Coupled Mullins effect and cohesive zone model for fracture and adhesion of soft and tough materials

Teng Zhang[1,2]*, Shaoting Lin*[1] *and Xuanhe Zhao*[1,3]

[1.] *Soft Active Materials Laboratory, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA;* [2.] *Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY 13244, USA;* [3.] *Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

0. Unit system used in the simulations

Quantity	Length	Force	Mass	Time	Stress	Energy	Density	Energy density
Unit	mm	mN	kg	s	kPa	10^{-6}J	10^{9}kg/m^{3}	kJ/m^{3}

1. Simulation of pure-shear tests

Two abaqus simulation files are included:

gel_h20_ogden1_s080md100_k2000_v0625.inp

gel_h20_ogden1_s080md100_k2000_v125.inp

The example is based on *Fig. 5* in the paper (Zhang et al., 2015) on predicting tough hydrogel toughness. The material parameters for the hyperelastic constitute law and cohesive zone are shown as follows:

Parameter	μ	α	D	r	m	β	$S_{\max}$	$\delta_{\max}$
value	10.81	1.879	0.001	1.516	4.274	0.1	80	2.0

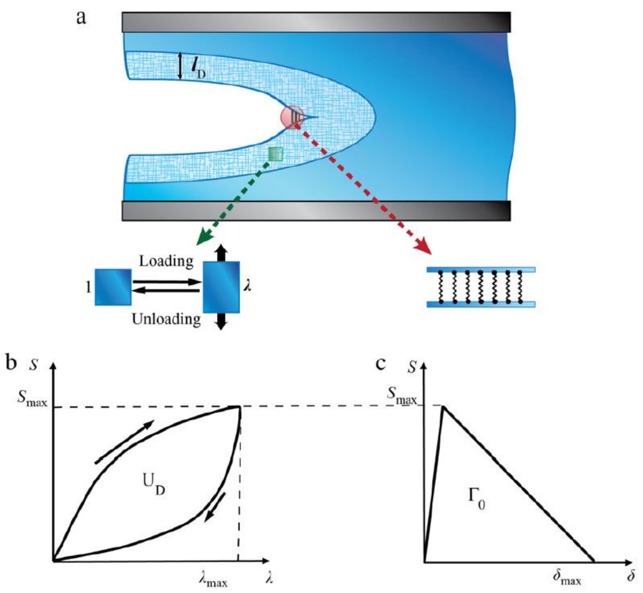

Figure 1. Coupled Mullins effects and cohesive zone model.

$$W_{ela} = W_{dev} + W_{vol} = 2\mu/\alpha^2\left(\bar{\lambda}_1^{\alpha} + \bar{\lambda}_2^{\alpha} + \bar{\lambda}_3^{\alpha}\right) + \frac{1}{D}(J-1)^2 \tag{1a}$$

$$\overline{W} = \eta W_{dev} + \phi(\eta) + W_{vol} \tag{1b}$$

$$\phi(\eta) = \int_1^{\eta}\left[\left(m + \beta W_{dev}^{mp}\right)\mathrm{erf}^{-1}\left(r(1-\eta)\right)W_{dev}^{mp}\right]d\eta \tag{1c}$$

$$\eta = 1 - \frac{1}{r}\,\mathrm{erf}\left[\left(W_{dev}^{mp} - W_{dev}\right)/\left(m + \beta W_{dev}^{mp}\right)\right] \tag{1d}$$

$$\left\{\frac{t_n}{S_{\max}}\right\}^2 + \left\{\frac{t_s}{S_{\max}}\right\}^2 = 1 \tag{2}$$

and

$$\Gamma_0 = 1/2\, S_{\text{interface}}\,\delta_{\max}\ . \tag{3}$$

The simulation set up and snapshots are shown in Fig. 2.

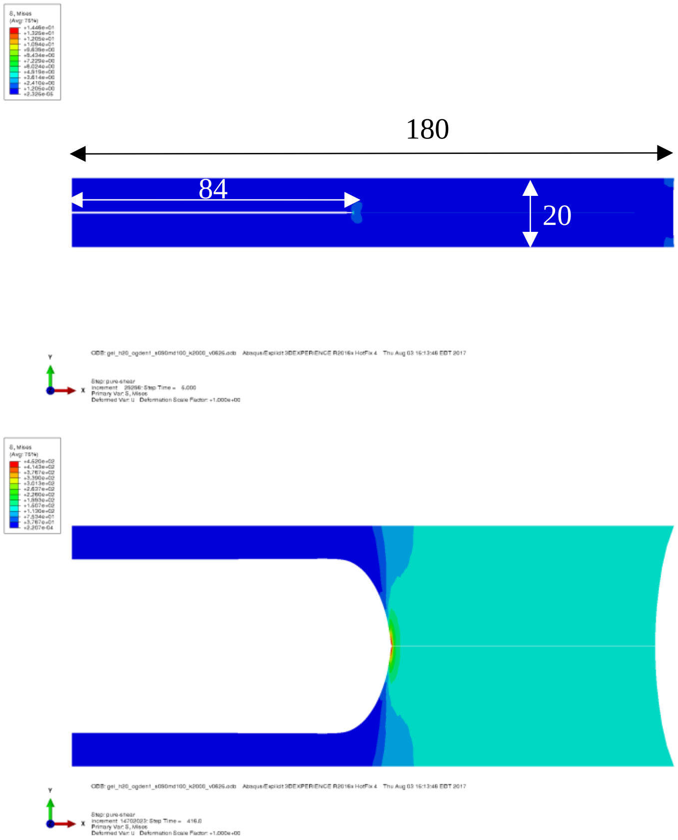

Figure 2. The snapshots of the hydrogel strip under small and large deformations.

These are two-dimensional (2D) plane stress simulations. The densities of bulk hydrogel and cohesive zone are set as 0.001. This is much higher than the real material density, as the real value (10^{-6}) will lead to a very small time integration step. To verify the results do not dependent on the current choices of the densities, two different loading velocity are applied to the top and bottom edge of the hydrogel strip. The force-displacement curves are shown in Fig. 3, clearly confirming that the effect of kinetic energy can be neglected.

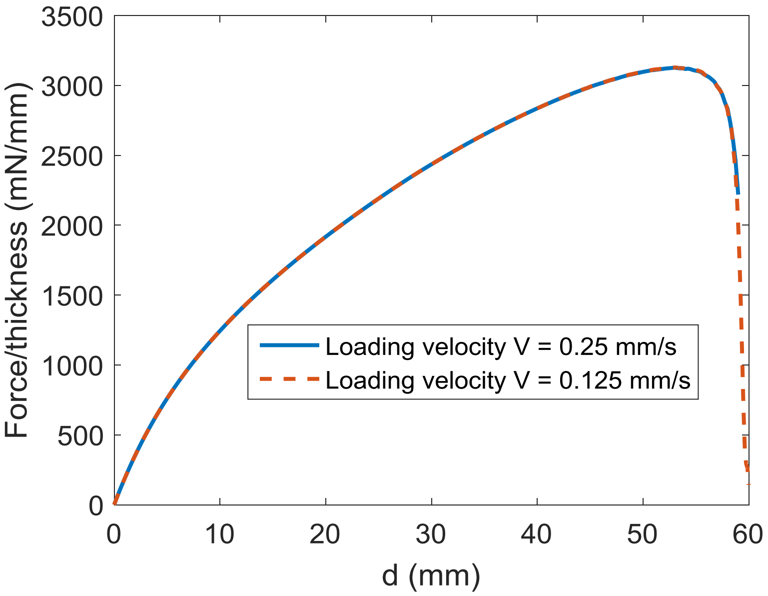

Figure 3. Force-displacement curved under different loading velocity. Note that we multiply the hydrogel strip thickness (4 mm) in the paper to compare with the experiments (Zhang 2015).

2. Simulation of 90 degree peeling tests

One abaqus simulation file in the paper (Zhang et al., 2017) is included:

gel_peeling_2d_ogden2_s200d30_h32.inp

The material parameters for the hyperelastic constitute law and cohesive zone are shown as follows:

Parameter	μ	α	D	r	m	β	$S_{\text{interface}}$	$\delta_{\text{interface}}$
value	36.57	1.473	0.0001	1.1	4.076	0.2818	200	3.0

The simulatin setup is shown as follows:

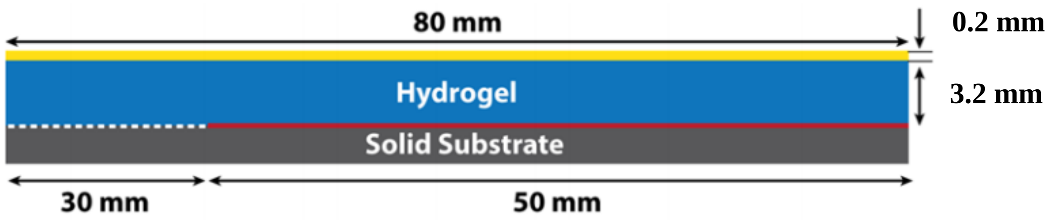

Figure 4. Simulation setup for the 90 degree peeling test.

This is a 2D plane strain simulation and contains three steps:

1. Rotating the left edge up to 90 degree.
2. Hold the left edge to equlibrium the structure.
3. Perfom 90 degree peeling with constant velocity.

Mass scaling is used to avoid extremely small time step. The minimum allowed time step is 10^{-5}. Figure 5a shows the reaction force of the left edge as a function of simlation time. The FEM snapshot at the steady state is shown in Fig. 5b.

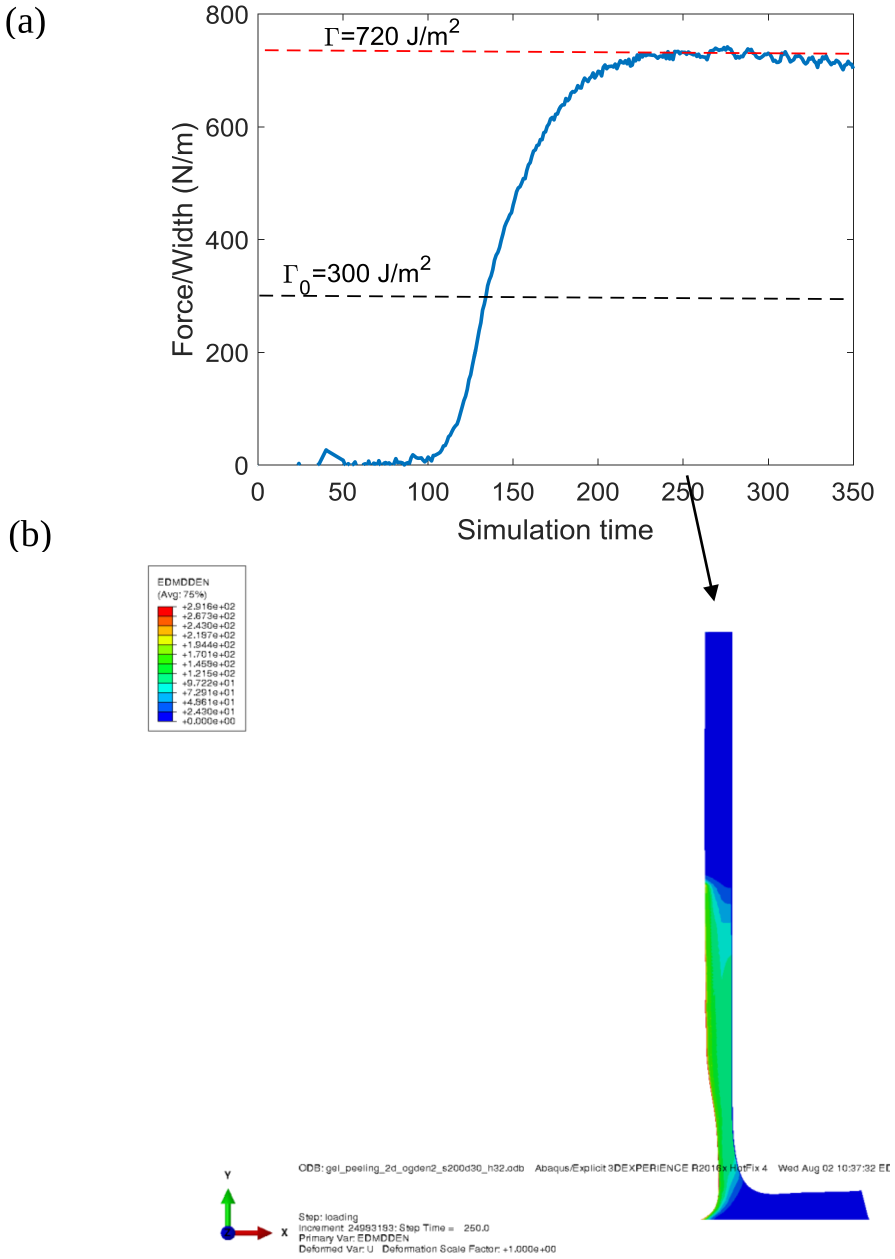

Figure 5. Simulation results of the 90 degree peeling.

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Reference

Zhang, T., Lin, S., Yuk, H., Zhao, X., 2015. Predicting fracture energies and crack-tip fields of soft tough materials. Extreme Mechanics Letters 4, 1-8.
Zhang, T., Yuk, H., Lin, S., Parada, G.A., Zhao, X., 2017. Tough and tunable adhesion of hydrogels: experiments and models. Acta Mechanica Sinica 33, 543-554.