

Hair breakage during combing. I. Pathways of breakage

CLARENCE ROBBINS, 12425 Lake Ridge Circle,
Clermont, FL 34711.

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Synopsis

Hair breakage during combing was evaluated by combing tresses and examining photographs of snags of hair fibers in combs. The resultant hair fiber arrangements suggest that breakage likely involves hair-on-hair interactions, and broken fragment size suggests that breakage occurs primarily at or near the hair-comb interface. Compression forces during combing were also measured, and impact loading of a hair fiber over another hair versus a hair fiber over a comb tooth shows that compression and abrasion are important to breakage during combing and that impact loading of one hair fiber over another during snagging is a probable and important pathway for hair breakage.

INTRODUCTION

There are several important papers in the scientific literature on the fracturing and breakage of human hair fibers (1–5). However, there is also literature that raises questions as to how relevant tensile test conditions are for simulating or even for predicting hair breakage on live heads (3–6) or from combing tresses in the laboratory. About 50 years ago, Hamburger *et al.* (6) conducted an interesting experiment in which they determined the load required to pull hair fibers out of the scalp. They found that this load at 65% RH is approximately equal to the Hookean limit and considerably lower than the breaking load for human hair fibers. Therefore, one of their conclusions was that hair fibers will not break on the scalp due to tensile forces alone, but will pull out of the scalp before breaking.

However, we know from studies that examined the ends of hairs removed by combing on live heads (7,8) that hair fibers do actually break on live heads during combing. Unbroken hairs that are simply pulled out of the scalp contain a bulb; on the other hand, those that are broken off do not contain a bulb, but a fractured end. In this type of study, even on chemically untreated hair, some of the hairs examined are found to be broken (7,8), more so for African hair (7) (average of 66% of total hairs from two persons) than from Caucasian or Asian hair (7) (from 3% to 24% among four panelists). Therefore, we are left with the conclusion that all of the hair fibers that break during combing on live heads are either damaged until their breaking force is below that of the Hookean limit of undamaged hair, or a more likely scenario, breakage of hair fibers during combing

“hair on the head is more complex than simple tensile fracture of single hairs,” a reasonable conclusion offered by Brown and Swift (3) about 30 years ago.

In this current work, hair snags were studied to determine the important hair-on-hair versus hair-on-comb arrangements and interactions during combing. Compression forces were also measured by combing tresses with a comb containing a compression cell, and impact loading was explored to try to determine hair breakage under conditions that more closely simulate actual breakage during combing hair on live heads.

EXPERIMENTAL

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

TRESS COMBING AND COLLECTING BROKEN FRAGMENTS

Eight-gram hair tresses from the above-mentioned 14-inch European hair were made: three were cross-cut two inches from the bottom, and three were angle-cut, two inches from the bottom to the tip, providing a tapered cut. All tresses were washed with a cleaning shampoo, gently detangled and combed out, and allowed to air dry overnight. Each tress was then gently combed about ten strokes to detangle the hair prior to testing. Each tress was clamped at the top into a fixed position and then combed 100 strokes. Each comb stroke started at a line behind the tress at 17.8 cm from the bottom of the tress so that each comb stroke was 17.8 cm. The broken-off hair fragments were collected on a large piece of white plastic, 76×84 cm, and separated by size into five different groups of 17.8 plus cm, 12.7 to 17.8 cm, 6.4 to 12.7 cm, 1.27 to 6.4 cm, and smaller than 1.27 cm. The fragments in each group were counted. This experiment was conducted at 41% RH and 70°F.

COMPRESSION COMB AND MEASUREMENTS

Making a compression comb. At the large-tooth end of an ACE hard-rubber comb (62746 part #), the second tooth from the end was cut off at the back and a small slot was made in the side of the comb back (about 0.05 to 0.1 inches). The cut areas were made smooth using a miniature file.

The compression cell (sub-miniature compression load cell LCMKD-10N from Omega Engineering, a 10 Newton or 1 Kg cell) was glued in place at the base of the comb, adjacent to the large end tooth of the comb, with the sensor of the cell pointing inward toward the next tooth, leaving a distance of 0.062 inches or 0.157 cm between the sensor of the cell and the adjacent comb tooth (Figure 1).

The removed tooth was cut (to shorten it) and glued on the inside of the large end tooth and on top of the edge of the compression cell (Figure 1). The compression cell on the

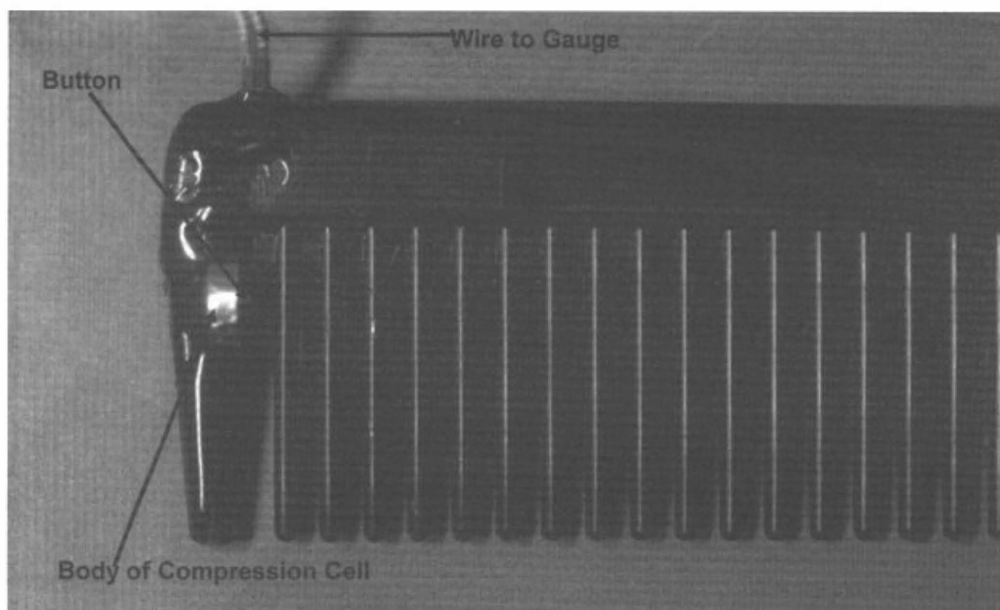


Figure 1. Compression comb.

comb was connected to Force Gauge DPiS 32 from Omega Engineering, following the user's manual instructions for wiring, and connected to a 115-volt cord with an on-off switch with a white neutral and a black hot wire. The unit was configured to read in grams and calibrated according to pages 17–23 of the user's guide. Small weights were added to each end of an attaching wire up to a maximum of 500 grams on each side, plus 2.5 grams (wire) to check the calibration. The safe-loading capacity of the cell was 1520 grams. When the maximum stress was exceeded, the zero and maximum load were rechecked with the calibration weights.

Estimating compression loads on single hairs in snags. Three 2-gram tresses of very curly hair (12-inch hair) described above were taken, and with the compression comb mounted in a vise and the teeth facing upward, about one-half of the tress was inserted into the comb, near the bound end of the tress, between comb tooth 1 (with compression cell) and comb tooth 2, with the rest of the tress on the outside of comb tooth 1. The tress was carefully pulled against the load cell at the very back of the comb for each comb stroke. The compression loads were observed and the maximum load recorded. This was done 17 times with three different tresses (five, five, and seven measurements per tress). The actual width of the compression cell in this area (between the cell button and the comb back where the hair rubs) was 1,524 microns. The cell responds to loads on the total back and not just the button. Care was taken to record data only when the snagged hair was actually touching only the cell button and the comb back. At the same time, no hairs were off the button, i.e., on any other part of the compression cell.

Making weighted hair fiber loops. Hair fiber 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 × 4-cm-long sections of tape] to hold the fiber securely). A weight (10 to 50 gm) was

attached to the tape holding the fiber ends together, through a 15-cm-long single-strand plastic-coated copper wire (#16) with a circle at one end to bind the fiber to the tape and a hook at the other end to attach the weight.

Hair loop over straight hair impact. 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 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 fiber slippage. The weighted loop was then dropped at a 15-cm height onto the horizontal hair fiber.

Hair loop over comb tooth impact. 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. The weight was raised up to the comb in the vise and dropped near the back of the comb tooth (drop 15 cm) (Figure 2). The comb teeth used were of two types cut from a Blue Goody comb, with measurements described below. 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).

Hair loop over hair loop impact. For this fiber loop over fiber loop experiment, the taped end of one hair loop was clamped into one vise with another hair loop threaded through it and weighted with a 30-gram load. The weighted hair loop (31 g total load) was dropped at an estimated height of 15 cm from the point of impact.

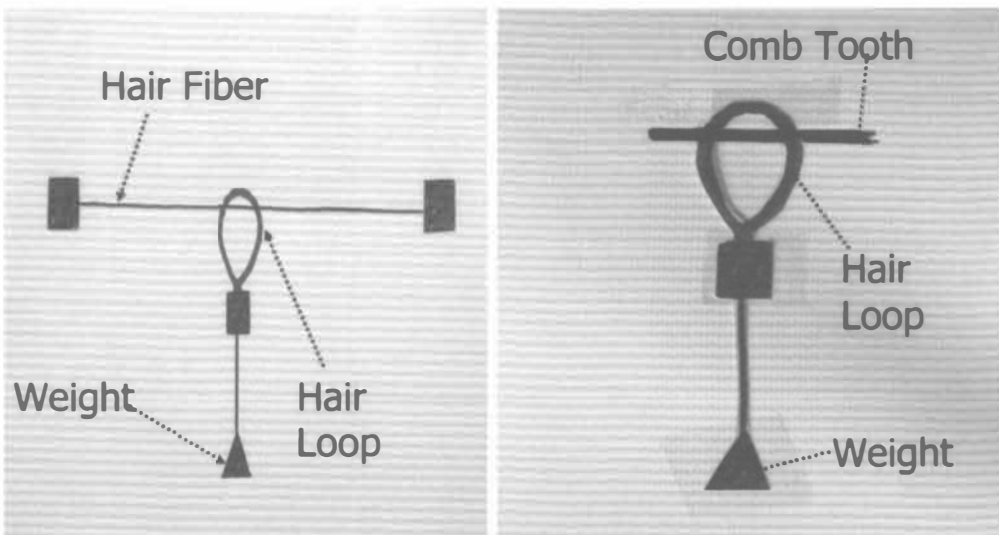


Figure 2. Hair loop over straight hair versus hair loop over comb tooth.

RESULTS AND DISCUSSION

HAIR BREAKAGE DURING COMBING OF TRESSES

Eight-gram hair tresses made from 14-inch dark brown European hair were both square-cut about two inches from the bottom (so the ends were of the same length) and angle-cut about two inches from the bottom to the tip (the ends were of varying lengths) and combed vigorously for 100 strokes, starting each comb stroke at 17.8 cm from the bottom of each tress. The broken hair fragments were all collected on a large piece of white plastic and separated by length into five groups and counted. See the data of Table I and the Experimental section for details.

The data of this experiment (Table I) show significant differences among hair lengths and between the two types of cut. Clearly more hairs are broken by crosscutting the hair where the ends are essentially of the same length. This technique of crosscutting hair provides more hairs at the end of the comb stroke and therefore a higher end peak force and thus more breakage. But, clearly another important factor is the larger number of shorter broken hair fragments than longer fragments. Only 3% to 5% of the broken fragments are longer than 17.8 cm (the comb stroke), while about 70% of the broken hairs are less than 1.27 cm. For both types of cut, only two broken hair fragments are longer than the comb stroke length. Therefore, most of the breakage occurs in short fragments at or near where the comb interfaces with the hair rather than above where the comb interfaces with the hair as one would expect from tensile loading.

Thus the comb is not functioning as a device to hold and stretch the hairs as in tensile fracture, but a more complex interaction is occurring at snags at or near where the comb interfaces with the hair, consistent with the conclusion of Brown and Swift (3). Therefore, to understand hair breakage during combing, the key to these interactions is to understand the snags where the highest combing forces and hair breakage are encountered.

ENTANGLEMENTS IN SNAGS AND PATHWAYS FOR HAIR BREAKAGE

Nearly 30 years ago, Brown and Swift (3) photographed hair snags in an SEM and related the entanglements to the fractured ends of human hairs. These scientists illustrated crossover entanglements and looped hairs, but also described how these entanglements lead to cuticle disruption caused by the abrasive actions of hair on hair rubbing during

Table I
Combing Hair Tresses and Breakage by Hair Length

Broken-hair lengths	Number of hair fragments	
	Cross-cut	Angle-cut
17.8 cm or longer	2	2
12.7 to 17.8 cm	33	16
6.4 to 12.7 cm	63	23
1.27 to 6.4 cm	192	64
<1.27 cm	754	238

combing, which seriously damages the hairs, leading to longitudinal splitting of the fibers.

In the current study, snags were created by combing one- and two-gram tresses of very curly steam-set hair and slightly wavy Caucasian hair, which were photographed using a digital camera with a close-up lens. These photographs show that crossover hairs in advance of the moving comb and behind the moving comb create snags in which:

- hairs can wrap and loop around other hairs and around comb teeth (single and multiple teeth) to create very tight entanglements with hairs in stressed positions (see Figures 3, 4, and 5),
- hair fibers can cross over taut hairs that are wrapped around comb teeth, creating a situation with a high probability for breakage (see Figures 3, 4, and 5).

Considering the above conclusions from photographs and the prior literature (1–4), the following mechanisms or pathways for hair breakage were hypothesized:

1. Impacting or compressing and extending one hair fiber against another taut hair (Figures 3–5). This condition may involve almost any angle of wrap from a simple perpendicular crossover to one hair fiber completely looped around another (3).
2. Impacting or compressing, extending, and abrading a hair fiber against a taut hair fiber (Figures 3–5). This is essentially pathway 1 with abrasion.
3. Extending and compressing or impacting hairs with flaws or cracks and/or chemically weakened hair. If the fibers have been sufficiently weakened, extension alone may cause breakage.

COMPRESSION FORCES DURING COMBING

All the above pathways for hair breakage suggest that compression forces in addition to extension are involved in breakage and that in two of these pathways (2 and 3), abrasion is also important. In other words, these pathways are consistent with Brown and Swift's



Figure 3. Slight wavy Caucasian hair snag beneath advancing comb.

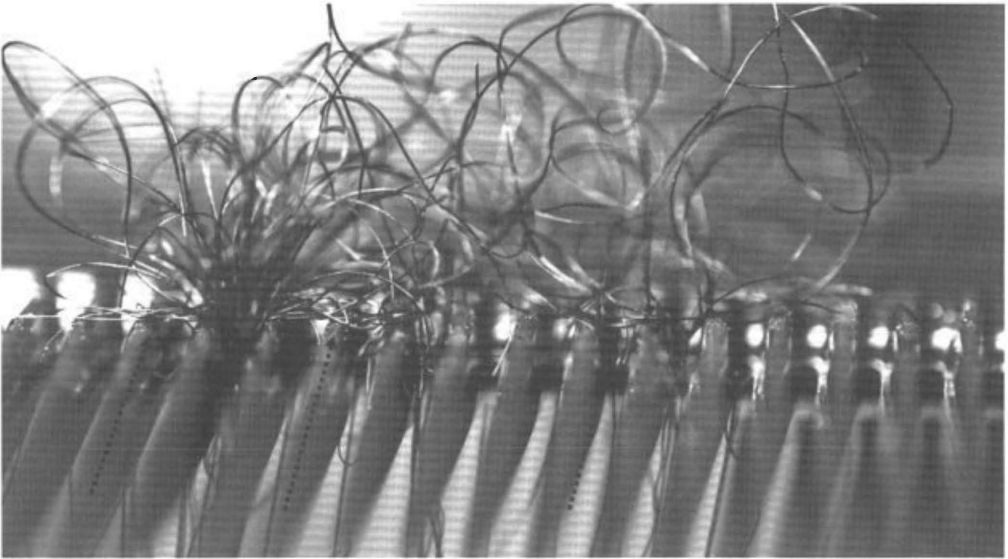


Figure 4. Very curly Caucasian hair snag underneath advancing comb. Note looped and crossover hairs at or near the hair-to-comb interface.

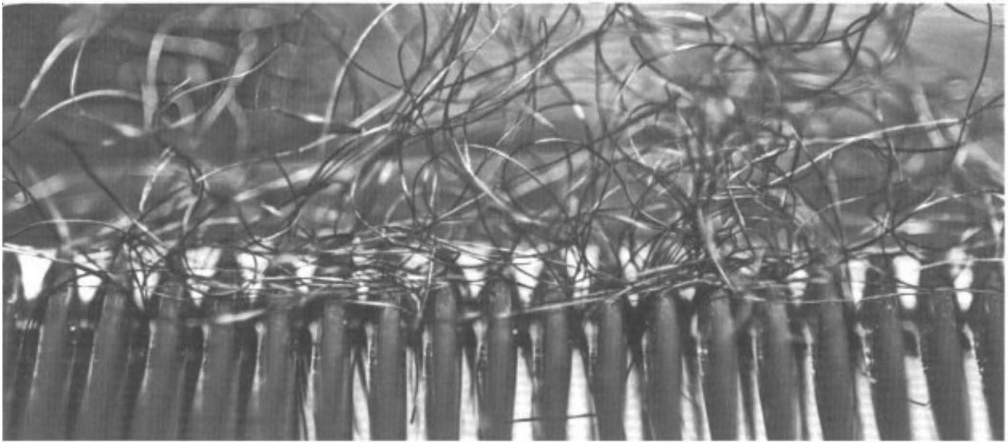


Figure 5. Very curly Caucasian hair underneath advancing comb. Note the looped and crossover hairs at or near the hair-to-comb interface.

conclusion that breakage during combing is more complex than simple tensile extension (3). Since the effect of compression on hair breakage is not a widely held view, compression loads during combing of hair tresses were measured using a comb containing a miniature compression cell mounted onto it. The compression comb used in this work is described in the Experimental section and is illustrated in Figure 1.

The following three different ways of combing were explored with the compression comb using two-, four-, and six-gram tresses of virgin Caucasian hair: The first way was holding the tress in the comb loosely with the thumb. The second way was to hold the hair snug against the back of the comb while pulling the hair so that the major stress is against the back of the comb. The third way was to hold the tress snugly in the comb

with the thumb while pulling the comb through the hair, placing the major stress against the load cell and the back and side of the comb. These data (Table II) show that thumb pressure is an important variable in the actual compression loads generated during combing. Furthermore, it is best (providing lowest compression loads) to use the thumb to ensure that all hairs remain in the comb teeth rather than to apply pressure that provides higher compression loads and more damage to the hair. These data also show that the size of the tress or the amount of hair in the comb also contributes to compression loads during combing.

Very high compression loads were achieved in these experiments. These compression loads are due primarily to the thickness of the tress, the comb teeth spacing, which in this case is large, and how hard one presses the hair against the comb or the compression cell. These variables are all difficult to control among different qualitative combers and undoubtedly account for variations seen in qualitative combing experimentation.

These factors determine the number of fibers that fit between the comb teeth and also how the tress is held against the comb during combing, and these loads are distributed over a large number of fibers and not in a uniform manner, suggesting that for some hair-on-hair contacts, very high compression loads are encountered.

ESTIMATING THE COMPRESSION LOAD AGAINST SINGLE HAIRS DURING COMBING

To estimate compression loads on single hairs during combing, hair-on-comb compression loads were measured in a snag underneath the advancing comb held in a vise to control the hair fibers in contact with a specific part (of known size) of the compression cell. A miniature trees of very curly hair (Caucasian hair steam-set to simulate African hair) was used, and only a small number of hairs, approximately 100, were inserted on each side of the comb tooth containing the compression cell to provide a snag and control the hair against the load cell button only. In this experiment the maximum total compression load for 17 determinations varied from 271 to 1867 grams. With two primary assumptions, the average maximum compression load between the comb and each single hair was estimated at 39.5 grams per fiber, and it varied from 16 to 110 grams per fiber. The assumptions are: (a) the hairs are perfectly aligned against the button of the load cell (1524 microns wide) and (b) each hair is assumed to take up 90 microns of space (70-micron average hair diameter plus 10 microns on each side for hair crimping and imperfect packing). Therefore, 17 hairs are assumed to be in direct contact with the load cell.

During these runs, for data to be recorded, a uniform layer of hairs against *only the button* of the load cell had to be apparent, and hairs could not be in contact with the rest of the

Table II
Average Combing and Compression Loads for Undamaged Wavy Caucasian Hair

Tress size	Thumb loosely	Against back of comb	Against cell
2-gram	22 ± 11	80 ± 50	449 ± 111
4-gram	56 ± 20	290 ± 82	602 ± 196
6-gram	205 ± 82	889 ± 316	994 ± 231

Date is expressed in gram load within the 95% confidence limit.

load cell because the entire compression cell surface provides compression readings and the button could be used to gauge the actual amount of contact between the compression cell and the hair. It is also assumed that the compression loads are distributed uniformly over these hairs.

These experiments demonstrate that compression loads between hair fibers and comb surfaces during combing can be very high. One can assume that the average compression load for a hair-on-hair interaction in a difficult snag would be of the same order per fiber or in some cases even higher, leading to very high compression forces per unit area in actual contact for one hair fiber against another.

Therefore, for hair breakage during combing or brushing, compression forces are involved in addition to extension forces, and this fact is consistent with all three of the previously suggested pathways for breakage. Furthermore, these compression forces can be very high, and with rubbing can lead to extensive cuticle disruption (3). Yet compression forces are not considered in ordinary tensile testing of human hair fibers.

IMPACT LOADING EXPERIMENT

Most tensile testing conditions employ very slow strain rates, of the order of 0.25 cm per minute. Under these conditions, hairs generally stretch about 40% to 60% of their length before breaking. However, during combing, hairs do not stretch to such lengths before breaking; therefore, another important variable is likely to be strain rate differences in combing versus those in tensile testing. During combing, strain rates can be very rapid, at least an order of magnitude faster than in normal tensile testing, and combing more closely simulates impact loading than slow stretching. Therefore, to more closely simulate the action of combing, experiments on hair fiber breakage using impact loading conditions were examined.

BREAKAGE OF HAIR OVER HAIR VS HAIR OVER COMB TOOTH

Hair loop over comb tooth vs hair loop over hair loop. Hair fiber loops were made as described in the Experimental section and the weighted loop (51-gm load) was impact loaded over a large thick-comb tooth (varying from 1800 to 1400 microns thickness). Hair breakage generally did not occur on the first impact (see Table III). However, when the comb tooth was thinner (varying from 1245 to 940 microns thickness), using one of the fine teeth on this same comb, breakage occurred with fewer impacts using the same 51-gm load (Table IV). Yet, when one hair fiber loop was impacted over another hair fiber loop

Table III

Impact Loading a Hair Fiber Loop Over a Thick-Comb Tooth (~1800 μ) Using a 51-Gram Load

4 Fibers broke on impact 1, near contact site
2 Fibers broke on impact 2, at contact site
2 Fibers broke on impact 3, not at contact site
3 Fibers broke on impact 4, at contact site
1 Fiber did not break after 10 impacts
(36 Total impacts and 11 broken hairs)

Table IV
Impact Loading a Hair Fiber Loop Over a Thinner-Comb Tooth (~1245 to 940 μ) Using a 51-Gram Load

8 Fibers broke on impact 1, 2 at contact site
2 fibers broke on impact 2 near contact site
2 fibers broke on impact 5, 1 near contact site
(22 Total impacts and 12 broken hairs)

Table V
Impact Loading a Hair Fiber Loop Over a Single Hair (Loop)

10 of 10 hairs broke on impact 1 for 51-gm load, all near contact site
(10 Total impacts and 10 broken hairs)
12 of 12 hairs broke on impact 1 for 31-gm load, all near contact site
(12 Total impacts and 12 broken hairs)

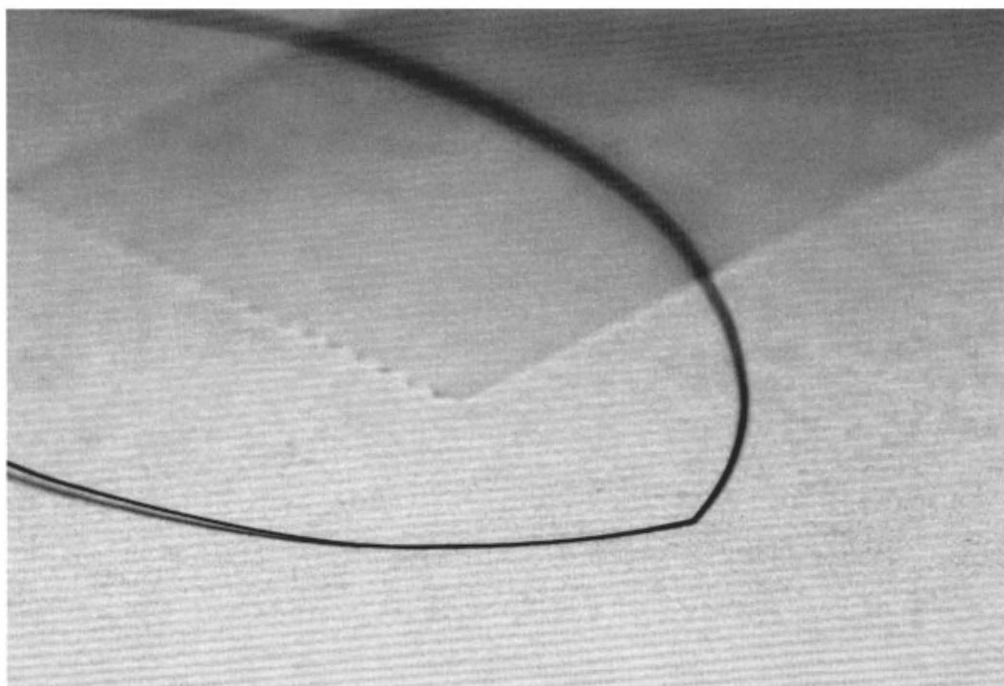


Figure 6. Crease in hair loop after impact over horizontal taut hair.

where the approximate average fiber thickness was 70 microns, breakage occurred with fewer impacts with either a 51-gram load or a 31-gram load (Table V, Figure 5).

In all but five cases, the bottom hair broke; however, no attempt was made to control fiber diameter in this experiment. In all cases, the unbroken loop was left with a small crease in it (see Figure 6). These simple experiments show that hair breakage occurs more readily when a hair fiber is impacted against another hair as compared to a hair against a comb tooth. Therefore, the force per unit area in the impacted region of the hair is

critical to breakage. So during combing, when a snag is encountered, and a single hair is impacted or pulled/stressed against another object, the smaller that object (hair over hair versus hair over thin or thick comb tooth), the more readily the hair will break.

CONCLUSIONS

By examining photographs of snags and the resultant hair-on-hair arrangements and interactions, three pathways for hair breakage were described. Compression loads during combing were estimated by combing hair tresses with a comb fitted with a miniature compression cell and by comparing impact loading of a hair fiber over another hair versus over a comb tooth. The results of these experiments show that compression and abrasion are important to breakage during combing and that impact loading of hairs over other hairs during snagging is a likely route for hair breakage. This preliminary conclusion, based on a few impact loading experiments, will be followed up in a subsequent publication focusing more on the impact loading of hair fibers, to try to more fully assess its relevance to hair breakage during combing.

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