Forces on fibers in low-consistency refining

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ABSTRACT: Forces on fiber flocs between passing bars have been measured in a "single-bar" refiner. It was found that substantial force on fibers could only be imposed over a relatively narrow range of gap size. The upper limit of this size occurred when the floc was compressed to near its zero void volume. The lower limit corresponded to a gap size in which flocs ruptured into two parts. The energy expenditure associated with these forces was found to compare favorably with energies per impact per fiber estimated in mill refiners using the C-factor.

KEYWORDS: Abies balsamea, *alkaline pulps, chemical pulps, consistency, energy, fibers, flocs, force, kraft pulps, low consistency, papermaking equipment, refiners, refining, softwoods, solids content, Tsuga.*

Refining is a process in which the physical structure of the papermaking fiber is modified by repeated strain. While there is extensive literature on the changes in fiber morphology produced by this strain, there is little on how the strain is imposed, that is, on the refining process itself *(1, 2)*. Of particular importance are the forces that impose strain.

Early attempts to measure forces on fibers were largely measurements of pressure on refiner bar surfaces or of thrust on refiner plates *(1, 3, 4)*. For example, Goncharov *(3)* measured the pressure distribution over the bar surface and found peak pressures of 3.5 mPa in a low-consistency (l-c) laboratory refiner operating at 2–3% consistency. Moreover, the peak pressure was found to occur over the first 2–3 mm of the bar and was approximately 13 times greater than the average pressure. In similar work, Nordman *et al. (4)* found pressures two orders of magnitude lower than those of Goncharov. In still later measurements in chip refiners, Atack *(1)* found pressures of the same order of magnitude as those of Nordman. Atack speculated that the pressure was determined by the thickness and compressibility of the pulp between refiner bars. In summary, pressure in refiners has been measured in a number of past studies, but the results vary greatly. None of these studies have linked the findings to forces on individual fibers.

Another approach to characterize refining action on individual fibers has been developed in recent work *(5)*. A new method of characterizing pulp refiners by the "C-factor" gave an average number of impacts (deformation cycles), N, and an intensity of each impact, I. The latter, expressed as energy/impact/fiber, represents the energy dissipated in a straining cycle. Since energy is the product of force and distance, I offers a basis for estimating force if the distance over which it is applied is known. However, there are insufficient data available in the literature to make this link.

The objective of this study is to obtain order of magnitude estimates of forces acting upon fibers during a single bar crossing, and to link these findings to pulp refiners.

Experimental apparatus and procedure

Apparatus

This study was carried out in a "single-bar refiner" constructed for this purpose. The apparatus, shown in **Figs. 1 and 2**, consists of two horizontal discs, approximately 25 cm in diameter, with one radial bar on each surface. The lower disc rotates at a low speed (30 rpm maximum). The upper stationary disc is coupled to a

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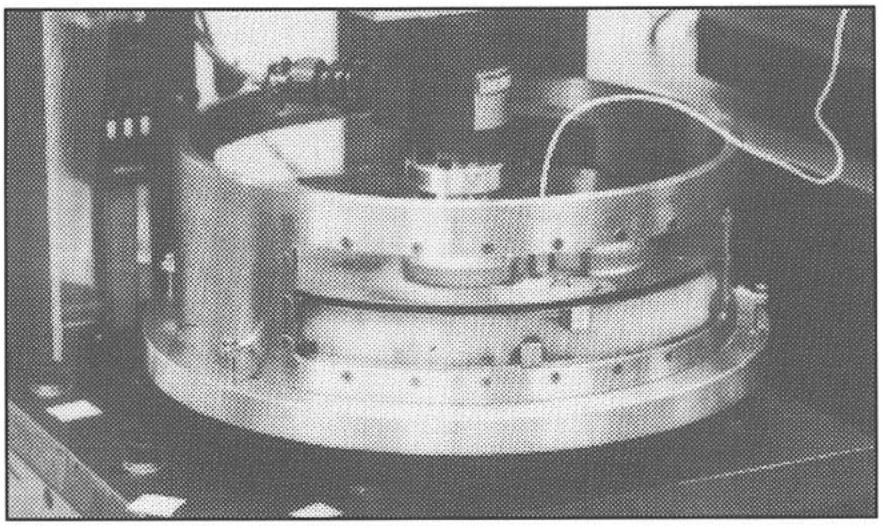
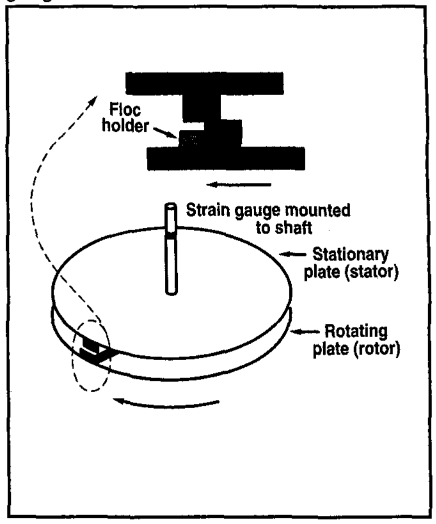


1. Photograph of single-bar refiner

2. Schematic of single-bar refiner showing the bars, floc support, and location of strain gauge



shaft instrumented with a strain gauge to measure torque. The bars on the discs are radially oriented and approximately 10 mm in width and height. The corners of the bars have been surface ground to a sharp edge.

A small support bracket was secured to the leading edge of rotor bar to hold individual flocs as the bars approached one another. This enabled reproducible positioning and reliable transport of the flocs to the refining gap. The "floc holder," shown in Fig. 2, was recessed 2 mm below the plane of the bar surface to avoid interference with the refining action itself.

Procedure

Individual flocs of fibers were prepared in an inclined rotating cylinder using the method of Jacquelin *(6)*. In this method, a suspension of fibers of known mass consistency in water was placed in a 2-L beaker, inclined at a 45° angle and rotated at 30 rpm for 24 h. This process produced individual coherent flocs which were then selected randomly and their diameter (L) measured using a micrometer. Most flocs were found to have an approximately spherical shape; therefore, their size was determined by averaging their diameter along two orthogonal axes. Flocs were removed from the suspension and tested in the refiner apparatus in air rather than water.

The flocs employed in this study were from a hemlock balsam mixture of semibleached kraft pulp. The average length-weighted fiber length was 2.29 mm and the average coarseness was 0.215 mg/m.

The force measurements on individual flocs were carried out by first adjusting the gap between the rotor and the stator to a size G using a feeler gauge. G was typically set between 70 µm and 200 µm. The rotor bar was positioned approximately 90° ahead of the stator bar and then rotation started at approximately 1 rpm (top speed 8 mm/s). As the bars approached one another, the flocs were compressed and sheared in the gap. Torque was recorded as a function of time at a sampling rate of 100 Hz. From this torque, the shear force, F_s, was calculated using

$$F_s(t) = T(t)/R$$

where

R = radial distance from the strain gauge to the flocs.

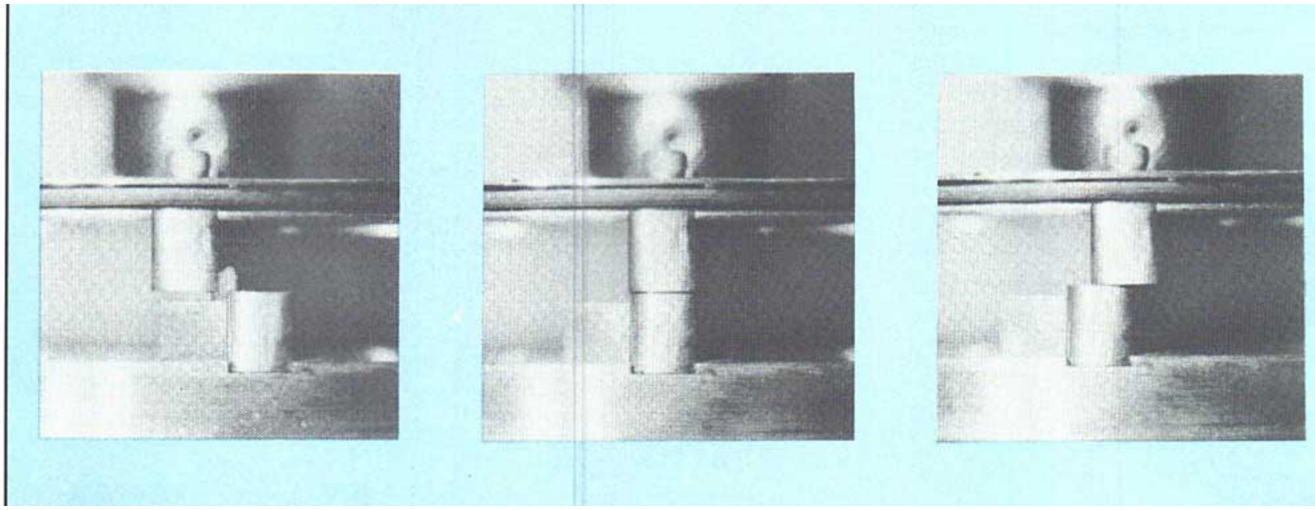
Results

Phenomenological behavior of flocs

The behavior of a typical floc during bar passage is shown in **Fig. 3.** In this example, a 5-mm diameter floc at 3% consistency (C_m=3%) is compressed and sheared in a gap spacing of approximately 0.07 mm. Clearly, as the bars approach (Fig. 3A), the floc was pinched between the leading edges of the rotor and stator. During the bar crossing, compression and dewatering of the floc occurred. When the bar surfaces were superposed, most of the floc was trapped within the gap, but a small fraction of it remained draped over the leading edge of the bar, as shown in Fig. 3B. The floc appeared "pinched" between the sharp corner of the rotor bar and the surface of the stator. This behavior is illustrated schematically in **Fig. 4.**

These observations agree with earlier work by others using high-speed cinematography in which flocs were found to behave in two ways during bar crossings: they remained intact or they were pulled apart *(6, 7)*. Both types of behavior were observed in this work. Flocs were found to remain intact at larger gap sizes,

3. Phenomenological behavior of a floc between passing bars of the "single-bar" refiner



but ruptured into two parts at very small gap sizes, as illustrated schematically in **Fig. 5**. The latter phenomenon may well be that which causes "pad collapse" and consequent plate clash in refiners.

Effect of gap size on forces on fibers

The effect of gap size on shear on flocs, F_s, is strongly determined by the mode of behavior described above. It is also determined by the size of flocs, L, and their consistency, C_m. The effect of these variables can be shown by normalizing the gap size with floc diameter (G/L) and comparing results at different consistencies.

The findings for the consistency range 6–7% are shown in **Fig. 6**. It is apparent that, within an upper and lower limit of G/L, F_s increases with decreasing G/L in an approximately linear manner. Above the upper limit of $G/L = 0.07$, F_s is zero. Below the lower limit, in this case approximately $G/L = 0.015$, F_s decreases abruptly, as shown by the dotted line in Fig. 6. The abrupt decrease corresponds to the transition in floc behavior from compression and shear to rupture as described above.

At a lower concentration of approximately 3–4%, a similar linear behavior is apparent (**Fig. 7**). However, in this case, the sudden decrease at the lower limit was not found, for reasons that are not evident. The upper limit was found by extrapolation to occur at approximately $G/L = 0.035$.

At both floc consistencies tested, the upper limit occurred when G/L approximately equaled the consistency of the uncompressed floc. This signifies that compression to near zero void volume took place. This level of interfiber contact appears necessary to support force on passing bars. In contrast, the lower limit occurs when the bar gap is sufficiently small to shear the floc into two parts.

Shear force distribution during bar crossing

In addition to the peak forces described above, we measured the force distribution as a function of time as the bars passed over one another. A typical force distribution from shearing a floc is shown in **Fig. 8**. As the bars approach one another, the force increased to a maximum at a time of 0.35 s, which corresponded to a distance of approximately 3–5 mm from the leading edge. The shear force then decreased gradually. The shape of this distribution appears to be similar to the "normal force distribution" curve reported by Goncharov *(3)*—although, in some cases, Goncharov observed a second peak which was not observed here.

Energy expended on fibers

The area under the curve in Fig. 8 gives the energy expended in shearing the floc through the single bar crossing. The energy/impact/fiber, I, may be determined by dividing this energy among the total number of fibers in the floc, N_f:

$$I = (1/N_f)\int F_s u \, dt$$

where

F_s = shear force

u = bar velocity

t = time.

For the distribution shown in Fig. 8, I was found to be about 10^{-5} J/impact/fiber. This agrees reasonably well with values of I of 10^{-5} to 10^{-6} J/impact/fiber calculated for mill pulp refiners using the C-factor *(5)*.

Discussion

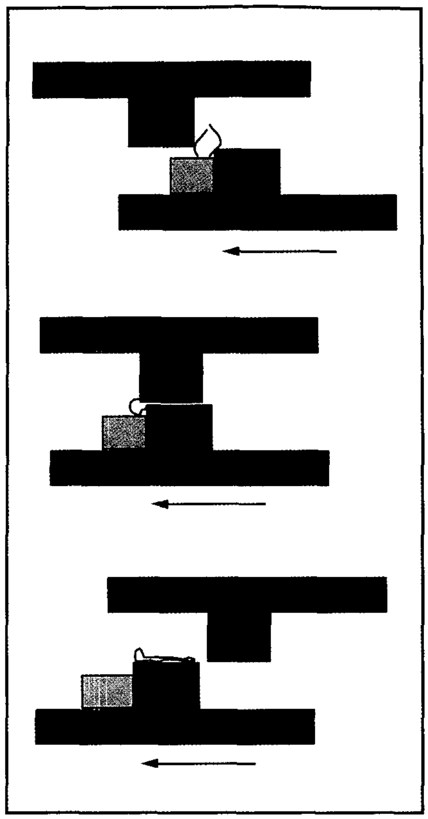
Having determined the force distribution and energy expenditure on individual flocs during a bar crossing, we may now estimate the same for individual fibers. To do so, we must make some assumptions.

If we assume that forces during bar passage are distributed evenly among fibers, we obtain from the peak force in Fig. 8 a value of 10^{-3} *N*/fiber. Assuming this produces strain in uniaxial tension, the peak strain ε is estimated to be about 0.1%, assuming a modulus of elasticity of 10 GPa *(9, 10)*. The energy associated with this peak strain (area under the stress strain curve) is approximately 0.1% of the energy required to cause fiber rupture *(11)*. The rest of the energy must be expended on other modes of strain (e.g., bending), but probably most is lost in frictional dissipation.

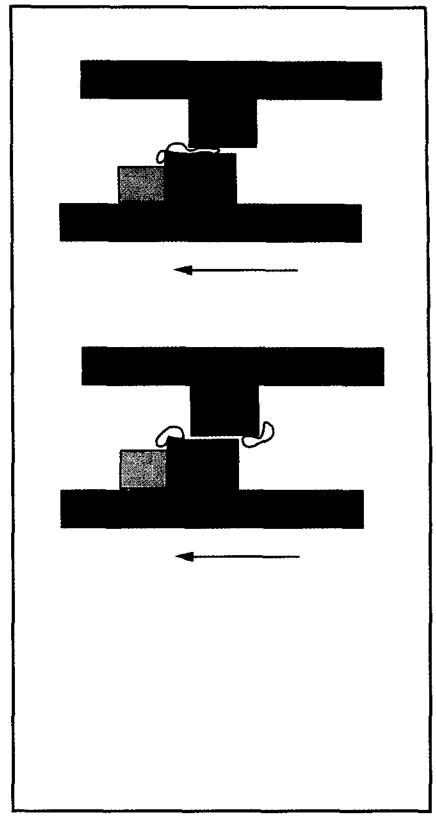
In earlier work *(5)*, we estimated a theoretical maximum *I* for refining as that which caused 3% tensile strain, following the approach of Leider and Nissan *(11)*. This gave $I \simeq 10^{-5}$ *J*/fiber. Since 3% strain is close to the level of rupture for fibers, we interpreted this as the level of *I* for fiber "cutting." Although this earlier theoretical estimate of *I* was comparable to that determined by the C-factor, the results of this work suggest that strains associated with this level of *I* are much less than those required for rupture. To estimate the level of *I* for rupture, we can assume the shape of the force distribution in Fig. 8; and, from this, we obtain an *I* of approximately 10^{-4} *J*/impact/fiber. This is an order of magnitude greater than the earlier estimate.

In closing, it should be noted that the estimates in this discussion are only order of magnitude values, and that they are based on clearly specified assumptions. However, given the state of the art in fundamental knowledge of refining, these estimates are important first steps in quantifying the action of refiners on individual fibers.

4. Schematic of observed behavior of a floc during bar crossing



5. Schematic of observed floc behavior between passing bars at small *G/L*



Summary and conclusions

1. Sizable forces could be imposed on fiber flocs only over a narrow range of gap size. The upper limit of this range corresponded to floc compression to near zero void volume, whereas the lower limit occurred at a gap size that ruptured the flocs into two segments.
2. The average energy/fiber expended in a bar crossing was found to be of the same order of magnitude as those calculated for pulp refiners by the C-factor, i.e., 10^{-5}–10^{-6} *J*/fiber.
3. Assuming all forces to be distributed evenly among fibers, the peak force associated with this energy expenditure corresponds to approximately 0.1% strain in uniaxial tension.
4. Assuming the shape of the force distribution measured in this study, the level of *I* required to cause fiber rupture in tensile elongation (3% strain) was estimated to be approximately 10^{-4} *J*/fiber.

In summary, the results of this work confirm the approximate order of magnitude of energy/impact on fibers measured by the C-factor. However, the results also suggest that only a small fraction of this energy is expended in tensile strain of the fiber. The remainder is assumed to be expended on other forms of strain and probably a great part is lost in frictional dissipation. ■

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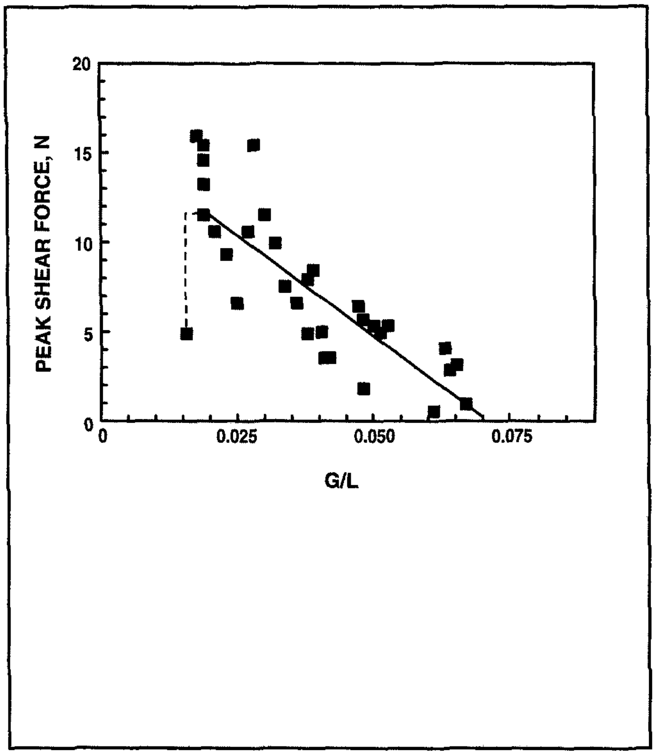
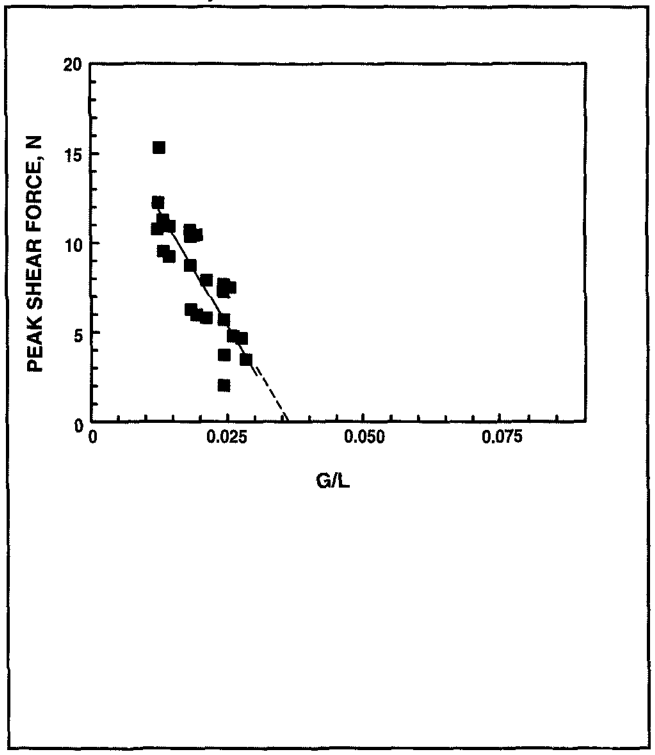
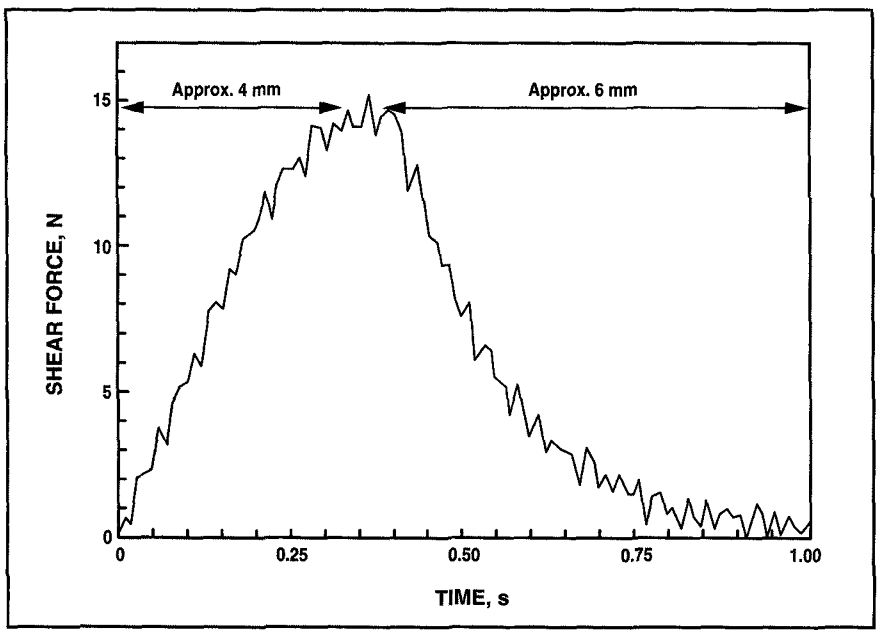
6. The effect of gap size on peak shear (C_m = 6–7%). The dotted line shows the abrupt decrease of shear force at low *G/L*.



7. The effect of lower consistency (C_m = 3–4%) on peak shear. The data extrapolate at zero shear to a level of *G/L* approximately equal to the floc consistency.



8. A typical shear force distribution along the width of the bar surface



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Nomenclature

C_m = mass consistency, %
F_s = shear force, N
G = gap size, m
I = intensity of refining, J
L = floc diameter, m
N_f = number of fibers in a floc
R = moment arm, m
t = time, s
T = torque, Nm
u = bar velocity, m/s
ε = strain