NBSIR 79-1722

Characterizing the Interfiber Bonding of Paper Pulps: Rationale for Bonding Parameters Derived From Tensile Test Data

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Polymer Science and Standards Division
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Bureau of Engraving and Printing
reasury Department
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SUMMARY AND CONCLUSIONS

As a result of some recent research a new technique is evolving for characterizing the interfiber bonding of paper pulps. Handsheets in the form of very low density webs are made from the pulp to be evaluated. Specimens from these handsheets are then extended in a sensitive tensile tester to obtain a force-elongation curve, from which various bonding parameters are derived.

The force-elongation curve for a web specimen has a jagged appearance; the force rises and dips through one or more peaks, and eventually diminishes to zero. Each jag in the curve is assumed to indicate the breaking of a bond between fibers. If the average elongation between successive jags is small, the web has a relatively large number of fiber crossovers per unit area, and most of these crossovers are bonded. On the other hand, if the average percent elongation per break is large, the web has only a few interfiber bonds per unit area. This means that there is a light density of crossovers, or that many of the crossovers are not bonded, or both. In order to characterize the areal density of interfiber bonding, the percent elongation of the web is plotted versus the number of bond breaks, and the initial slope of this curve is used as the appropriate parameter.

Each time a bond breaks as the network is being extended, the force drops abruptly, indicating that some of the fibers are no longer carrying load. The magnitude of a force drop is related to the force that one of the interfiber bonds was able to withstand before it gave way. For example, if the bond is strong, the fibers connected by it carry a heavy load, and the force drop resulting from bond break is large. Thus the average of a series of force drops should provide a parameter for characterizing bond strength. Unfortunately the magnitude of a force drop also depends on the size of the mesh that is opened up by the break. As there is a wide variation of mesh sizes

in a web network, there is a correspondingly wide variation of force drops. Thus it is difficult to determine an average force drop that adequately gauges interfiber bond strength.

Each time a bond breaks, some of the strain energy stored in the network is dissipated. This energy loss can be calculated from the slope of the force-elongation curve just before a break occurs, and the values of the force just before and just after break. The energy loss is closely related to the strength of the bond that breaks, so that the average of a series of energy losses should provide a parameter for characterizing bond strength. Unfortunately the value of the energy loss parameter is dependent on mesh size and mesh size distribution, thus its effectiveness in gauging bond strength is limited.

Studies with mathematical models simulating a network of pulp fibers have suggested that a force drop is approximately proportional to $f^{0.5}$, and the corresponding energy loss is approximately proportional to $f^{1.5}$, where f is the force before break in the fibers joined by the bond. The studies also suggest that the force drop and energy loss are approximately linearly proportional to a length characterizing the mesh involved in the bond break. Thus the ratio of energy loss to force drop should be dependent on bond strength but insensitive to mesh size. A good bond strength parameter could be obtained by averaging this ratio over a series of bond breaks. This parameter measures the energy loss per unit force drop. It has the dimensions of length. Thus it provides a characteristic elongation representative of the amount a network must be stretched in order for a bond to break.

This report comprises a consolidation of knowledge derived from previous researches. It suggests several parameters for use in characterizing interfiber adhesion. These parameters must be tested experimentally . Tests should also be made to verify the assumptions involved in the derivation of these parameters and in the interpretation of their meaning.

INTRODUCTION

There is a need to develop parameters that can be used to characterize quantitatively the adhesion between fibers in a sheet of paper. Such parameters, for instance, would be useful in selecting, blending and treating batches of pulp to produce a paper with improved interfiber adhesion.

One way to obtain information on interfiber adhesion is to perform tensile tests on handsheets in the form of low-density open webs made from the pulp of interest. Appropriate parameters can be derived from the force-elongation curves obtained in these tests. Bond strength can be characterized in terms of an energy parameter, obtained by averaging the energy dissipated by the fibrous network for each of a number of selected bond breaks. Alternative characterizations can be obtained by averaging the drops in force sustained by the network for each of a number of bond breaks, or by calculating a characteristic elongation representative of the amount the network must be stretched in order to cause a bond break.

Another useful parameter is obtained by plotting the percent elongation of the specimen as a function of the number of bond breaks. The initial slope of this curve, or initial percent elongation per break, can be used as a parameter characterizing the areal density of bonding between fibers constituting the network.

In order to derive these and other parameters, and to interpret their meaning, it is necessary to make some assumptions about the mechanical processes taking place as the fibrous network is elongated. It is also necessary to have some ideas about the effect of such variables as network size, specimen shape and existence of flaws. These topics have been discussed in previous reports [1-4], and a better understanding of them has gradually developed. In this report an attempt is made to consolidate these and other concepts, and discuss them in depth in order to record the current understanding and provide a background for future research.

THE TENSILE TEST

Consider a random fibrous network formed from the pulp to be evaluated. The network should be an open web approximating a "2-dimensional" web in thinness. In a 2-dimensional web the number of constituting fibers is so small that the area covered by more than two fibers intersecting at a given point is negligible. The concept and statistical geometry of 2-dimensional networks has been discussed by Kalmes and Corte [5].

If a specimen cut from this network is stretched to break in a sensitive tensile tester, a jagged force-elongation curve is obtained in which the force rises and dips through one or more peaks, and eventually diminishes to zero. Each jag in the curve signifies the breaking of a bond between fibers. (It is assumed that the fibers are much stronger than the bonds between them so that the fibers themselves do not break).

During the straining operation the following behavior sequence is observed in the fibrous network: The fibers tend to align themselves in the direction of the extension with the straightest and most perfectly aligned fiber segments bearing most of the load. As the specimen is elongated it contracts laterally forming a fluted structure in the portions not restrained by the end clamps. Bond breaks often occur at random points, causing only local damage and leaving the surrounding network essentially intact. However a breakage of some bonds usually in the vicinity of network flaws or irregularities, results in more extensive damage. Often a succession of breaks occurs in the same region because of stress concentrations that develop. In the regions of more extensive damage parts of the network lose their strain and sag away. As the extension continues further deterioration occurs. Portions of the network midway between the ends of the specimen tend to collapse into threadlike structures in which the longitudinal forces are concentrated. These forces in turn are diffused through the uncollapsed portions of the network at either end. In the final stages of the breaking process often only one long threadlike structure remains. This structure sustains relatively large elongations before breaking.

Figure 1 is a tracing of the force-elongation curve obtained in an actual test on a well bonded web of 2.5 g/m^2 mass per unit area. The specimen, 2 cm long by 1 cm wide, was elongated at a rate of 0.2 cm/min. Chart speed was 20 cm/min, and full scale deflection corresponded to a force of 50 mN (5 g). (Note that the elongation scale on this tracing reads from right to left). The points at which bonds are thought to break have been indicated and numbered.

Various types of jags in the force-elongation curve are encountered throughout the course of the test. The jags numbered 1, 3, 12, 19, 30, 57 are all well defined, and the associated drops in tension are small. These jags are thought to denote bond breaks in which only local damage results.

At points 4, 9, 15, 26, 44, 47 the force exerted by the network does not drop, but over a short elongation remains constant or else does not increase at its previous rate. This behavior may result from the breaking of weak attachments between fibers that were only slightly stressed, because of low orientation or because of a local concentration of neighboring fibers sharing the stress. It could be due to the action of frictional forces between fibers. Small force drops may occur but might not be resolved if the full-scale force setting of the recorder chart is too high. In addition, inertia of the clamp and coupling to the load cell can slightly limit the sensitivity to small changes in force. Although the cause of these discontinuities in slope is uncertain, the most noticeable ones should probably be counted as bond breaks.

At jags numbered 2, 5, 22, 39 large drops in force are apparent, implying bond breaks in which parts of the network incur appreciable damage. However the network, although damaged, may develop large and occasionally even greater resistant forces as the elongation proceeds. This behavior is exemplified by the force-elongation curve of figure 2, which was obtained by an identical test on another specimen of the material used in figure 1. Note here that after the force drop at jag 27, the force level gradually rises with increased elongation, and at jag 70 has regained its earlier value.

So far the elongation of the web has been described from the standpoint of an observer watching the process. Two examples illustrating the force-elongation behavior were then given. It should be noted that most of the test specimens have irregularities in structure, and that the size of these irregularities is of the same magnitude as that of the specimen itself. Thus the behavior of any given web specimen may be different from that of another specimen of the same material. The description given only points out behavioral features that may or may not occur in each instance. In order to understand the behavior, an assumed network response mechanics is now presented. Some of the expected behavior of the web network is described, but the extent to which features of the behavior take place will vary from specimen to specimen.

In the early stages of the stretching process segments of the fibers composing the network tend to orient themselves in the direction of the extension, and to resist the extension through the combined action of forces along their length. As the extension proceeds more and more of these segments between bonds become oriented and bear load. As a result of this process the force-extension curve has a slope that increases with increasing elongation. This initial nonlinear region is apparent in the force-elongation curves of figures 1 and 2.

After this initial behavior a state of elongation is attained in which all of the segments that can be oriented now share in maintaining the force resisting stretch, and the force-elongation curve becomes more linear. The total force however is still sustained by relatively few fiber segments, and the individual forces in the segments are very unevenly distributed. Most of the fiber segments in the network bear little or no load, because they are unaligned, or because most of the load is borne by adjacent fibers with straighter segments between bonds. When the force on a given segment becomes sufficiently great a bond at the end of the segment breaks, and the network opens up in the vicinity of the break.

The subsequent force-elongation behavior of the network will depend upon the size of the hole that opens up. Often the first breaks occur randomly throughout the network, and only small or moderate holes result leaving the network essentially intact. In this instance other fiber segments in the vicinity of the break assume the load relinquished by the broken bond. In the web there is a redundancy of these previously unoriented unloaded fibers. Thus the web can be expected to behave as though the force overall were sustained by the same number of load bearing elements before and after the break.

The breaking of a bond tends to increase the initial unloaded length of the specimen. Thus the force-elongation curve is shifted so that a given force corresponds to a slightly greater elongation. If the bond break leaves the specimen essentially intact, the shape of the force-elongation curve should be almost unaffected by the break. In particular, the slope of the force-elongation curve at the force level of the break should be practically the same before and after the break. This is exemplified by the first 35 breaks in the force-elongation curve of figure 1, where most of the slopes before and after break have the same value.

The process just described in which bonds break randomly but leave the network essentially intact changes the distribution of forces in the load bearing segments. The bonds bearing a disproportionate share of the load are most likely to break. Thus the distribution of forces becomes more even after a number of breaks, and better cooperation between load bearing segments ensues. Under these conditions the network gradually sustains a higher force level, and the shape of the force-elongation curve changes so that the slope at a given force level becomes greater. This effect is particularly pronounced in the force-elongation curve of figure 2, where the slopes in the vicinity of break 25 are greater than the earlier slopes in the vicinity of break 5.

During the elongation of a fiber network specimen any number of different bond breaking situations might arise. Figure 3 depicts some of them schematically. In figure 3a, for instance, a region of the specimen is shown in which the meshes are uniform and of moderate size. If the bond denoted by the black dot should break, the mesh would open up slightly, and some of the strain energy stored in the vicinity of the bond would be dissipated. The force with which the network resists elongation, however, is sustained by a relatively large number of parallel fibers in the surrounding meshes, so that the decrease in force resulting from the break would be small. The force-elongation behavior in this instance might be somewhat analogous to that of a number of short springs in parallel.

In the situation depicted in figure 3b, two bonded fibers are holding together a large mesh. If the bond between these fibers should break, a hole would form associated with a large distortion of the network. Some of the force relinquished by the broken bond would be assumed by the meshes to either side of the hole, but the forces previously channeled through the meshes at the top and bottom would be greatly diminished. Thus a large decrease in force would occur, and a large amount of strain energy would be dissipated.

Long strip or threadlike configurations frequently form in the specimen after a substantial elongation. Figure 3c represents schematically the unstrained structure of these portions of the network. This striplike structure is often observed by itself, but with increasing elongation it condenses so that its shape is that of a single thread. The fibers in such a long narrow condensed strip become highly oriented when straining takes place, and the force borne by the resulting thread is sustained by only a few parallel pathways. When a bond breaks in the thread the force usually drops by a significant fraction, and a comparatively large elongation is usually required before the force builds up to near its pre-break value. The force-elongation behavior of the thread might be considered as somewhat analogous to that of a long spring composed of many shorter springs joined end to end.

Figure 3d depicts the appearance of a web specimen in which three threadlike structures have formed. The total force borne by the specimen is concentrated in these three threads, but elsewhere is diffused throughout the specimen. When the web specimen has a configuration similar to this, any of the three types of bond breaks just described may occur. For instance if the center thread should give way the specimen would incur significant damage as in situation 3b. The central portion of the web would be unloaded and the large amount of strain energy previously stored in these portions would be dissipated. The total force would drop by a large amount, and consist of the forces channeled through the two remaining threads. In addition some fiber segments in the web portions at the ends of the specimen might lose their previous orientation and carry less load. With increasing elongation the force level would build up, but the force-elongation curve would have an initial region in which the slope increases with elongation as the load bearing fiber segments become better oriented. This post break behavior can be observed in many of the later breaks of figure 1.

If in figure 3d the two threads at the sides should break the force resisting elongation would be concentrated in the central condensed thread, and would be diffused through the uncollapsed parts of the network at either end. If the parallel fiber segments constituting the central thread are well oriented, and the forces in these segments are evenly distributed, the total force sustained by the thread may be quite large. In such case the force level may rise to high values, and the bond breaks will most likely occur in the web portions of the specimen at either end. The appearance of the force-elongation curve will be similar to that for a specimen that remains intact during a series of breaks.

If the forces in the thread are not evenly distributed, and are concentrated in only a few parallel pathways, the thread will be unable to sustain a high force level. With each successive bond break in the central thread, this force level will diminish. Furthermore the slopes of the force-elongation curve between successive breaks will be low and nonlinear, because many of the load bearing fibers in the uncollapsed end portions of the specimen will have lost most of their previous orientation. Post-break behavior at low force levels in which the slopes are low and nonlinear can be noted in the concluding breaks of the curves in figures 1 and 2.

Some of the behavior just described is further exemplified in the force-elongation curves of figures 4 and 5. These curves were obtained from tests on specimens of the same material used in figure 1. The specimens were 2 cm long and 0.5 cm wide, but in other respects the test conditions were the same as before. During the elongation the condition of the specimen was noted on the chart, so that the effects of progressive damage to the specimen could be ascertained.

In figure 4 the post break slope increases for breaks up to the 10th, indicating a severe maldistribution of forces among the load bearing fiber segments. The specimen web remains essentially intact up to the 37th break when a strip forms. Post-break slopes up to the 45th break are low, but increase as the load distribution improves in the fibers composing the strip. The strip condenses into a thread at break 45. The force rises to a relatively high value for breaks 52 through 55, which probably take place in the web rather than in the thread. The force then drops almost to zero, but rises again to a high value at the final break.

In figure 5 the specimen web remains essentially intact up to break 34 when a gap opens on the right hand side. Despite the web damage the slope of the force-elongation curve is only slightly decreased for breaks up to break 45 when the force drops and a strip starts to form. The force then rises after a series of breaks to break 60 when the strip condenses into a thread. Post-break slopes from break 35 to break 70 have almost the same high value, indicating that most of the breaks are occurring in the web rather than in the strip or thread. The final post break slopes from break 78 on have a low value indicating that breaks are occurring within the thread.

CHARACTERIZING THE TIGHTNESS OF A WEB STRUCTURE

A tightly bonded web structure is one that has a large number of interfiber bonds per unit area. The number of these bonds depends upon the number of fiber crossings and on the number of crossings that bond together. This concept is illustrated in figure 6. Here the symbol A denotes a web in which the meshes are approximately uniform in size and bonds occur at each fiber crossover. Symbol B represents a web having the same number of fiber crossovers per unit area as A, but in which only those crossings denoted by dots are bonded. The areal density of bonding of web B is less than that of A, so web B is said to be relatively looser. Web C is a more finely meshed web with greater areal density of bonding than web A, and so is said to be relatively tighter.

If a structure is tightly bonded it can be seen intuitively that on the average only a small percent extension is required before the force applied to one of the bonds is sufficient to break it. For a loosely bonded network a larger percent extension on the average is required. Thus a small initial value of average percent extension per break would be characteristic of a tight network, and a larger initial value of average percent extension per break would be characteristic of a looser network. The initial average percent extension per break for a given web specimen is equal to the initial slope of the curve of percent extension versus number of breaks obtained by a tensile test.

The areal densities of bonding of two different networks thus can be determined relative to each other by comparing data from tests on specimens of each network. In order to insure a reliable comparison however, the specimens used should all have the same dimensions, and the comparisons should be made between average values from a number of tests. It is also desirable that the areal density of fibers in the two networks should not be too large; otherwise a high level of force would prevail during extension, and the sensitivity of the test record to small changes in force would be correspondingly reduced. In such case some of the breaks would not be detected.

An example of a plot of percent elongation versus number of bond breaks for a typical web is given in figure 7. Data for this plot were obtained from the force-elongation curve, figure 1. The initial portion of the curve, figure 7, is linear up to break 50. The value of the initial slope, determined by a least squares fit of the elongation values between breaks 5 and 50, is 0.149 % per break. In the later stages of elongation the average extension between breaks increases, reflecting the increased damage to the web and the formation of strips and threadlike structures. Other examples of elongation-break curves can be found in previous reports [1-3].

AN ENERGY PARAMETER FOR CHARACTERIZING BOND STRENGTH

In the discussion of figure 1 the jags numbered 1, 3, 12, 19, 30, 57 were selected as examples of well defined bond breaks with small associated drops in force. Presumably only local damage results from these breaks. Drops in force associated with some of the other breaks are much larger, reflecting more extensive damage to the network. Some force drops are so small as to be almost undetectable on the record chart. However a range of breaks in which only local damage occurs could be defined by requiring that the associated force drops lie between two suitably chosen values. If the energy dissipated by each break in this range is calculated, an average energy per break E_0 could be determined for the specimen. The E_0s for a number of specimens could then be averaged to obtain a value E that could be used as a parameter to characterize bond strength. For instance, if the fiber crossings in the web specimens are strongly bonded, this energy dissipation parameter would have a high value, and if the crossings are weakly bonded the value of the parameter would be low.

In order to estimate the average energy dissipated per bond break it is necessary to make some assumptions about the relationship between the force sustained by a network and the energy stored in it. In an extension process in which none of the interfiber bonds are broken this relationship could be found by integrating under the force-elongation curve to obtain data on work of extension versus force. During the extension a small part of the work done would be dissipated by friction involved in aligning fiber segments, but if the extension were removed and the specimen then reextended, most of the frictional dissipation would not recur, and the work of extension would be stored as strain energy in the network.

Thus a force-energy relationship would be obtained. It is important to know how a force-energy relationship of this type is affected by a bond break.

According to the previous discussion the shape of the force-elongation curve should be almost unaffected when a bond breaks, if the network remains essentially intact. This can be checked by noting whether the slope of the curve is the same before and after the break. The principal result of the break then is to shift the force-elongation curve so that a given force corresponds to a slightly greater elongation. In this circumstance the force-energy relationship for the network is unchanged by the break; i.e., points on the force-elongation curve before and after the break, where the force is the same, correspond to states of the network in which the stored energy is the same. The calculation of energy dissipated by a bond break depends on the validity of this assumption.

Figure 8a depicts a jag of the type suitable for use in calculating the energy dissipation. On this diagram point 0 designates the force and elongation values prevailing just after a bond break. As a specimen is elongated the force increases up to its value at point 1 where the next break occurs, and the force drops to point 2. During subsequent elongation the force should rise again in such a way that the slope of the force-elongation curve is the same as it was before the break. Elongation e_3 is the elongation at which a force F_3 is attained that is equal to the force after break F_2. Presumably the energy stored in the network at elongation e_3 is the same as the energy remaining in the network after the break. The work done in extending the network from elongation e_3 up to elongation e_1 is therefore all dissipated when the bond breaks. Its value U is given by

$$U = \frac{F_1 + F_2}{2} (e_1 - e_3) \qquad (1)$$

In some instances such as that depicted in figure 8b the energy dissipated when a bond breaks exceeds the work done in extending the network between breaks. However by performing the construction indicated, eq (1) can still be used to calculate the energy dissipated. In this case the accuracy of the calculation can be improved by estimating the slope between points 0' and 1, using other slopes in the vicinity as a guide and drawing the construction line with this slope.

Sometimes the force-elongation curve immediately after break is not linear, but becomes linear just before the next break. In such case it may be necessary to use a slope partially estimated from neighboring values, as in figure 8c, before calculating the dissipated energy.

If the force drop $F_1 - F_2$ is designated by F_d, and M is the slope of the force-elongation curve between points 0 (or 0') and 1, the difference in elongation $e_1 - e_3$ is equal to F_d/M. Eq (1) then becomes

$$U = \frac{F_{av}F_d}{M} \qquad (2)$$

where F_{av} is the average force $(F_1 + F_2)/2$. This alternative calculation provided by eq (2) is more convenient because the construction for determining e_3 is unnecessary.

The energy parameter E_0 for a given web specimen is obtained by averaging the calculated energy dissipations U associated with a selected group of jags on the force-elongation curve. The jags are chosen so that the force drop F_d lies between two bounding values D_ℓ and D_u. The lower bound D_ℓ eliminates from consideration those jags that are not well defined, and for which there is some uncertainty as to the nature of the associated bond break. The upper bound D_u screens out bond breaks that result in significant damage.

An appropriate value for D_ℓ might be 0.002 S, where S is the full-scale force of the record chart. The quantity 0.002 S then would be the smallest force difference that could be read with certainty from the chart. The value of D_ℓ should be the same for all of the calculations. Thus if the web specimens to be compared were tested at different force levels, the value of D_ℓ to be used should be defined in terms of the highest value of S that was used in the tests. The values of D_u should be selected after data from all of the tests have been examined. This same value of D_u should then be used in the calculation of E_0 for each of the specimens.

In calculating E_0 it is advisable to use only the data for breaks within a certain range. The first few breaks should be excluded because the network forces are unevenly distributed and the load bearing segments are not well oriented at this stage. The last 60 % of the breaks might also be excluded because the specimen has probably by then incurred significant damage. Although the values of U calculated from these later breaks might not be affected by the damage, it would be prudent not to rely on them. In a few instances the slope of the force-elongation curve after a bond break may differ noticeably from the slope before the break. In this event eqs (1) and (2) are invalid, and the break involved should be excluded from the calculation of E_0.

A FORCE DROP PARAMETER FOR CHARACTERIZING BOND STRENGTH

Adhesion between pulp fibers can be characterized alternatively by means of a force drop parameter F. This parameter can be obtained by averaging force drops incurred in a series of bond breaks to obtain F_0 for a given specimen, and then averaging the F_0s for a number of specimens. The parameter F has not been tested experimentally but its use as a parameter to characterize adhesion seems feasible.

In order to calculate an energy parameter E it is necessary to measure the slope of the force-elongation curve in the vicinity of a force drop. The parameter F can be calculated more simply, as only the force drops are used in its evaluation.

For a definition of F_0 consistent with the procedure for obtaining E_0, the first few force drops and the last 60 % of the force drops should be excluded from the average. The values of the force drops used in the average should be greater than a lower limit D_ℓ and less than an upper limit D_u. The quantities D_ℓ and D_u should be the same as those used in the calculation of the energy parameter E. In some instances the slope of the force-elongation curve after a force drop may differ noticeably from the slope before the drop. When this occurs the force drop involved should be excluded.

In order that the force drop parameters F_0 be mutually comparable the test specimens must all have the same initial length. In other respects the force drop parameter F is similar to the energy parameter E. Both parameters are sensitive to mesh size and mesh size distribution in the test specimen network. Model studies [4] suggest that neither parameter is linearly related to the average of the local bond breaking force, and that the functional dependence of F on the average bond breaking force is different from that of E.

DISCUSSION

The force-elongation curve of a web network specimen provides various data that may be of use in estimating interfiber bonding forces; such as, forces sustained by the specimen, elongation to break of the specimen, slopes of the curve, average elongation between bond breaks, and the force drops resulting from bond breaks. The force drop data are most directly related to the individual bond breaks; thus an average force drop parameter such as F would apparently provide a good characterization of interfiber adhesion. An energy dissipation parameter such as E, which is derived from force drop data and the slopes of the curve, should also provide a good characterization of adhesion.

Other parameters might be used; such as, the work to break the specimen, or the average force level obtained by dividing the work to break by the elongation at break. These and similar parameters would seem to be more practical because they are easily measured. However, they are likely to vary appreciably from specimen to specimen, because they are very sensitive to structural imperfections. The parameters E and F derived from force drop data and slopes are not so sensitive in this respect. The parameters E and F are also better understood; i.e., it is possible to describe in a qualitative way what kind of average interfiber bond strength these parameters represent.

Model studies in which a fibrous network was simulated by arrangements of springs in parallel [4], suggest that when a bond breaks, the energy lost by the network is approximately independent of the size and length-to-width ratio of the specimen that is being elongated. To a similar approximation the force drop is inversely proportional to the length of the specimen, but is independent of its width. If these assumptions are valid for actual test specimens, one might infer that the values of the force drops and energy losses observed in a test are not appreciably affected by cumulative damage to the specimen as it is being elongated. This is an important advantage.

The force drop and energy loss parameters also have serious disadvantages:

1. The force drops and curve slopes cannot be measured very precisely.

2. The model studies suggest that the force drop resulting from a bond break is approximately proportional to a length characteristic of the hole that is opened up. As there is a large variation of mesh sizes in a test specimen, the deviations of the individual force drops and energy losses from their average values will be large.

3. Some experimental studies have shown that the frequency distributions of the force drops and energy losses are not level; i.e., there are many small force drops and energy losses, and the frequency of the drops and losses diminishes as their size increases. As more information becomes available on these frequency distributions, it may be possible to derive improved parameters that take the distributions into account. This, however, has not yet been done.

4. Model studies [4] suggest that the force drops and energy losses are not directly proportional to the local forces in the fiber segments separated when a bond breaks.

5. Bond breaks sometimes occur between fiber segments that are not aligned close to the direction of stretch.

6. The magnitude of a force drop or bond break thus depends in a complicated way on the mesh size, the mesh size distribution, the forces in the fiber segments involved in a bond break, and on the orientation of these fiber segments. These individual effects probably cannot be separated out, but ways might be found to minimize some of the undesirable ones.

7. In order to characterize the adhesive properties of different kinds of pulp fibers, using the E and F parameters, it

is necessary that the web specimens formed from these pulps have the same mesh size and mesh size distribution.

In order to obtain good precision in the measurement of E and F, the force drops should be as large as possible. Therefore the length of the specimen should be small. Practical considerations require that the length of the specimen should be at least twice the width, in order to minimize the number of load bearing segments appreciably inclined to the direction of stretch. The width of the specimen should be small so that the full scale force setting on the recorder chart can be made small, and a small change in force will then cause a noticeable jag on the force-elongation curve. The areal density of the sample from which the specimen is cut should be as low as feasible, so that the average mesh size of the specimen will be large.

The model studies [4] suggest that the force drop resulting from a bond break is approximately proportional to f^{α}, where f is the force at which a bond at one end of a load bearing segment breaks, and α is a constant. For a model consisting of equal square meshes formed from springs with the same spring constant, α is approximately 0.5 . The model studies also suggest that the energy loss resulting from a bond break is approximately proportional to f^{β}, where β is approximately 1.5 . These differing values for α and β imply that the force drop parameter F is not as sensitive to the interfiber bonding force f as is the energy loss parameter E.

The value of E_0 obtained from the data for a test specimen may perhaps be interpreted in terms of the following formulation : Let the energy losses be measured for each of a series of n breaks, and let the energy loss U_i for the i^{th} break be given by

$$U_i = K\varphi(\theta_i, f_i)g(x_i).$$

K is a constant that may vary slightly from break to break, if the network is significantly altered by the breaks. g(x) represents the functional dependence of U_i on a characteristic mesh length x_i associated with the bond i. This relationship probably is almost a linear one. φ is a function of Θ_i, the angle before break at which the debonded segment was oriented with respect to the direction of stretch, and f_i the force in the segment at bond break.

Under these assumptions the characteristic energy E_0 for the specimen is given by

$$E_0 = \frac{1}{n}\sum_{i=1}^{i=n} K\varphi(\Theta_i, f_i)g(x_i) \qquad (3)$$

The force drop parameter F_0 may be interpreted similarly. In this instance, however, the function φ will be different.

It should be noted that bond breaks are most likely to occur when Θ is small; i.e., when the connected segments are oriented close to the direction of stretch. When Θ is large the longitudinal force along a fiber segment is small, and debonding would only occur if the bond was weaker than average. Thus the behavior of a test specimen might be approximated by that of a model consisting of springs arranged to form square meshes, and for which Θ is zero. For such a model the function φ used in the calculation of E_0 is approximated by $f_i^{1.5}$, and the function φ used in the calculation of F_0 is approximated by $f_i^{0.5}$.

A BOND STRENGTH PARAMETER THAT IS INSENSITIVE TO MESH SIZE

The most serious shortcoming of the E and F parameters is their dependence on the mesh sizes in the network that is being tested. There is a large variation of mesh sizes, so standard deviations of the values obtained for E_0 and F_0 from measurements on a given specimen will be large. It seems reasonable to assume, however, that for a given bond break the dependence on mesh size will be almost the same for the energy dissipated U, and for the force drop F_d. Thus the ratio U/F_d should be almost independent of mesh size. This suggests the possible use of a new parameter G, obtained by averaging values of U/F_d for a given specimen to obtain a value G_0, and in turn averaging the G_0s for a number of specimens to obtain G.

The quantity U/F_d is the energy dissipated by the network per unit force drop; i.e., the energy associated with a mesh of such size that a bond break would cause a unit force drop. From eq (2) it is seen that the quantity U/F_d is equal to F_{av}/M, and thus has the dimensions of length. The average of the quantities U/F_d obtained from a number of bond breaks, then, would give a characteristic elongation; i.e., a length characteristic of the elongation that must be given a network in order to produce a bond break.

The quantity F_{av}/M is depicted graphically in figure 9, where the force-elongation curve for a network is shown schematically. Here BC is the force drop F_d, and CE is the average force F_{av}. The line AB is constructed tangent to the curve at B and thus has the slope M. The lind CF is constructed parallel to the line AB, and intersects the elongation axis at point F. The length FE thus represents the elongation F_{av}/M. This elongation is seen to be the amount the network must be extended to attain a force F_{av}, assuming the force-elongation curve to be linear with a slope M.

The parameter G may be considered as the average energy dissipated per unit force drop, or as a characteristic length related to the average elongation required to produce a bond break. As the parameter G is assumed to be insensitive to mesh size of the network for which the bond strength is being characterized, it should be especially useful in evaluating the relative bond strengths in networks having different areal densities. Thus bond strengths between fibers of different materials or fibers of different morphology could be compared. This parameter, however, has not yet been tested experimentally, so its usefulness has not been ascertained.

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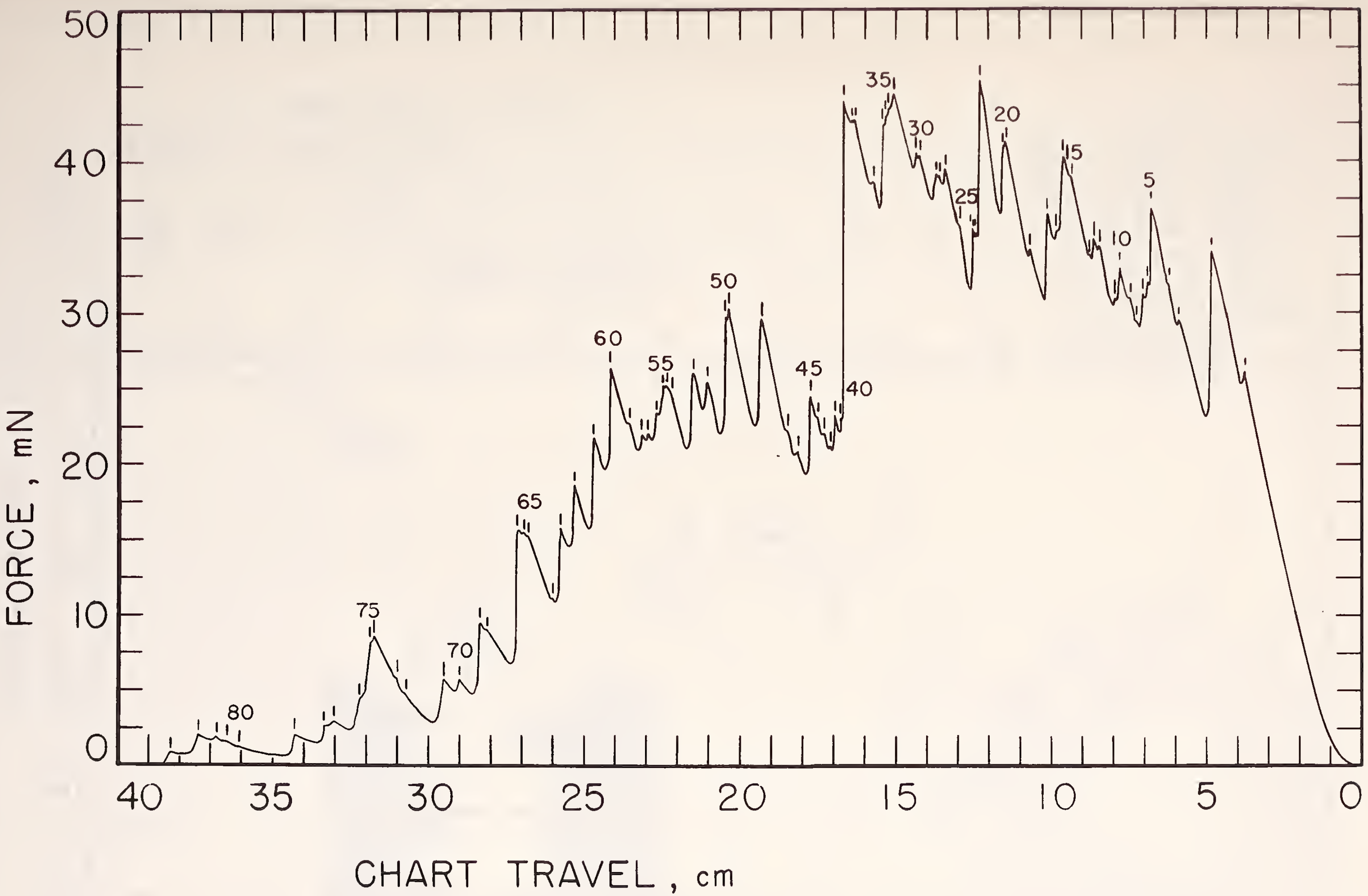


Figure 1. Force-elongation curve for a well bonded web of pulp fibers, 2.5 g/m^2 mass per unit area.

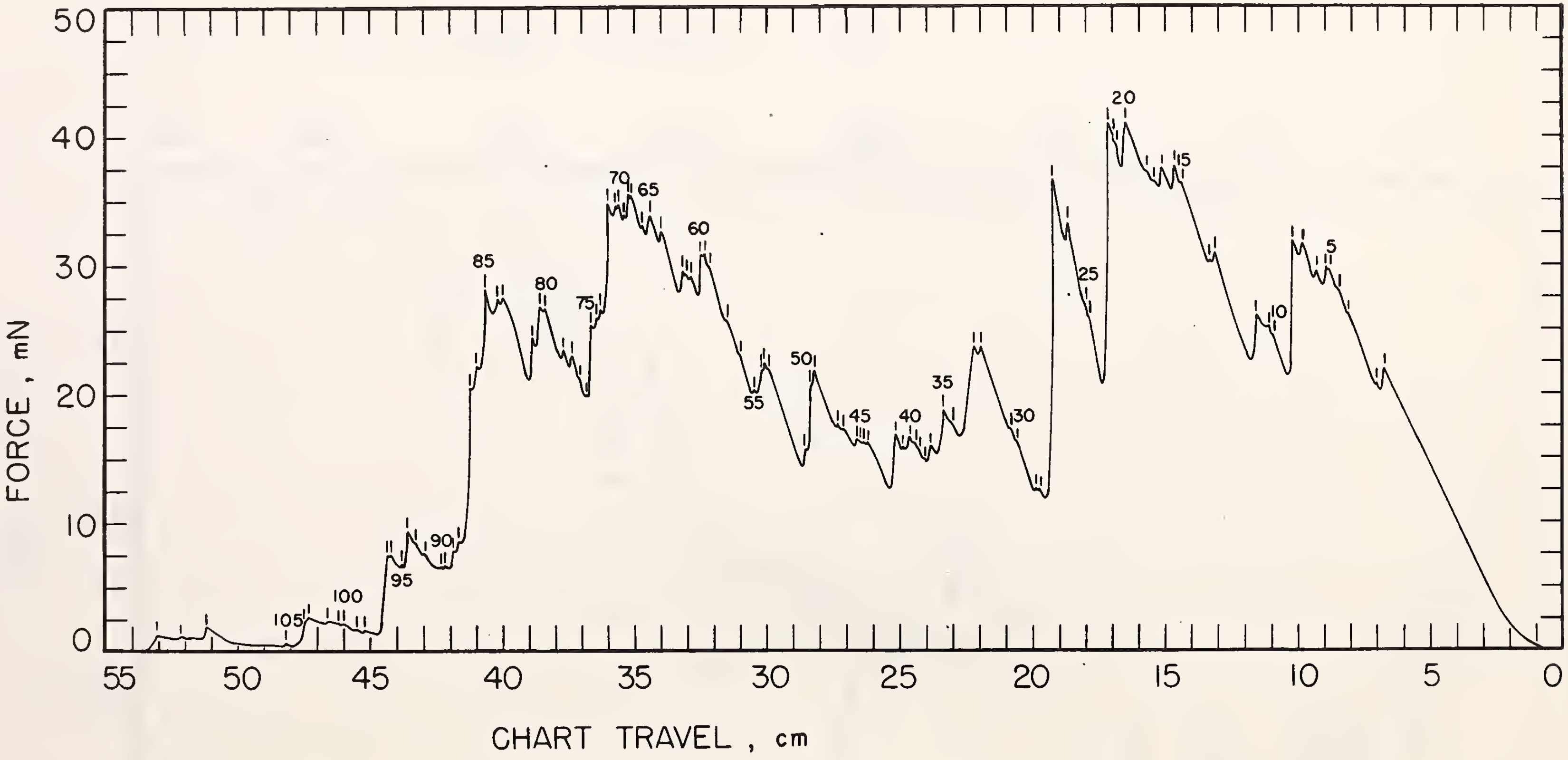
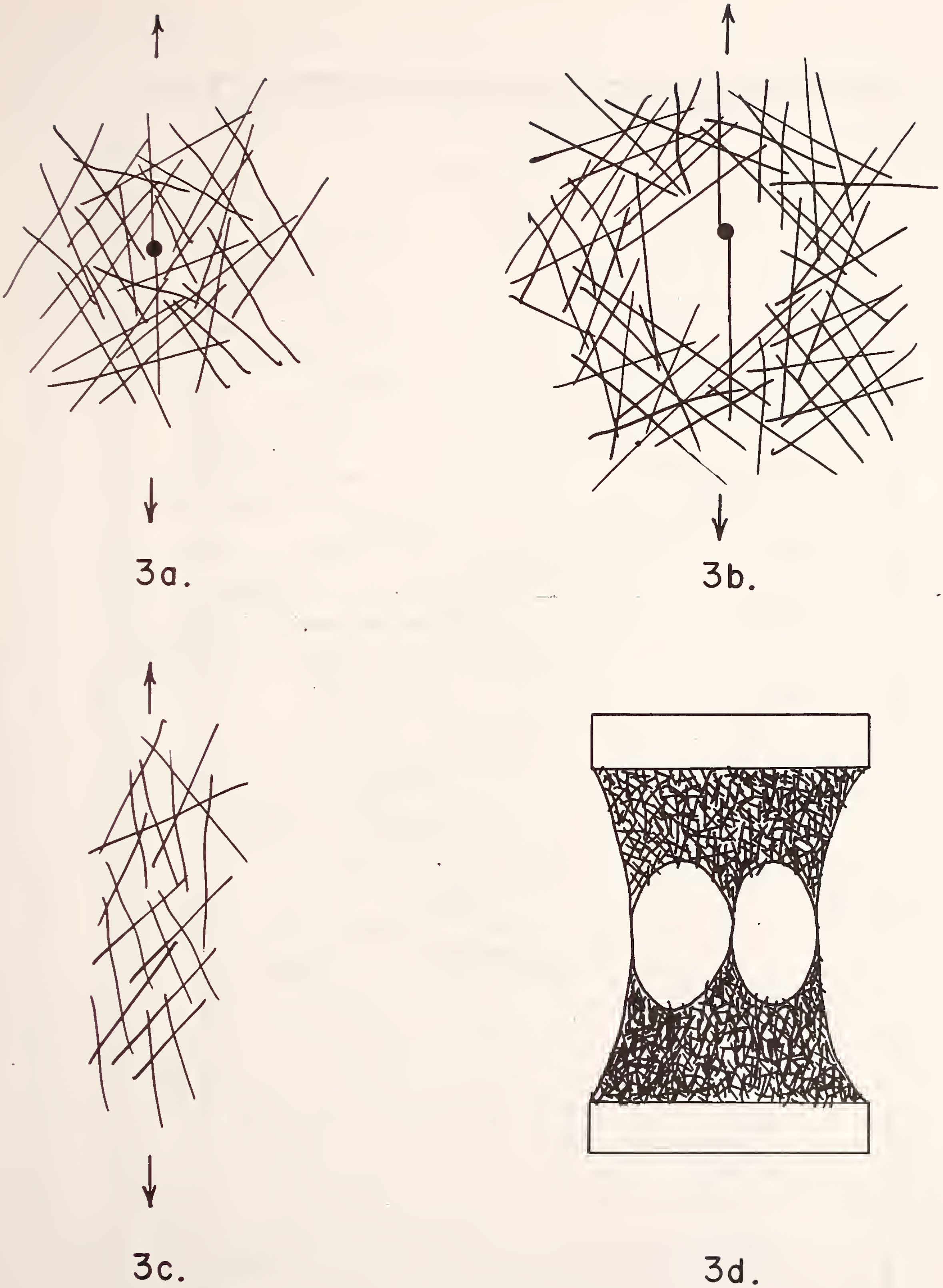


Figure 2. Force-elongation curve obtained by a repeat of the test used for figure 1.



3a. 3b. 3c. 3d.

Figure 3. Possible situations encountered in a tensile test of a fibrous network.

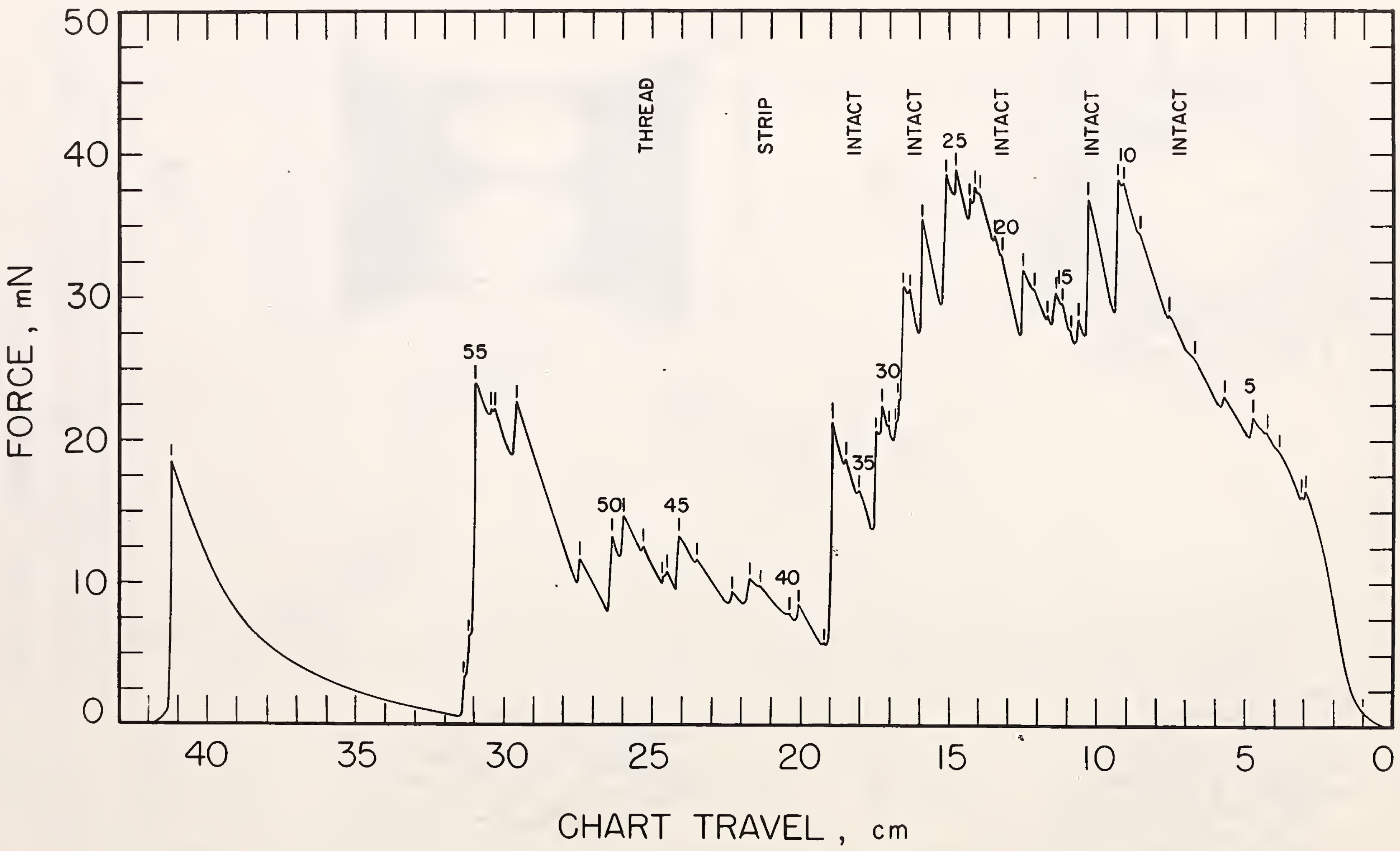


Figure 4. Force-elongation curve obtained on a narrower specimen of the same material used for figure 1.

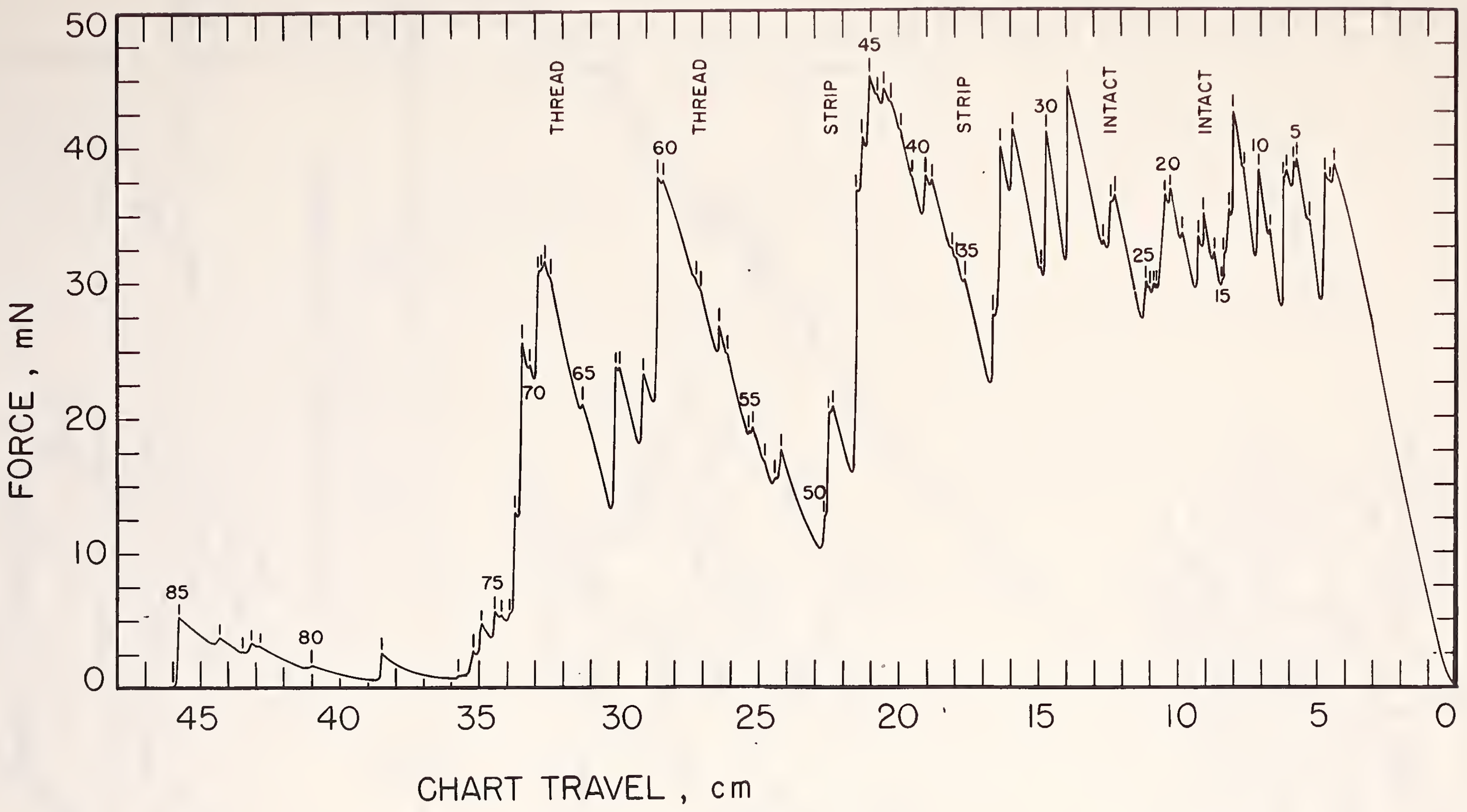


Figure 5. Force-elongation curve obtained by a repeat of the test used for figure 4.

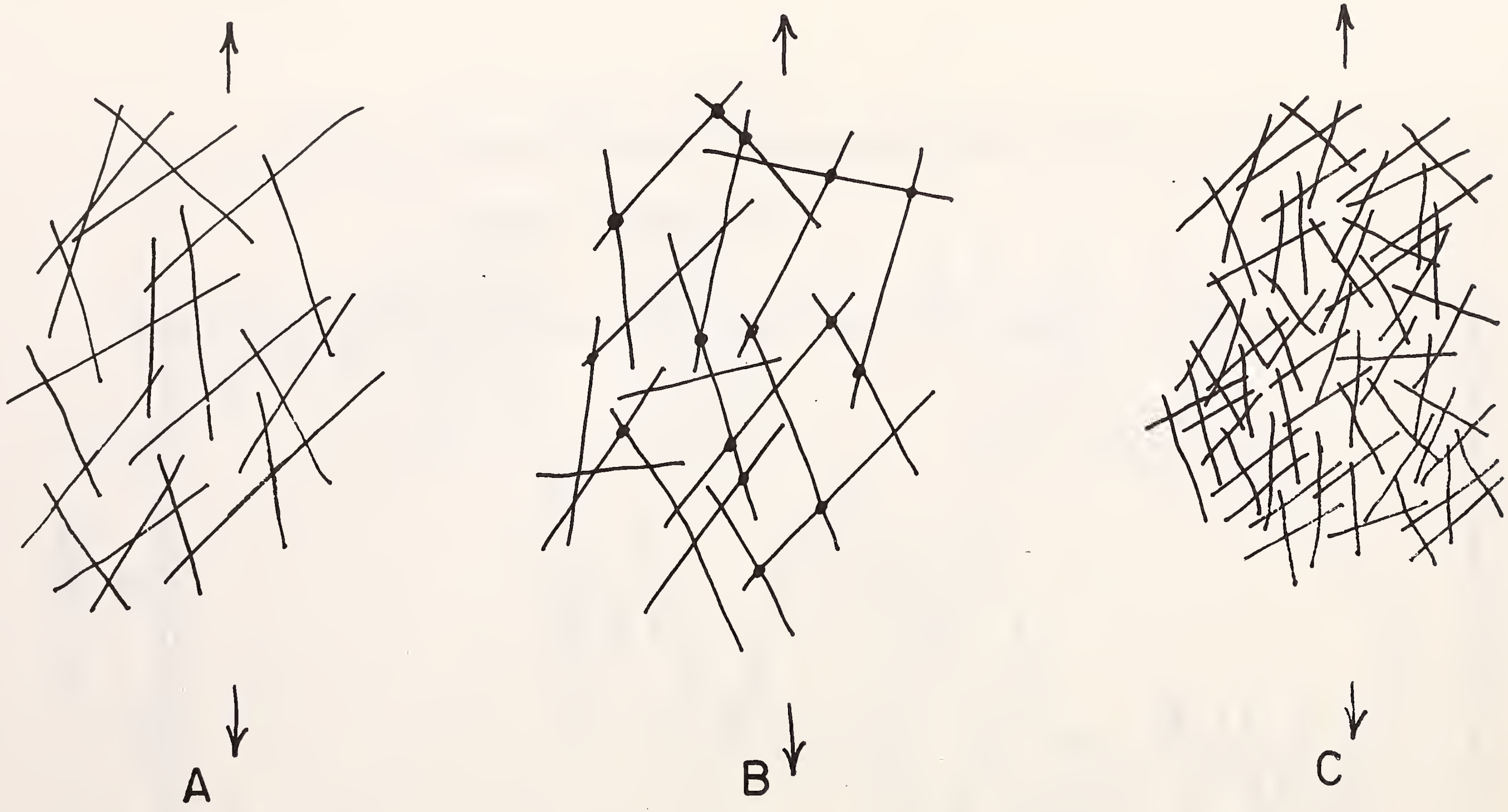


Figure 6. Webs of different tightness of structure.
Web A has uniform well bonded meshes. Meshes of web B are of same size as those in web A, but are bonded only at points indicated by dots. Thus web B has a looser structure than web A. Web C has a large number of well bonded meshes, and a tighter structure than web A.

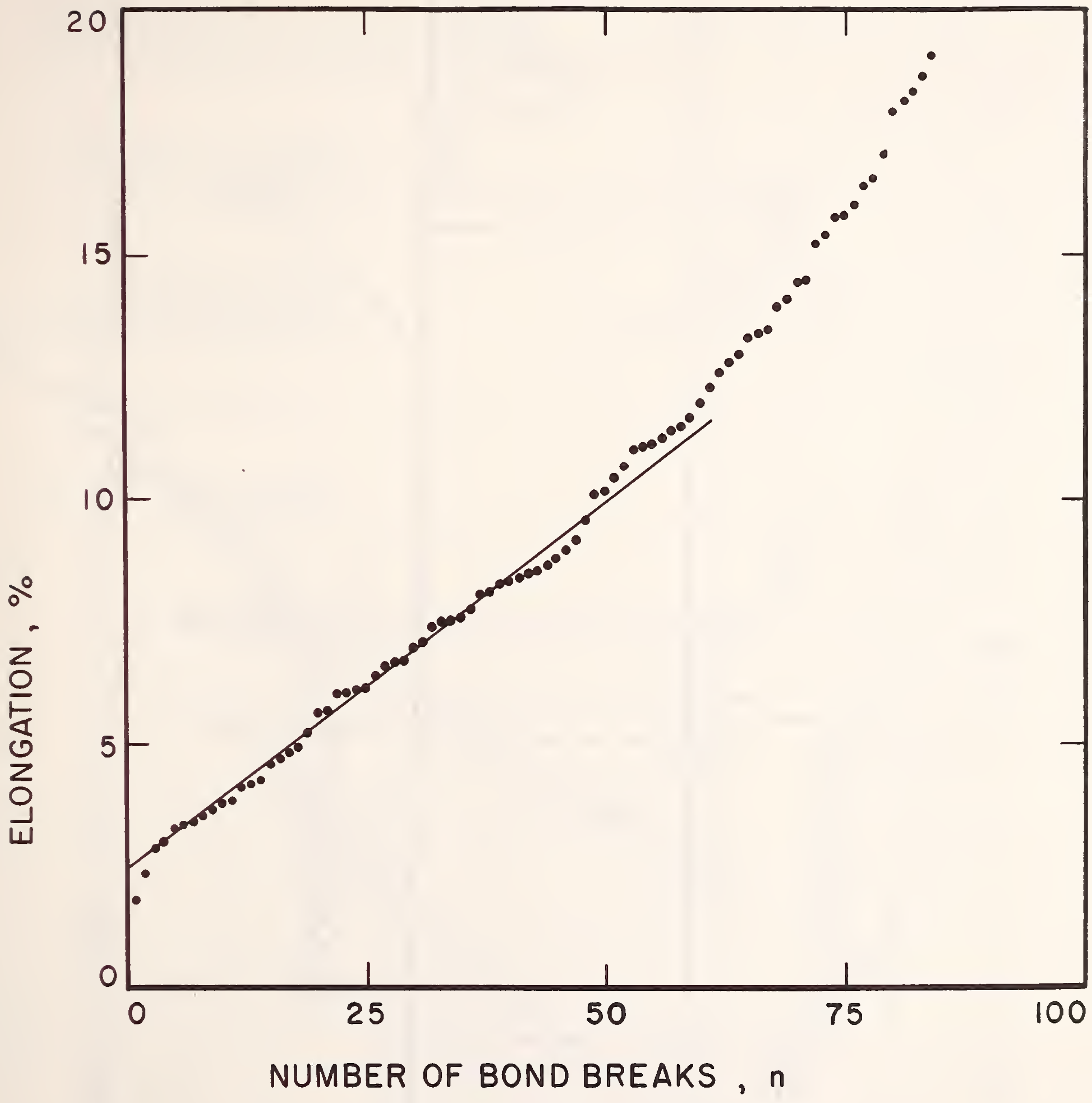


Figure 7. Plot of percent elongation versus number of bond breaks from force-elongation data, figure 1. Initial slope of 0.149 % per break, indicated by straight line, was obtained by a least squares fit of elongation values between breaks 5 and 50.

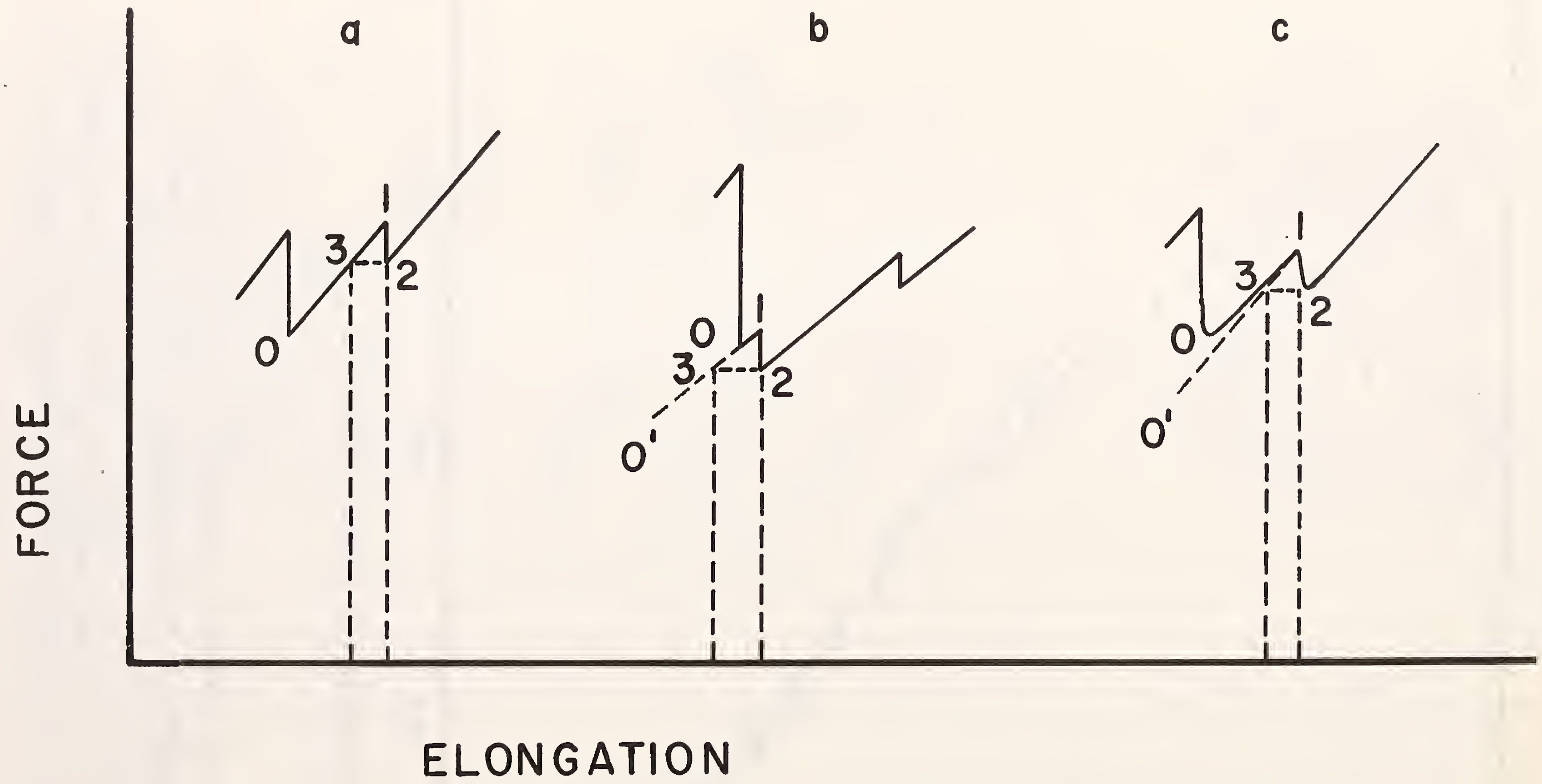


Figure 8. Types of breaks encountered in calculation of energy dissipation.

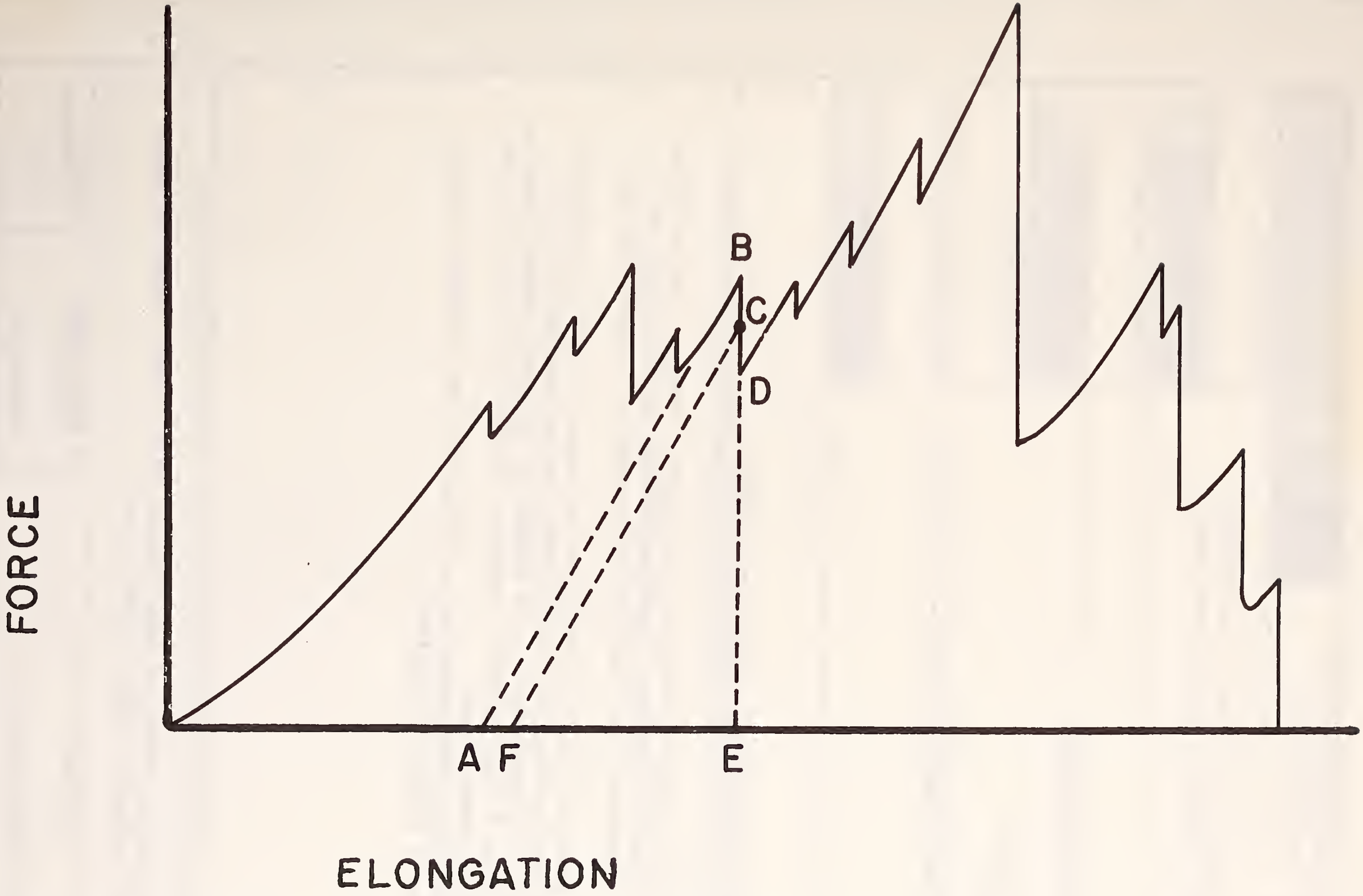


Figure 9. Graphical representation of the quantity F_{av}/M. A bond break at force BE causes force drop BD. Line CE represents force F_{av}, and M is slope of line AB. Line CF of slope M cuts axis at F. Thus F_{av}/M equals elongation FE, and is indicative of the stretch needed for a break.

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBSIR 79-1722

[illegible] No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Characterizing the Interfiber Bonding of Paper Pulps: Rationale for Bonding Parameters Derived From Tensile Test Data

5. Publication Date

6. Performing Organization Code

7. AUTHOR(S)
Jack C. Smith

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

If low density open webs of paper pulp are tested in tension, the resulting force-elongation curves have numerous force drops caused by the breakage of interfiber bonds. Parameters characterizing the bonding are derived from these data.

The relative number of bonds per unit area is characterized by the average elongation between bond breaks. The bond strength can be characterized by an average of the force drop magnitudes, by an average of the energy losses resulting from bond breaks, or by a characteristic elongation indicative of the stretch in the network needed to cause a break.

Methods of obtaining these parameters are given, and the rationale involved in their derivation is carefully explained.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Adhesion of paper fibers; bonding of paper fibers; paper; paper fibers; bonding; paper pulps, characterization; paper, tensile tests.

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21. NO. OF PRINTED PAGES
35

22. Price
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