# Viscoelastic crack propagation: is the fracture process zone contribution to dissipation rate-dependent?

Ali Maghami[1], Qingao Wang[2], Michele Tricarico[1], Michele Ciavarella[1], Qunyang Li[2], and Antonio Papangelo[*†1]

[1]TriboDynamics Lab, DMMM, Polytechnic University of Bari – Italy

[2]AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, 8 China – China

**Abstract**

Soft viscoelastic materials are attracting increasing attention as they play a crucial role in advanced technologies, including grippers, manipulators, soft robotics, pressure-sensitive adhesives, rubber supports, and dampers. Elastomers, silicones, and rubbers exhibit time-dependent behavior; their response at time "t" depends not only on the current state of stress and strain but also on the contact history. Furthermore, soft contacts are inherently compliant, allowing them to conform easily to the countersurface and exhibit macroscopic adhesion. The key parameter that determines interfacial stickiness is the thermodynamic surface energy, defined as the energy per unit area required to separate two infinite flat surfaces from their equilibrium position to infinity. However, for viscoelastic materials, the "apparent" surface energy of the interface must also account for energy dissipation within the bulk material.

First, we will introduce our current understanding of viscoelastic crack propagation theories, focusing on: (i) an accurate description of the stress and displacement fields at the crack tip through a cohesive zone model (1, 2), and (ii) the energy balance approach proposed by Persson and Brener (PB) (3). We will demonstrate that both approaches (i and ii) yield very similar results. As a paradigmatic test case, we consider the contact between a rigid Hertzian indenter and an adhesive broad-band viscoelastic substrate. A modified power-law constitutive model for the viscoelastic material is assumed, defined by only four parameters: the glassy and rubbery elastic moduli, a characteristic exponent n, and a timescale t0.

The dependence of the maximum adhesive force (the pull-off force) on the unloading rate will be studied numerically using a scheme based on the boundary element method, assuming that unloading begins from a fully relaxed substrate. By comparing predictions made using the PB theory with numerical results, we found excellent agreement, suggesting that PB theory accurately accounts for internal viscoelastic dissipation in the material. Through a comprehensive numerical analysis, we determined the minimum contact radius required to achieve maximum amplification of the pull-off force at a specified unloading rate and for various broadness of the viscoelastic material spectrum.

Additionally, we compared the numerically predicted pull-off force versus unloading rate

*Speaker

†Corresponding author: antonio.papangelo@poliba.it

with experimental results. Tests were conducted using a glass lens indenting a PDMS substrate, showing that numerical and experimental data align up to an unloading rate of approximately 100 um/s. This finding suggests that, contrary to current numerical and theoretical models (1-3), the fracture process zone may contribute to dissipation through a rate-dependent term. In our experiments, we estimated this term to be of the same order of magnitude as the energy dissipated within the bulk material (4). Thus, we discuss the limitations of current numerical and theoretical models for viscoelastic adhesion, considering recent contributions to the literature on this topic.

*References*

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