface. All cyclic SMFS studies were performed with Biolever nominal spring constant 6 pN/nm, whose accurate spring constants were measured by the thermal tuning method. Cyclic SMFS studies were designed using the ForceRampSimple panel on Igor Pro 6.22A software on an Asylum MFP-3D AFM. The surface trigger was set to 500 pN, and the pull-off distance usually varied somewhere between 100–200 nm and was determined experimentally. Extension and retraction velocities were always set to be equal, and were varied between 125, 200, 250, 400, and 500 nm/s. Pause after retraction was set to 0.5 seconds for all loading rates before the next cycle. Maximum extension before retraction was aimed to be around 60 – 70 nm away from the surface, corresponding to a slightly shorter distance than the fully extended and ruptured distance of an 8-mer according to the MacroModel results. For data analysis, only rejoining forces were examined on the retraction path as described in the text. Manual determination of loading rate on the rejoining path from the force versus time curve was omitted due to low signal-to-noise ratio in the lower pN portion of the force-retraction curve. Instead, the simpler equation of \( \mu = k_c \times v \), where \( k_c \) is the cantilever spring constant measured by the thermal tuning method and \( v \) is the velocity, was used. A semi-logarithmic plot of most probable rejoining force versus loading rate was constructed, from which a least squares linear fit of the data was obtained in a similar manner to the pulling experiments. From the slope of the linear fit was derived \( \Delta x_f^\gamma \) according to the equation (Equation 16 in ref.15):

\[
F_{\text{rejoin}} = - \left( \frac{k_B T}{k_f^0} \right) \ln \mu - \left( \frac{k_B T}{\Delta x_f^\gamma} \right) \ln z_r
\]

where \( z_r = \frac{e^{\gamma \Delta x_f^\gamma}}{k_B T} \). \( F_{\text{rejoin}} \) is the most probable rejoining force, \( k_f^0 \) is the folding rate in the absence of external force, \( \Delta x_f^\gamma \) is the distance on the reaction coordinate diagram from the transition state to the unfolded energy well, \( \mu \) is the loading rate, and \( \gamma = 0.577215 \) is the Euler constant. We note the Euler constant only serves to offset the intercepts, and has no effect on the slope from which \( \Delta x_f^\gamma \) is derived.

In order to correct for the systematic errors introduced in calculating \( \Delta x_f^\gamma \) from simplifying the loading rate to \( \mu = k_c \times v \), we employed methods reported by Ray et al.16 to estimate the error in determining \( \Delta x_f^\gamma \) (equation 27 in ref. 16). For \( F^* \) (most probable force) the values for Gaussian center force from Table S2 were used, and for \( k_c \) the values determined from the thermal tuning method (4.03 pN/nm) was used. \( F_f \) and \( F_p \) were calculated as described in ref. 16 using the uncorrected \( \Delta x_f^\gamma \) (1.05 nm) and \( l_p \) (0.38 nm), respectively. \( L_c \) was set to be 60 nm on average based on our maximum extension parameter on ForceRampSimple. Errors using equation 27 in ref. 16 were calculated separately for each Gaussian center force, and averaged together to obtain 18.5 % average error for \( \Delta x_f^\gamma \). When this error percentage is employed, \( \Delta x_f^\gamma = 1.22 \pm 0.65 \) nm.
Table S2: Summary of cyclic SMFS data

<table>
<thead>
<tr>
<th>Spring Const. (pN/nm)</th>
<th>Velocity (nm/s)</th>
<th>ln µ</th>
<th>Gaussian Center Force (pN)</th>
<th>Gaussian Width Force (pN)</th>
<th>Width</th>
</tr>
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<tr>
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<td>6.06</td>
<td>18.7</td>
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<tr>
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<td>6.32</td>
<td>17.4</td>
<td>5.7</td>
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<tr>
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<td>16.2</td>
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<tr>
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<td>7.08</td>
<td>14.3</td>
<td>7.1</td>
<td></td>
</tr>
</tbody>
</table>

Figure S7: a. Histograms and Gaussian fits for rejoining force at various retraction rates. b. Gaussian fits for rejoining force for retraction cycle of cyclic SMFS experiments.

Derivation of equilibrium rupture force.
As described in the main text, Diezemann and Janshoff’s method of extracting $K_{eq}$ requires the extrapolation of the equilibrium rupture force to a cantilever spring constant of $k_c = 0$. As predicted by the authors, a higher cantilever spring constant manifests as a higher apparent equilibrium rupture force. From the data obtained in the rupture mode, the three lowest loading rate data points obtained with the 30 pN/nm cantilever were treated as being in the quasi-equilibrium regime and was averaged to obtain 83.9 ± 0.26 pN equilibrium rupture force with the 30 pN/nm cantilever. The lowest two loading rate data points obtained with the 6 pN/nm cantilever were treated as if in the quasi-equilibrium regime for an average equilibrium rupture force of 71.0 ± 0.30 pN with the 6 pN/nm cantilever. A linear extrapolation (of $F_{eq}$ versus $k_c$) to $k_c = 0$ provided the equilibrium rupture force of 67.8 ± 0.40 pN.

Figure S8: Derivation of quasi-equilibrium regime rupture force. Red lines denote the equilibrium rupture forces with 30 pN/nm and 6 pN/nm cantilevers.
**Derivation of equilibrium rupture force.** As described in the main text, Diezemann and Janshoff's method of extracting $K_{eq}$ requires the extrapolation of the equilibrium rupture force to a cantilever spring constant of $k_c = 0.15$. As predicted by the authors, a higher cantilever spring constant manifests as a higher apparent equilibrium rupture force. From the data obtained in the rupture mode, the three lowest loading rate data points obtained with the 30 pN/nm cantilever were treated as being in the quasi-equilibrium regime and was averaged to obtain $83.9 \pm 0.26$ pN equilibrium rupture force with the 30 pN/nm cantilever. The lowest two loading rate data points obtained with the 6 pN/nm cantilever were treated as if in the quasi-equilibrium regime for an average equilibrium rupture force of $71.0 \pm 0.30$ pN with the 6 pN/nm cantilever. A linear extrapolation (of $F_{eq}$ versus $k_c$) to $k_c = 0$ provided the equilibrium rupture force of $67.8 \pm 0.40$ pN.

![Figure S8: Derivation of quasi-equilibrium regime rupture force. Red lines denote the equilibrium rupture forces with 30 pN/nm and 6 pN/nm cantilevers.](image)
Part V. Bulk characterization of SB-UPy-DCL polymer

Mechanical Testing.

Tensile testing. The bulk static tensile properties of the SB-UPy-DCL polymer were measured using an Instron 3365 with a 500 N load cell with a pulling rate of 100 mm/min. Sample dimensions were measured (l,w,t: 12.0 x 3.4 x 0.20 mm) and the sample was pulled at ambient temperature until break (Figure S9a).

Multi-cyclic and dimensional recovery tensile testing. Temperature was controlled during the experiment with an Instron SFL 3119-506 ‘Heatwave’ chamber. The dimensions of the sample used were 13.0 x 3.4 x 0.15 mm (l,w,t). The sample was loaded onto the Instron and equilibrated for 1 h at 60 °C, following which a multi-cyclic tensile test was performed for ten cycles at 100 mm/min, 80% maximum strain each cycle. The sample was then allowed to recover at 60 °C for 5 min, 1 h, and 12 h before an additional cycle was performed. For the final recovery, the sample was heated to 80 °C for 5 min, following which the sample was re-equilibrated at 60 °C for 30 minutes before the last cycle was performed (Figure 4a).

Temperature dependent tensile testing. The dimensions of the sample used were 0.20 mm (thick) x 12.0 mm (long) x 3.4 mm (wide). The sample was loaded onto the Instron and equilibrated for 1 h at each corresponding temperature (50, 60, 70, 80, 90 °C), following which the sample was extended to 100% strain (Figure S9b).

![Graph](image)

Figure S9: a. Static tensile behavior of bulk SB UPy-DCL material at room temperature. Young’s modulus is ~250 MPa, yield strength is ~20 MPa, and strain at break is ~250%. b. Temperature dependent stress-strain behavior of material. As expected, the material yields at lower stress with increasing temperature. Above the glass transition temperature (90 °C), the material shows virtually linear stress-strain behavior.
**Dynamic Mechanical Analysis.** Multi-frequency temperature sweep tests were performed using a TA Instruments DMA Q800 with attached cryo accessory. Sample dimensions were measured (l,w,t: 10.5 x 1.85 x 0.2 mm) and loaded into furnace, after which the sample was equilibrated at the lower boundary temperature for 1 h. The temperature was then incremented by 1 °C and kept isothermal for 3 min with frequency sweep, until the upper bound temperature was reached. On initial run, temperature was swept from -80 to 100 °C with 3 °C increments in order to identify the two transitions. Following this, for analysis of the alpha transition the temperature was swept between 70 to 110 °C with 1 °C increment at 0.1, 0.3, 1, 3, and 10 Hz (Figure 4b). For analysis of beta transition, the temperature was swept between -75 to 25 °C with 1 °C increment at 1, 2, 5, 10, and 20 Hz (See Figure 4c).

**Modulated Differential Scanning Calorimetry.** Modulated DSC (MDSC) was performed using a TA Q800 instrument in conventional MDSC mode. 11 mg of polymer sample was placed in a non-hermitic pan and scanned against and empty reference. A heat-cool-heat cycle (120 to -80 to 120 °C; 10 °C/min) was performed prior to scanning to remove thermal history. The MDSC experiment was carried out with a heating rate of 10 °C/min, a period of 60 s, and an amplitude of 1 °C/min.

![Figure S10. MDSC results of bulk SB UPy-DCL material.](image-url)
## References

2. APEX2 v.2.2-0 (Bruker AXS, Inc., Madison, 2007).
3. SAINT v.7.46a (Bruker AXS, Inc., Madison, 2007).
5. SHELXTL (Bruker AXS, Inc., Madison, 2008).