STRESS-STRAIN CURVE OF A FIBER NETWORK

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Summary We investigate a stress-strain curve of a fiber-based material such as paper and particularly how the bonding properties of fiber affect the shape of the curve and the onset of failure. By using a detailed particle level simulation tool, we accurately track the sequence of events happening prior to failure.

INTRODUCTION

Paper is probably the most explored commercial fiber-based material. The mechanism governing the in-plane stress-strain curve of paper has been a matter of discussion already during the 60^s and 70^s last century [1]. The theme for discussion was "*fibers* versus *bonds*". Since the effect of the bonds is invisible in the stress-strain curve [2, 3], it is still unknown what the processes are, which precede the final rupture and control the strength. Strength of paper is one of the main quality parameter. As so much effort is being invested in improving the bond strength to increase the strength of paper, it is vital to understand how it contributes to it. At the same time, fiber strength is just one of the three bonding parameters. The remaining two are the stiffness of fiber joint region and work of separation which can be captured with a cohesive zone model, for example. Stiffness affects the amount of elastic energy accumulated in the bonds prior to the onset of failure and the work of separation affects how fast this energy is released as well as the total fracture energy. The effect of these parameters should be evaluated in conjunction with other system properties.
Several attempts have been made to reproduce paper fracture numerically [4-6]. The objective of this study is to describe a stress-strain curve of the network of fibers and parameters that dominate its shape and development of failure. By using detailed particle level simulation tools we investigate, among others, the impact of bonding parameters, such as compliance of bonding regions, work of separation and the actual number of effective bonds.

MATERIAL AND METHODS

We considered a three-dimensional network of fibers. A 2x2 mm^2 snippet of a typical fiber network is shown in figure 1. The network was created with the help of a deposition technique and principles of fiber conformation. Each fiber is represented as a series of Timoshenko quadratic beam elements with a tubular cross-section. We accounted for large deflections, rotations and strains.
Fiber-to-fiber bonds were modeled by a point-wise contact with friction [7]. The bond failure was modeled with a bilinear cohesive zone model. A mixed I + II debonding mode was simulated. When a bond fails, the contact between corresponding fibers is described with a frictional contact. This is probably the first three-dimensional model which is capable of simulating the fracture process of paper accounting for nonlinearities at the fiber level and bond failures. Nonlinear stress-strain behavior of a single fiber was described by bilinear isotropic hardening plasticity.
A quasi-static tensile test of a 4x2 mm^2, 25 g/m^2 network with fibers having an average length of 0.8 mm is discussed here. We considered four cases: no bond failure, bond failure with the reference bond strength (referred to as weak bonds), doubled and tripled the reference bond strength (referred to as strong bonds).

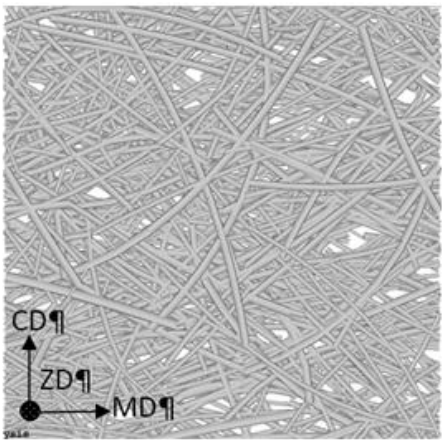

Figure 1: A 2 mm x 2 mm snippet of a large fiber network with a basis weight of 40 g/m^2. MD stands for machine direction, CD – cross-machine and ZD – thickness directions.

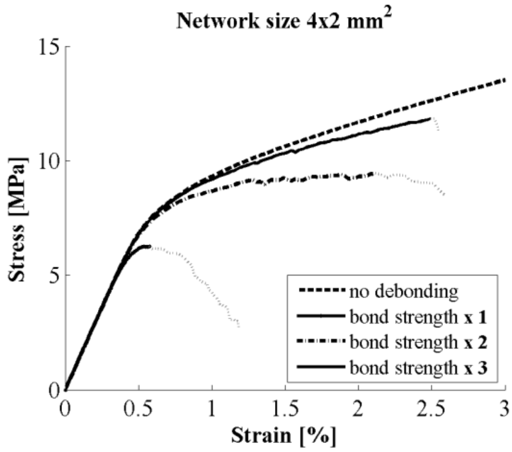

Figure 2: Stress-strain curves for different bond strength

RESULTS

Figure 2 shows the stress-strain curves for different bond strengths. The end of the dark part of the curves indicates the maximum stress value reached during straining. The higher the bond strength is, the closer the curves are to the case with no bond failure. Remarkably, the factor of 3 in bond strength, which is lower than the variation found in the literature, transformed the behavior of the network from ductile to brittle with a given bond compliance and relation between fracture and separation distances.

Surprisingly, very few bonds, namely, 0.4% of the total number, failed completely in the network with stronger bonds before catastrophic failure. There is no clear path in bond failure, which suggests that it is driven by the fiber deformations primarily. Although there more contacts failed in the network with weaker bonds, the total number of debonded contacts was below 10%.

At the same time, the locations of separated bonds correlated with the areas where the local strains were larger. This confirms that the bond failures are largely affected by local strains and not the other way around. The local strain variations depend, in their turn, on the initial details of the network structure, such as local fiber orientations, number of bonds and density. With given fiber properties, the bond strength can control the change between ductile and brittle failure.

In case of strong bonds, very few bonds break prior to catastrophic failure of the network. At the same time, the growth rate of the number of failed bonds is almost constant during hardening part of the stress-strain curve regardless the bond strength.

CONCLUSIONS

The results show that locations of clusters of failed bonds visually correlate with local strain concentrations. By comparing networks with weak and strong bonds, we concluded that strain concentrations are the precursors of bond failures. Inhomogeneous local damage (large elongation) triggers plastic deformations of the fibers at that point. Large stress concentrations cannot be transferred by bonds and they fail. The width of strain concentrations regions have a size of fiber length and obviously depend on initial details of the network structure, such as local fiber orientations, number of bonds and density.

The failure behavior of the small networks considered in the study could be changed from ductile to brittle by relatively small changes in bond strength, as compared to the scatter in bonding data found in the literature. However, changes in bonding do not influence the elastic behavior of the networks, though affecting only sensitivity to fracture. This means that the desired material properties cannot be adjusted by changing only one parameter, rather than changing the whole system – fiber and bonding properties.

Although the data is not presented per this abstract, we also showed an important role of unconventional bonding parameters such as bond compliance, work of separation and initial number of bonds, all of which can significantly affect the strength and type of failure at the considered scale.

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