

## **Hair breakage during combing. II. Impact loading and hair breakage**

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### **Synopsis**

During combing of hair, short fiber fragmentation (less than 2.5 cm) and longer segment breaks occur by different pathways. Longer fiber breaks most likely occur principally by impact loading. Impact loading causes hair breakage at lower loads than tensile loading, with essentially no increase in strain versus normal tensile testing, which produces large strain increases. Strain rates in impact loading are more similar to combing rates than rates of extension in tensile loading, and the looped and crossed hair formations in snags fit impact-load breakage better than simple extension of straight/non-crossed hairs in tensile testing. Extension or impacting hair fibers with flaws or damaged hair sections such as damaged wrapped ends produces short fiber fragmentation, while longer segment breaks may be produced in fibers with natural flaws such as fiber twists, cracks, or badly abraded or chemically weakened hair or even knots.

### **INTRODUCTION**

The objective of this work was to provide a better understanding of how human hair fibers break during combing or brushing, with the hope of ultimately leading to approaches for assessing the strength of hair fibers under conditions that are relevant to actual hair breakage. In the first paper in this series (1), hair snags were examined to determine the important hair-on-hair versus hair-on-comb arrangements and interactions that might be involved in breakage. In addition, the inadequacies of tensile testing for explaining hair breakage on live heads were presented, and one impact-loading experiment was reported, suggesting that impact loading may be more relevant to breakage than simple tensile loading, a conclusion consistent with the observation by Brown and Swift about 30 years ago (2) that hair breakage on the head “is more complex than simple tensile fracture of single hairs.” The focus of this paper is to explore additional variables via impact-loading experiments with hair fibers and to examine the ends of hairs broken by combing and impact loading to try to determine those conditions most relevant to breakage during the combing of hair.

### **EXPERIMENTAL**

The hair used in all of these experiments was purchased as 12-inch dark-brown virgin

hair from Caucasians, reported to be undamaged, and purchased from DeMeo Brothers of New York City. This hair actually measured 14 inches. In some experiments, small tresses of highly coiled steam-set hair (12-inch hair), purchased from DeMeo Brothers, was also used. All experiments were conducted at  $41 \pm 2\%$  RH and room temperature.

#### MAKING WEIGHTED HAIR FIBER LOOPS

Hair fiber circles/loops (about 6.4 cm in diameter) were made from the 14-inch hair using tape (Scotch® brand mending tape) to bind long sections of the ends together (folding the hair back on itself over separate pieces of tape (using  $4 \times 4$ -cm-long sections of tape) to hold the fiber securely). A weight (10–50-gm load) was attached to the tape holding the fiber ends together, through a 15-cm-long wire (single-strand plastic #16 coated copper wire) forming a wire circle at one end to bind the fiber to the tape and a hook at the other end to attach the weight.

#### IMPACTING HAIR LOOP OVER STRAIGHT HAIR SECTION

A straight horizontal hair was threaded through one of the fiber loops (described above) and the loop was weighted with a 20-gram load (total wt 21 g). The horizontal hair was held firmly and taped and clamped to the jaws of one vise and draped over the bottom jaw of a second vise (vise jaws 4.5 cm apart) and pulled taut with a 10-gram weight attached to the free end of the fiber. Then the part of the fiber on the vise jaw was taped to the bottom hard rubber jaw of the second vise to minimize slippage. The weighted loop was then dropped at a 15-cm height onto the horizontal hair fiber.

#### IMPACTING HAIR LOOP OVER COMB TOOTH

Hair fiber loops (6.4 cm in diameter) were made as described above. Each loop was placed over a comb tooth and a 50-gram or a 30-gram weight was connected to the wire, providing a total weight of 51 to 31 grams. The weight was raised up to the comb in the vise and dropped near the back of the comb tooth (15 cm) (Figure 1). The comb teeth used were of two types cut from a Blue Goody comb, with the measurements described below. The comb tooth measurements were made with a spindle-type caliper micrometer from General Tools Mfg. Inc.:

Thick tooth: Tooth thickness 0.070 inches, tapering to 0.056 inches (tooth to about midpoint of micrometer spindle or approximately 1778 to 1422 microns)

Fine tooth: Tooth thickness 0.049 inches, tapering to 0.037 inches (tooth to midpoint of micrometer spindle or approximately 1245 microns to 940 microns)

#### ATTACHED-LOOP EXPERIMENTS

A 14-inch hair fiber with tape on each end was hung over two adjacent thick teeth of a comb, held in a vise. Twenty-gram weights were attached to each end of that hair via clamps. One end of another 14-inch hair fiber was held firmly by taping it to a marked position on the table top alongside the vise, and the free end was fed between the two comb teeth and over the taut hair (Figure 2). A weight (10 to 30 grams) was attached

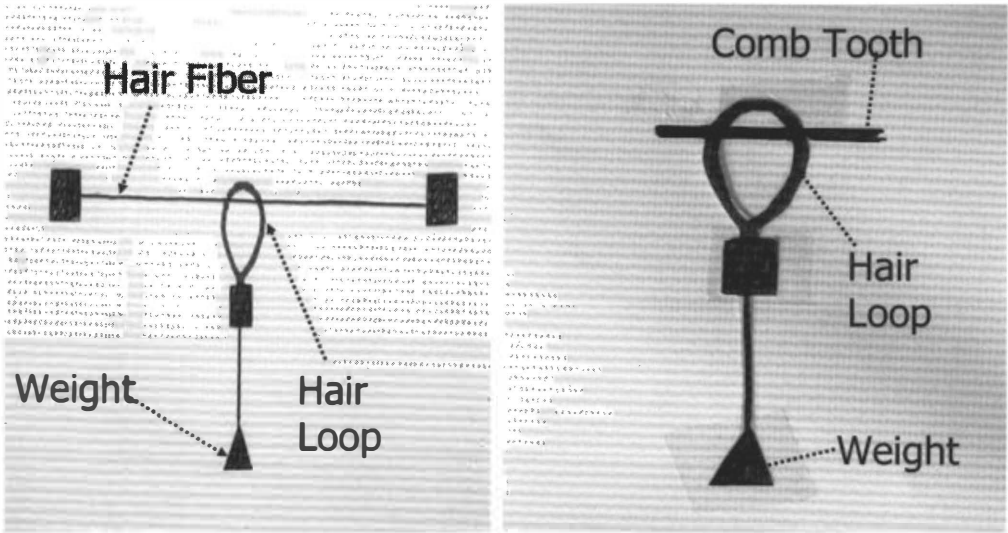


Figure 1. Schematic illustrating a hair loop impacting over a straight hair versus a hair over a comb tooth.

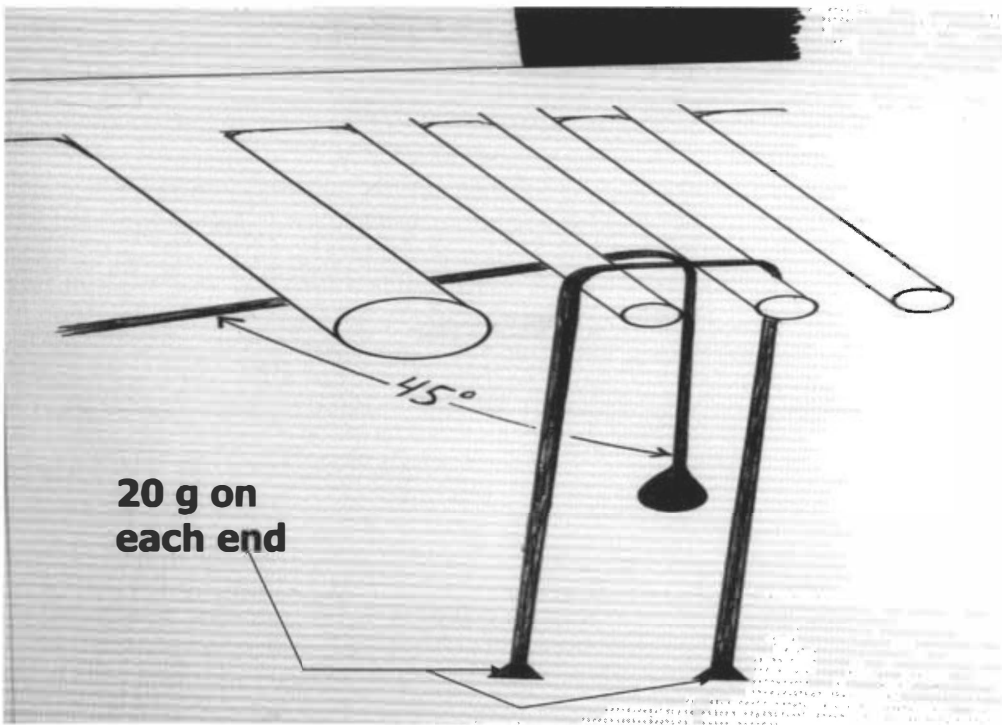


Figure 2. Schematic for attached-loop breakage.

to the free end of this fiber, and it was raised either 8 or 15 cm and dropped so that the top hair impacted on the taut hair and the number of impacts required to break either of the hairs was noted. The broken hairs were saved for microscopic examination of the broken ends.

## EQUALIZED-LOOP EXPERIMENTS

Single hair loops were formed from a 14-inch hair fiber with the ends taped together 5 cm apart, forming an arch. The hair was folded back onto itself at each end and bound by tape to prevent slippage, using several 4 × 4-cm-long sections of tape to hold the fiber securely. These hair loops were taped to the 15-cm single-strand plastic-coated copper wire at the center of the tape, and the wire was formed into a hook at the free end to attach weights ranging from 10 to 50 grams (total weight 11 to 51 grams). These hair loops were individually impacted over a comb tooth or another hair similar to the attached loop setup (Figure 3).

## MICROSCOPE EXPERIMENTS

Broken segments of hair fibers from all of the above experiments were collected and either put into small bottles (shorter fragments), which were labeled, or the longer segments were collected and the fibers labeled. The ends of the hairs were placed on a microscope slide with a cover slip and one to two drops of Cargille Immersion oil, Type A, were allowed to flow under the cover slip to cover the hair prior to examination under a Trinocular Phase Accu-Scope fitted with a Nikon D-100 digital camera.

## RESULTS AND DISCUSSION

In Part I of this series (1) and from the prior literature (2–5) and this paper, the following mechanisms or pathways for hair breakage were hypothesized:

1. Impacting or compressing and extending one hair fiber against another taut hair. This condition may involve any angle of wrap from a simple perpendicular crossover to a hair fiber completely looped around another (2).
2. Impacting or compressing, extending, and abrading a hair fiber against a taut hair; this may be pictured as pathway 1 with abrasion.
3. Extending and compressing or impacting hairs with flaws or cracks and/or chemically weakened hair. If a hair is sufficiently weakened, extension alone may cause breakage. Short-fiber fragmentation of wrapped hair ends is likely the most common subset of this type of breakage, with hairs that contain knots a less common subset (6).

## IMPACT-LOADING EXPERIMENTS

Most of the impact-loading experiments reported in this paper were of two types and are described as attached loop or equalized loop in the Experimental section. In the attached-loop experiments, one end of a hair fiber is held firmly and the free end is impacted over a straight section of another hair fiber that is held either between two vises or strung taut over comb teeth (Figure 2). The top hair fiber has a weight attached to its free end, and the weight is raised and dropped so that the top hair impacts on the taut hair (bottom hair) and the number of impacts required to break at a fixed load are noted. In a slightly different version of this experiment, called the equalized-loop experiment, a single hair loop or arch with weights attached is impacted over a comb tooth or another hair similar to the attached loop setup (see Figure 3 and the Experimental section for details).

The first paper in this series (1) showed that hair fibers break more easily by impact

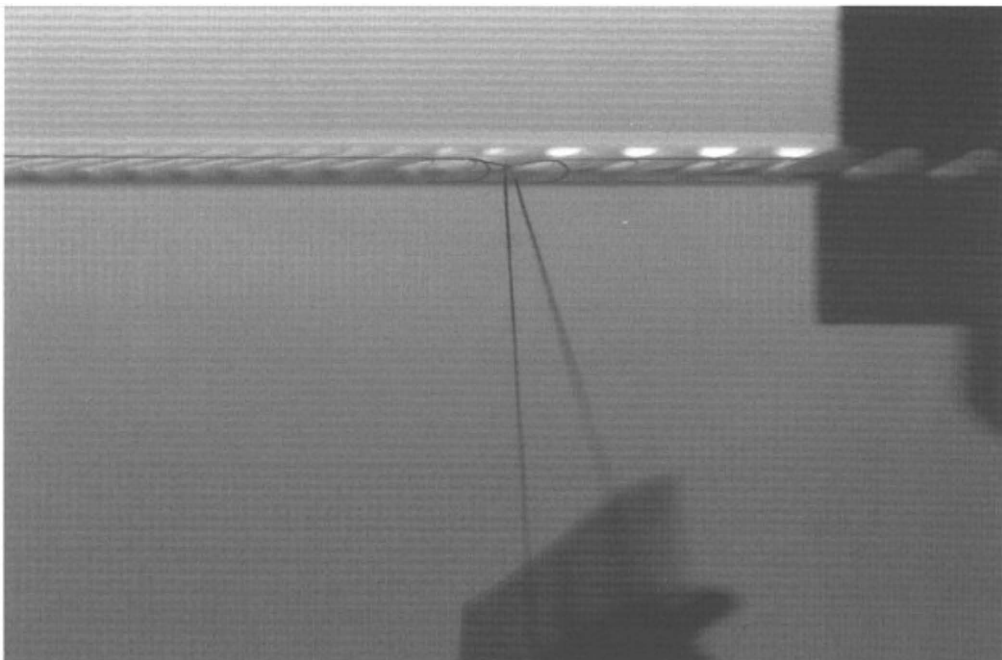


Figure 3. Equalized-loop breakage with equal stress on both legs of the hair loop.

loading one hair over another hair versus over a comb tooth. Therefore, a second more detailed experiment was conducted to measure changes in strain from impact loading hair fibers in addition to breakage over a hair versus a comb tooth. The results of this experiment (Table I) using a 33-gram load confirm that hair fibers break more easily by impact loading over another hair fiber (nine impacts and 11 broken hairs over another hair versus 109 impacts and nine broken hairs over a comb tooth). Furthermore, there is no increase in length (or strain) when the fibers break by impact loading over other hair fibers. The hairs impacted over the comb tooth generally did not break on the first impact, but they did increase in length with each impact, averaging a little more than 12 percent total increase in length (data summarized in Table I). The fact that hairs break more easily when impacted over hairs than over a comb tooth shows that the force per unit area that is impacted is critical to hair breakage, and therefore impacting hair fibers over another hair that averages about 70 microns in diameter will cause breakage

Table I  
Breakage of Hair Over Hair Versus Over a Comb Tooth and % Strain

Hair impacts a hair	Hair impacts a comb tooth
9 Impacts, 11 broken hairs	109 Impacts, 9 broken hairs
Length change -0.64%	Length change +12.4%
—No length change	—Large length change
	—Length $\Delta$ is significant by Mann-Whitney U-test

Initially all hairs 200 mm long  $\pm$  20 mm.  
Using a 33-gram load and 3–4-cm drop at 40% RH.  
Comb tooth tapered from 940 to 1245 microns thickness.

more readily than impacting a hair fiber over a comb tooth that is about ten times as thick.

In another attached-loop experiment (see Table II), 11 of the top impacting hairs broke on 16 impacts while seven of the bottom hairs broke, all on the first impact. There is no significant difference in breakage by top versus bottom hair using the chi square statistical test procedure. The diameters of the hair fibers used in this experiment were measured, and a significant diameter effect was found by chi square, showing that the smaller-diameter hairs break more readily whether on the top or the bottom of the impact. Twelve finer-diameter hairs broke, and two thicker hairs, and four broke simultaneously by impact loading under these conditions. In this experiment, the top hair was in the form of a loop, but the bottom hair was essentially straight, suggesting that severe bending is not necessary for breakage to occur because loops do not appear to break more easily than straight sections of hair. This effect will be examined in more detail in another experiment.

#### FRAGMENTATION PATTERNS OF HAIRS FROM COMBING AND IMPACT LOADING

The broken hairs from all of these experiments were collected, labeled, and held for microscopic examination of the ends. Hair fiber fragments from the combing experiment described in the first paper of this series (1), which had been separated by fragment length, were also examined under the light microscope. The ends of the 6.35–12.7-cm fragments and the fragments less than 1.27 cm in length from the combing experiment, and the broken hairs from attached-loop and equalized-loop experiments, were examined and classified according to smooth fractures, step fractures, fibrillated ends, and splits as described by Kamath, Hornby, and Weigmann (3,4). The results are summarized in Table III.

The ends of the longer hair fragments from the combing experiment showed more fibrillation and splits than the ends produced by the attached-loop impact-loading experiments. Therefore, additional impact-loading experiments were run, where the ends of the hairs were both bound or equal (equalized loop), and the effects of abrasion immediately before impacting on the fragmented ends were also examined. Rubbing over the spot (to be impacted) prior to impact produced more fibrillation and splitting similar to the ends produced from the combing experiments.

In addition, the equalized-loop type of breakage provided fragmentation percentages

**Table II**  
Effect of Fiber Diameter on Impact Loading and Top-Versus-Bottom Hair Breakage  
(attached-loop setup)

Top hair (loop)	Bottom hair (straight)
11 Breaks of 16 impacts	7 Breaks of 16 impacts

16 Impacts and 18 broken hairs (above).

No significant top-vs-bottom effect by chi square.

Diameters measured and 12 thinner-vs-thicker broke, 2 thicker broke, and 2 broke simultaneously (significant diameter effect by chi square).

33-gram load, 3–4-cm drop, 40% RH, fibers 200 ± 20 mm.

**Table III**  
 Classification of Broken or Fragmented Ends From Combing versus Impact-Loading Experiments

Size	Combing (N=35)	Attached loops (N=22)*	Equalized loops (N=20)*
6.35 to 12.7 cm	Steps 56% Splits 14% Fibrous end 14% Smooth 16%	Steps 82% Splits 9% Fibrous end 9% —	Steps 60% Splits 10% Fibrous end 20% Smooth 10%
<1.27 cm	Very fibrous with splits		

\* Rubbing prior to impact produced mainly fibrillation and splitting with very fibrous fragments.

more similar to those of the larger fragments from combing. However, once again there was not as much splitting or fibrillation, and the step fractures were shorter, leading to the conclusion that the fragmented ends are probably a combination of these two types of breakage, with some abrasion prior to and even after impact producing more fibrillation, splitting, and fibrous fragments.

The smallest fragments from combing (those less than 1.27-cm length) were even more fibrous and fibrillated and they contained larger segments of exposed cortex than the longer fragments (Figure 4). In fact, some of the shorter fragments were largely exposed cortex. These differences in fragmentation collectively suggested that the mechanism for breakage for the shortest fragments might be different than for the longer fragments. Therefore, the short fragment formation was re-examined, starting with another combing experiment.

FRAGMENTATION BY COMBING

In this experiment, tresses from 14-inch Caucasian hair were combed in 25 comb stroke increments up to 100 comb strokes, and the broken fragments were collected on a large

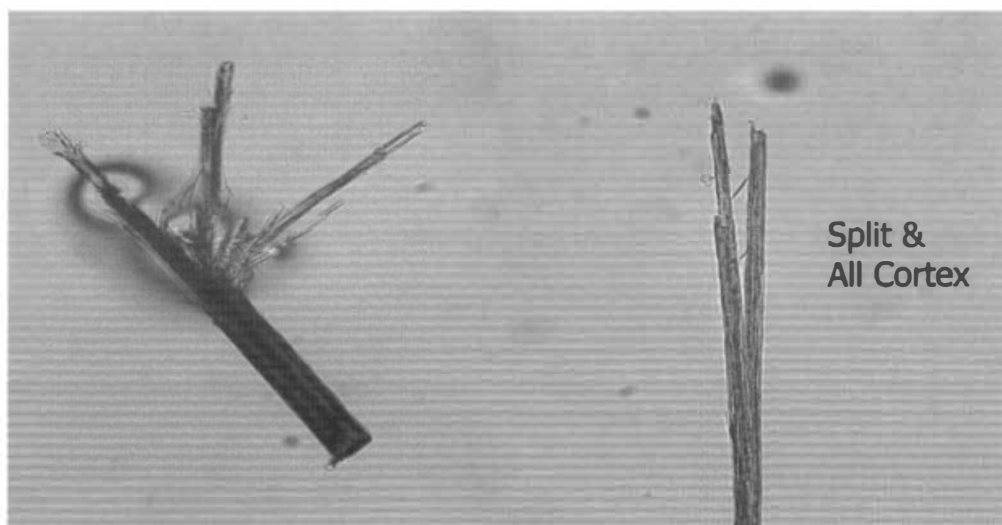


Figure 4. Light micrographs of the shortest fragments from combing tresses.

piece of white plastic after each series of 25 comb strokes and separated by length into five different fragment sizes. The results of this experiment are summarized in Table IV.

A two-way analysis of variance shows significant differences in breakage by hair fragment length and by comb strokes. This experiment shows more fragments at the shortest two lengths, especially at the shortest length of 1.27 cm. It also shows that the number of shorter fragments increases with an increasing number of comb strokes. For example, the number of the smallest fragments at 75 and 100 comb strokes is significantly larger than at 25 and 50 comb strokes. This effect is most likely attributed to the fact that the ends are becoming abraded, stressed, and damaged with increasing comb strokes. Therefore, breakage of the shorter lengths is likely associated with increasing physical damage to the ends.

As a result of these hair fragmentation effects, snag formation at the ends of the hair was reexamined through close-up photographs of hair tresses in snags at the very ends, in which the hair had been crosscut at the ends to promote snagging. Crosscutting the tress is a technique used in the past to generate split-end formation by providing more hair ends of the same length and therefore a higher end peak force or peak combing load.

Figure 5 shows the snagging effect at the ends of a tress that was combed with a white plastic fork. The white fork was used for photographic reasons. It shows that the ends of the hair fibers wrap around the teeth of the fork at varying angles, forming crossed hairs and snags. This same effect is produced by combing the same tress with a normal comb, also showing multiple ends of the hair fibers wrapped around the comb teeth (Figure 6), providing a higher end peak force and a situation where damaged hair fiber ends can be gripped tightly and abraded, compressed, and extended to break. When hair fibers wrap around a comb tooth, the ends reverse their orientation on the opposite side of the comb tooth, providing an interlocking scale effect with hair fibers that are in a normal orientation and adjacent to the wrapped hairs. This effect enhances abrasion and snagging (Figure 7). It also increases fragmentation of the ends.

#### MECHANISMS FOR SHORT-VERSUS-LONG-FRAGMENT BREAKAGE

The results of these experiments suggest the possibility of a different mechanism for long-fragment (6.4 cm or longer) breakage versus very short (~2.5 cm or less) fragment breakage. For short-fragment breakage, the hair ends wrap around comb teeth and other

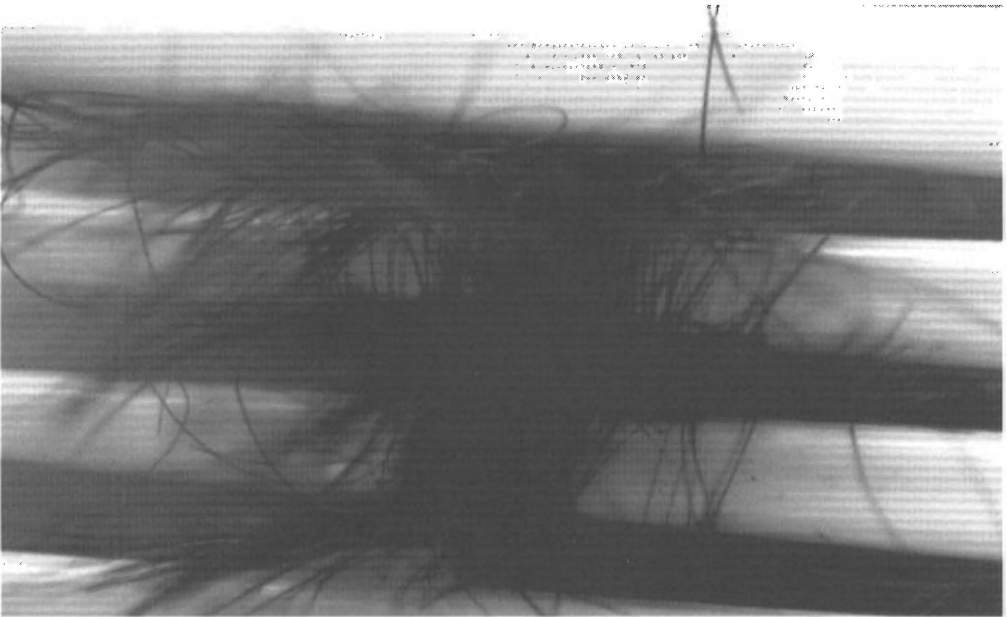
**Table IV**  
Combing Experiment and Short Fragments Versus Number of Comb Strokes

No of Strokes	Comb strokes versus broken fragment length from 4 tresses				
	<1.27 cm	1.27–6.4 cm	6.4–12.7 cm	12.7–17.8 cm	>17.8 cm
25	99	56	13	4	1
50	149	44	12	4	1
75	226	94	21	3	1
100	194	74	13	4	1

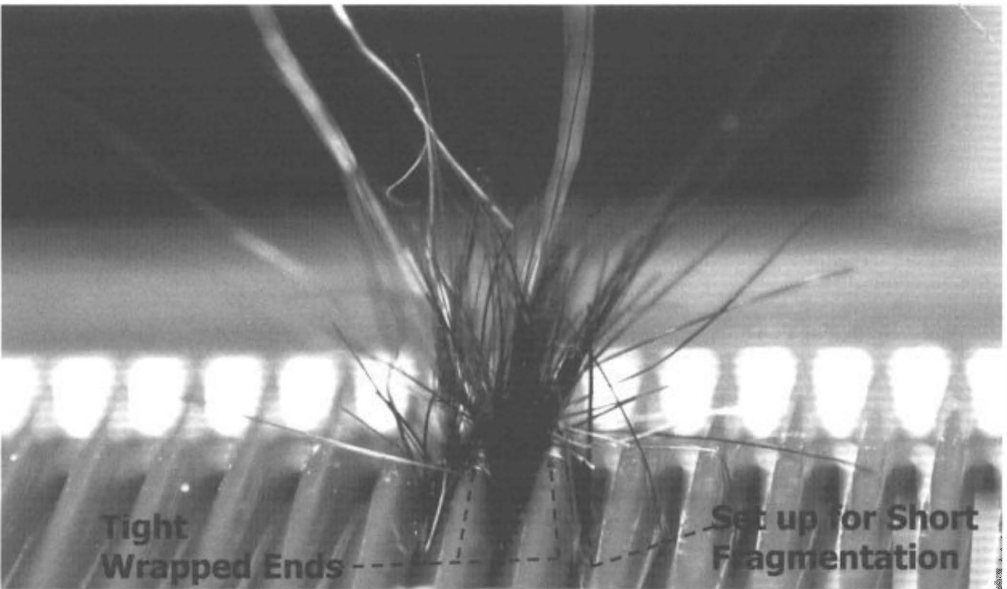
2-Way ANOVA: Significant differences in breakage by length and by comb strokes.

1.27-cm Lengths different from all others as is 1.27–6.4 cm.

The two longer lengths: No significant difference.



**Figure 5.** Snag of slightly wavy Caucasian hair on a white plastic fork showing wrapped hair ends. Note hair ends wrapped around teeth and crossed over other hairs.



**Figure 6.** Slightly wavy to straight Caucasian hair in a snag. Note hair ends wrapped around comb teeth and crossed over other hairs.

hairs, causing damage to the fiber ends by abrasion as these hair ends grip the comb and other hairs. Combing or pulling on the snag induces extension and compression on the damaged weakened site and, if weakened sufficiently, produces short-fragment breakage.

The longer fragments (longer than 6.4 cm or longer) most likely break by impact

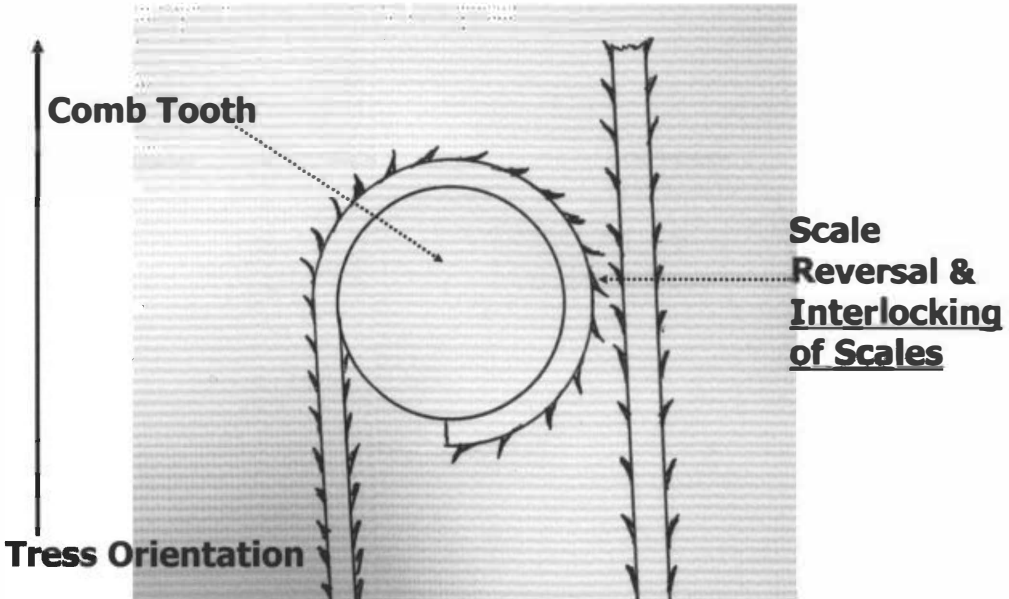


Figure 7. Wrapping of hair ends around comb teeth reverses the scales.

loading of one hair fiber against another hair in a snag, as described previously. On impact loading a hair fiber loop over another hair, severe bending of the fiber loop on impact (sometimes with abrasion) initiates crack formation in the highly bent and extended surface layers. If the crack extends deep enough into the hair, catastrophic failure results, i.e., complete breakage occurs in one of several ways, producing a smooth fracture, a step fracture, or a split or fibrillated end. The mechanisms for the different types of fractures have been described very well and in detail in the paper on fractography of hair fibers by Kamath and Weigmann (3). In this paper on fractography, the primary route for crack initiation involves bending and thus extension in the outer layers of the surface, and it is likely that this is the most common type of crack initiation.

However, there is evidence that some hairs may initiate fracturing by impact loading primarily involving compression rather than extension, e.g., straight sections of hair fibers rather than loops appear also to break readily on impact loading, as in the one case described above where the top and bottom hairs of the attached-loop experiment broke equally and where the bottom hair is a straight section of a hair and not a loop.

Therefore, another experiment was conducted where a straight section of a hair fiber in a special holder was impacted onto another straight section of another hair held in a vise (Figure 8), providing the results summarized in Table V. These results confirm that straight sections of hair fibers can break on impact loading.

It may be argued that some bending occurs in this experimental setup, but not nearly as much bending as by impacting hair loops. Furthermore, eight bottom hairs and 16 top hairs broke. It can be argued that crack initiation still occurs on the side opposite to the impact site where bending and extension will occur, but the simple fact that breakage occurs almost as readily for straight sections of hairs as for severely bent hair loops suggests that another mechanism for breakage may be involved. These details

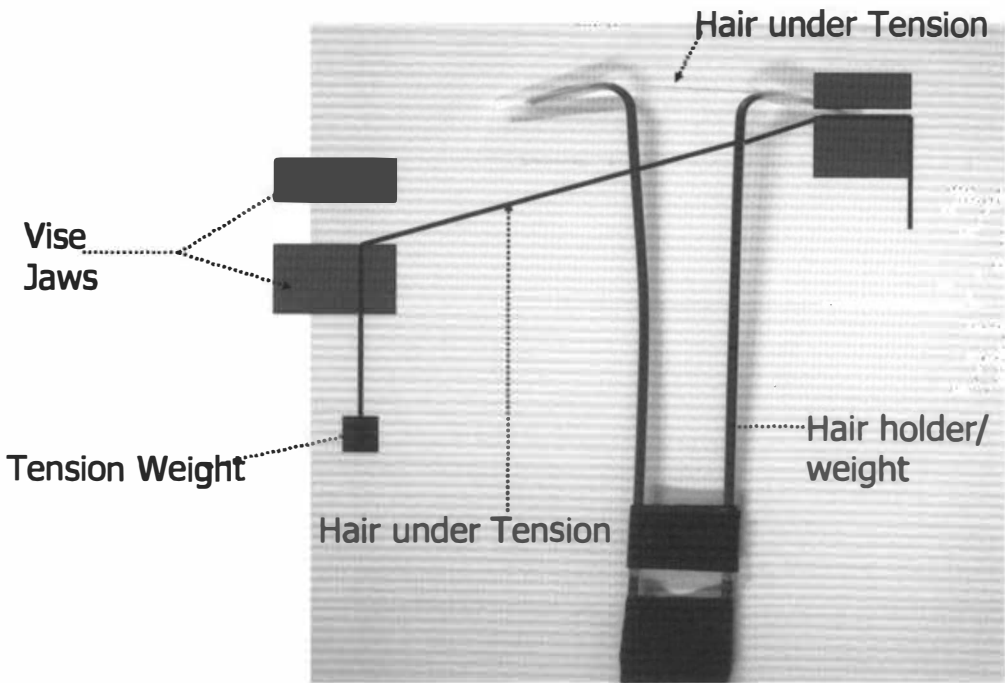


Figure 8. A schematic illustrating a straight section of a hair fiber impacting over a straight section of another hair.

Table V  
Impact Loading Straight Hair onto Straight Hair

26 Impacts and 27 breaks (2 hairs broke on 1 impact).
8 Bottom hairs broke (10-gram taut load).
19 Falling (top) hairs broke (30-gm taut load).
Experiment at 41% RH, 72 degrees F, using an 11-gram impacting load and a 7–8-cm drop.

suggest that impact stresses involving compression can initiate cracking and delamination, and if the crack is sufficiently deep, i.e., through the center of the hair, extension forces will result as the top hair continues to “move” through the bottom hair and ultimately catastrophic failure will result. This type of crack initiation involving impact stresses with compression and delamination is analogous to the impact fracturing of composite structures described by Fleming (7) and by Qiu *et al.* (8) and should produce multiple step fractures, fibrillation, and splits, as are observed in hairs broken by combing and impact loading.

At the beginning of the Results and Discussion section of the first paper in this series, the following three pathways for breakage were described, and these were derived from the analysis of snags, the prior literature, and this current study:

1. One hair impacting on another taut hair fiber in a snag at almost any angle of wrap analogous to the attached-loop or equalized-loop impact-loading setups.
2. Abrading and impacting of one hair fiber on another taut hair fiber in a snag, producing a variety of breaks with more abrasion and fibrillation and splits resulting from the abrasion to the weakened impact site.

3. Extension or impacting hair fibers (a) with flaws or damaged hair sections, resulting in short-fiber fragmentation on damaged ends, (b) with natural flaws such as fiber twists (2) or cracks, or (c) in chemically weakened hair or even knots.

The first two pathways above apply to the breakage of longer fiber fragments and the third pathway pertains to short-fiber fragmentation and fragmentation of hairs that contain natural flaws, knots (see below), or have been badly damaged by other routes.

#### BREAKAGE BY KNOTS

Hair fibers were looped into a knot near the middle of 14-inch hairs and impact loaded with a 31- or 21-gram load using a 15-cm drop. All fibers broke on the first impact, compared to control hairs with no knots, which did not break on the first impact. The breakage of knots often occurred leaving one end of the break with a hook or curl near one of the broken ends, and this hook could be seen with the naked eye, but the fractured end usually contained a smooth fracture when observed microscopically. This result suggests that severe bending (under these conditions) as in a knot tends to promote smooth fractures.

The relevance of knots to hair breakage is described in a paper by Khumalo *et al.* (6) in which these scientists found only 0.15% of Caucasian and Asian hair with knots, but found 13% of African hair with knots, suggesting that knots are not important to the breakage of Asian or Caucasian hair, which is not highly curled or coiled. However, it is more relevant to African hair or highly coiled hair such as highly coiled permanent-waved hair.

#### CONCLUSIONS

During the combing of hair, short-fiber fragmentation (less than 2.5 cm) and longer segment breaks occur by different mechanisms. Longer fiber breaks generally occur by impact loading of one hair against another hair in a snag. Impact loading causes hair breakage at lower loads than normal tensile testing, with essentially no increase in strain versus tensile loading, which produces large strain increases. Strain rates in impact loading are more similar to combing rates than rates of extension in tensile loading, and the looped and crossed hair formations in snags fit impact-load breakage better than simple extension of straight/non-crossed hairs in tensile testing. Therefore, the conclusion is that hair fibers break during combing by pathways that are more complex and completely different from tensile-test conditions, similar to the conclusion offered by Brown and Swift more than 30 years ago (2). Furthermore, hairs on live heads break more frequently from conditions more similar to impact loading involving hair-on-hair interactions than by tensile loading. Extension or impacting hair fibers with flaws or damaged hair sections such as damaged wrapped ends produces short-fiber fragmentation, while longer segment breaks of damaged hair may be produced in fibers with natural flaws such as fiber twists or cracks or in badly abraded or chemically weakened hair or even knots.

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