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# On dissipative effects of paper web adhesion strength

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ABSTRACT

This work is concerned with the adhesion strength between a paper web and a metal roll surface, which is a common situation in paper machines world-wide. It is shown that the classic expression relating the work of adhesion to the peeling angle and web tension is, in general, insufficient. An improved model is suggested to take into account the energy dissipation due to elastic–plastic deformation behavior of wet paper materials. To judge the model, an industrially relevant example of wet newsprint and a mild steel surface is studied. It is found that the agreement between theory and experimental observations is excellent. A key result is that elastic–plastic material behavior must always be included for wet paper materials in peeling processes.

## 1. Introduction

Paper materials are widely used on a daily basis for a variety of goods and services, e.g. printing and packaging qualities or for household needs. Paper essentially consists of a stochastic network of discontinuous cellulose fibers and is usually manufactured by dewatering a cellulose fiber-suspension on a wire. The fibers have an inherent capability to form bonds between them without any additives. Since the fibers are much longer than the thickness of the paper sheet, the network is approximately planar. However, during the manufacturing of paper, the paper web pass through a number of steel rolls on its way from the wet end of the paper machine to the jumbo reel at the other end. When the dry solids content of a paper web is low, i.e. when the paper is wet, the adhesive forces between the rolls and the paper may become significant. A particularly important location in the paper machine where this is crucial is the so-called open draw section, which is situated between the press and the drying section. Here the paper web is transferred between two rolls in which the web frequently becomes loaded by substantial tension variations that frequently lead to web breaks.

There are several causes that may produce unwanted web tension variations. Examples of such causes are: roll materials and their topology as well as the constituents of the paper itself, e.g. quality of utilized wood fibre, moisture content, chemicals etc., cf. (Edvardsson and Uesaka, 2010, 2009; Ahrens et al., 2004; Kurki et al., 2000, 1997). However, the adhesion strength is one of the most paramount factors for the web tension variations in paper machines. In previous works, e.g. (Ahrens et al., 2004; Kurki et al., 2000, 1997; Mardon et al., 1958; Mardon, 1961, 1976), a simple relation, originally suggested by Rivlin (1944), between web tension and adhesion work was assumed: $G_a = F(1 - \cos\theta_0)$, where $G_a$ is the work of adhesion per unit surface, $\theta_0$ is the peeling angle and $F$ is the web tension (force per unit width). $G_a$ is assumed to be a material constant that needs to be measured and evaluated. However, it turns out that the experimental observation of the peeling tension versus the peeling angle shows that the specific work of adhesion between paper and a given metal surface is not constant as the peeling angle changes (Mardon, 1961). This leads to a suspicion that there might be other dissipative processes involved in the peeling process than solely the work needed to overcome the adhesion forces. In a number of publications, cf. (Kim and Aravas, 1988; Kinloch et al., 1994; Gent and Hamed, 1977; Chang et al., 1972; Williams et al., 2005; Kawashita et al., 2005), plastic bending of polymer films have been considered. In this investigation, an analogous approach for the specific peeling process of paper materials is adopted.

## 2. The peeling model

Consider a slender cantilever beam with thickness $t$ and unit width as illustrated in Fig. 1. A Cartesian coordinate system is attached to the beam with its origin on the beam's neutral surface. The slope $\theta$ at an arbitrary position $(x,y)$ along the beam is given by $\theta = \tan^{-1}[dy/dx]$, where $dy/dx$ is the derivative of $y$ with respect to $x$. At $x \leqslant 0$ the beam is clamped whereas the beam at the position $(x_0,y_0)$ is subjected to a tensile force $F$ per unit width directed in the beam's tangential direction (Fig. 1). The bending moment $M$, per unit width, in the position $(x,y)$ is given by:

$$M = F\cos\theta_0(y_0 - y) - F\sin\theta_0(x_0 - x) \quad (1)$$

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