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An experimental investigation of the stability of peeling for adhesive tapes

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ABSTRACT

A fundamental question of interest in peeling is the stability of the debonding process. A new experimental configuration has been developed to investigate the stability of the peeling process of elastic tapes. The experimental method allows for independent variation of the applied load and stiffness of the system. The role of various parameters including the stiffness of the loading system and geometry of the tape on the stability of peeling is investigated. The change in stiffness can be tuned to trigger or delay the onset of instability. Theoretical stability criteria are used to develop insights into the role of various experimentally varied parameters on the stability of the peeling process.

1. Introduction

The applications of peeling and adhesion are widespread in both engineering and biology. A specific problem that has captivated the attention of a diverse group of scientists during the last decade is the enhancement of the adhesive strength by studying analogous behavior in nature such as the gecko. More specifically, investigations focused on naturally-occurring reversible adhesion in biological systems can be applied to the development of engineered adhesive systems, which have a wide range of applications including pressure sensitive tapes (Benedek and Feldstein, 2008), biomedical devices (Bundy et al., 2000), microelectronic storage and packaging (Harris and Rubel, 2008), and surgical robotics (Balicki et al., 2010).

A fundamental question of interest in peeling is the stability of this process. The role of various parameters including adhesion energy, compliance of the loading system, and geometry of the film on the stability of peeling are of interest. Recent studies have focused on understanding the role of stability in the gecko adhesion problem (Autumn et al., 2006; Tian et al., 2006; Yao and Gao, 2006), particularly with regard to the force distribution in the contact of the gecko's foot to a surface and the detachment of setae (Autumn et al., 2006; Cheng et al., 2011).

The investigation of the stability of peeling can be viewed as an application of concepts in fracture mechanics (Hutchinson, 1979; Hutchinson and Paris, 1979) to the peel test but has received relatively little attention. This study aims to investigate the stability of peeling including the role of compliance of the loading system. Experiments are conducted to monitor the position of the peel tip in an inextensible adhesive tape over time subject to a constant vertical load applied at the tape extremity while the width of the tape is decreased as a function of the tape length. In addition to examining the effect of the applied load and the change in width on the stability of the debonding process, the stiffness of the loading system is varied using an elastic spring. This change in stiffness in a direction parallel to the substrate also affects the peel tip velocity, and can be tuned to trigger or delay the onset of instability. Experimental observations are interpreted

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within a theoretical framework for the stability of the debonding of an inextensible tape from a rigid substrate.

A brief summary of results from the theory of stability for peeling (Molinari and Ravichandran, 2013) is presented in Section 2, which provides the background to interpret the experimental results presented later. The materials and experimental methods employed in this study are described in Section 3. A new method for altering the system compliance is introduced and is used to investigate its effect on stability of peeling. Results of the investigation are presented in Section 4 and are discussed in light of the theoretical model outlined in Section 2. The conclusions for the study are presented in Section 5.

2. Theory

Consider the peeling of an inextensible tape from a rigid substrate. The tape is subjected to a vertical force (F_{perp}) through a dead load (weight) and a horizontal force (F_{par}) through a compliant spring loading mechanism that is parallel to the tape adhered to the substrate. The loading arrangement, forces acting on the tape and the geometry of the tape are shown schematically in Fig. 1(a–c). F_{par} and F_{perp} represent the forces parallel and perpendicular to the substrate, respectively (Fig. 1(b)) resulting in the net force F acting along the tape. The loading arrangement in Fig. 1(a) is analogous to the adhesion system of a gecko, where the vertical force (F_{perp}) can be interpreted as the weight of the gecko while the horizontal force (F_{par}) is due to the compliant mechanism of the muscles in the legs. The vertical force F_{perp} in this configuration will remain constant during experiments to be discussed here, to ensure the peeling condition.

The resultant force, F acting along the backing of the tape provides the driving force for peeling the tape from the substrate,

$$F = \frac{F_{perp}}{\sin\theta}, \tag{1}$$

where θ is the current peel angle.

The peel tip position is defined as a, with $a = 0$ corresponding to the initial tip position at the onset of peeling. The peel angle θ evolves with the advance of the peel front. If the tape is assumed to be inextensible and the tape extremity is constrained to move vertically (either by vertically guided dead weight, F_{perp} or displaced vertically), the peel angle decreases from an initial peel angle θ_o according to the following relationship:

$$\theta = \cos^{-1}\left(\frac{l_o\cos\theta_o + a}{l_o + a}\right), \tag{2}$$

where l_o and $l = (l_o + a)$ are the initial and current lengths of the peel arm, respectively.

In the present analysis, the tape is assumed to be inextensible, and the debonding or adhesion energy is assumed to be a material constant, which is independent of position, peel angle, and peel velocity. For constant adhesion energy γ and inextensible tape, Rivlin (1944) derived the expression for the peel force per unit width,

$$P_f = \frac{\gamma}{1 - \cos\theta} \tag{3}$$

and the adhesion energy can be expressed as,

$$\gamma = P_f(1 - \cos\theta). \tag{4}$$

Eq. (3) can be used to plot the peel force as a function of the peel angle and will be referred to hereafter as the Rivlin

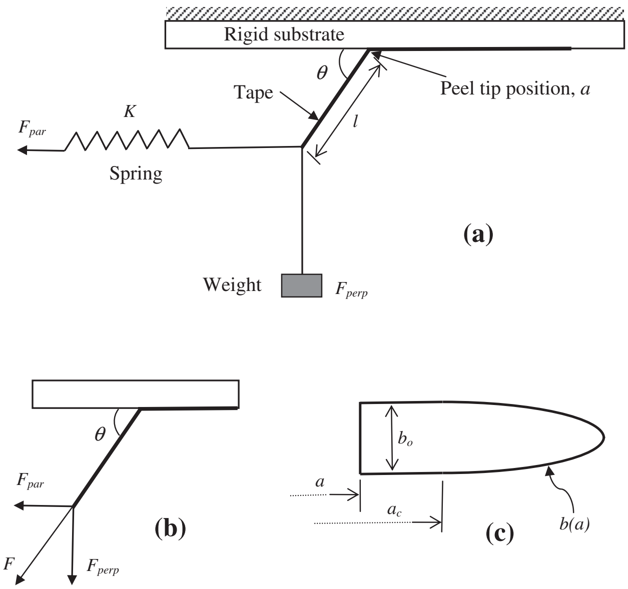

Fig. 1. (a) Schematic of the peeling configuration for studying stability under combined loading with varying system stiffness provided by the horizontal spring. The vertical force F_{perp} is not necessarily confined to fixed plane perpendicular to the substrate during peeling. When required to confine the load F_{perp} to a fixed plane, a vertical guide is used. (b) Forces acting on the tape that is being peeled: F_{par} and F_{perp} are the forces in directions parallel and perpendicular to the tape adhered to the substrate, respectively. F is the resultant peel force acting along the backing of the tape. (c) Geometry of the tape adhered to the substrate: the tape width has a constant value, b_o, which may change to a variable width $b(a)$ when the peel tip reaches the position, $a = a_c$.