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Fracture Match: A Validation Study of Paper Tears, Part 1

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Forensic document examiners are frequently asked to analyze evidence that requires the identification of a torn document by reconstruction. The reconstruction and identification of a rip or tear is also known as a fracture match. Fracture match examinations have important forensic applications in that they may establish a relationship between 1) the suspect and the crime scene, 2) the victim and the crime scene, or 3) the suspect and victim. Be it a ransom note torn from a pad of paper, pieces of a gum wrapper containing drugs, or a spent paper match, these products are often forwarded to the forensic document examiner, who endeavors to determine if the separated items are associated.

In this study, the authors examined single sheets of paper torn under controlled conditions to investigate the uniqueness of their torn edges. The results of the study showed that the fractured edges of single sheets of paper torn under controlled conditions were unique. A 4-point measurement methodology, used to determine the tear profile, was validated statistically.

Introduction

A fracture match is defined by the Association of Firearms and Toolmark Examiners as "the examination of two or more objects either through physical, optical or photographic means which permits one to conclude whether the objects were either one entity or were held or bonded together in a unique arrangement" (AFTESC 1984). The determination of a fracture match for paper products ultimately relies to a great extent on the knowledge and experience of the forensic document examiner. The examiner must formulate a reliable opinion as to whether 2 or more paper fragments were once joined together. This is typically done via a side-by-side comparison of the edges using comparability; visual inspection; and manual realignment, edge-to-edge realignment, surface markings, and pattern count. While these are proper procedures, they do not address some fundamental questions relating to how many points must match along 2 torn edges before it can be declared a fracture match. It is commonly held that no 2 pieces of paper will tear exactly alike. The nature of the paper-making process and the manner in which the paper fibers are arranged make this a generally accepted assumption that has not been validated scientifically. An experimental determination of fracture characteristics and a statistical analysis of point-to-point correspondences along a torn edge are necessary to validate or refute such a claim. For the purpose of this study, the hypothesis is that 2 separate pieces of paper which are torn under exactly the same conditions will result in identical tears.

Methods and Materials

Research within the questioned document field must be properly designed and analyzed to meet rigorous valid scientific standards. Within that research there are 2 broad considerations that must be addressed. The 1st deals with the validity of certain questioned document analyses, and the 2nd deals with the measurement and characterization of attributes that relate to the matter under investigation.

This study deals with the quantitative measurement and characterization of distinctive elements in paper tears that lead to fracture-match determinations. Specifically, this study addresses the following questions: 1) Are paper tears unique?

2) How many points of correspondence are sufficient for an identification? 3) Are there class characteristics pertaining to paper tears? 4) What is the probability that p points of correspondence will be found between m and n measurements on similarly torn pieces of paper?

Experimental Design

To answer these questions, the authors set out to create a protocol that would control for paper composition, taking into account such variables as paper mass, mass accumulation, tear dynamics, and fracture tear measurements.

Paper

Six types of paper were used in this research: Boise Aspen paper 20 lb, Office Depot copy paper 20 lb, Staples copy paper 20 lb-84B, HP printing paper 22 lb-92B, Staples inkjet paper 24 lb-102B, and Staples laser paper 24 lb-102B. All papers were kept at the same ambient conditions for several days and were torn whilst orientated in the same "portrait" position with felt side up, which provided for less feathering along the tear.

Paper Mass Measurements

Each sheet of paper was measured in grams utilizing a calibrated scale with an accuracy of ±0.001 g.

Tear Force Measurements

Tear force was determined by the successive addition of mass to a 50 g weight hanger attached via a pulley system to the edge of the paper. Mass was added to the tear apparatus by first attaching a 50 g weight hanger, then adding individual masses in the following sequence: 100 g, 100 g, 20 g, 20 g, etc., until the tear was initiated. The total mass required to initiate a tear was then converted to force by multiplying by 9.8 m/s^2.

Fracture Tear Measurements

The following procedure was used to generate data for this study.

- Sheets from a selected ream were removed and measured using a calibrated scale.
- Each sheet of paper was placed into a frame that anchored the sheet along 2 adjacent edges of the paper.
- The papers were always oriented with the felt side up.
    a. Mass was added to a weight hanger suspended over a pulley attached to the paper with a clamp (Figure 1).
    b. Once the tear was initiated, the sheet of paper was removed from the apparatus, and the tear pattern was carefully measured.
    c. Measurements were taken at 4 data points (Figure 2) along the tear and entered into Table 1. Each tear pattern was determined from 4 positions (5 cm, 10 cm, 15 cm, 20 cm), measured from the initiation point of the tear along a line parallel to the long edge of the paper to an accuracy of ±0.0005 m. The distance to the tear from the 5 cm longitudinal line is described as Meas. #1, while measurements at 10 cm, 15 cm and 20 cm are referred to as Meas. #2, Meas. #3 and Meas. #4, respectively.

Data Analysis

In order to accurately calculate the probability of a match, the number of accessible points along the tear needs to be determined. Several statistical models were considered in order to calculate the probability of a match. Under the conditions of this study, 2 sheets of paper torn were considered to constitute a match if we measured m points on 1 sheet and n points on the other sheet and found p matches between the 2 sheets. According to basic binomial equations, the probability of m and n points measured with p matches, out of a total possible M points, is given by

$$P(M,m,n,p)=(m!(M-m)!)\,(n!(M-n)!)/p!(m-p)!(n-p)!(M-m-(n-p))!M!$$

Since we want 4 points on each sheet to be measured and those 4 points to be equal in order to define a match, we demand that m=n=p=4.

$$P(M,4,4,4)=(4!(M-4)!)\,(4!(M-4)!)/4!(0!)(0!)(M-4-(0))!M!$$
$$P(M,4,4,4)=(4!)(M-4)!/M!$$

This expression was developed on the assumption of a random walk probability which assumes that all possible directions are equivalent for each step of the tear propagation. Under these assumptions, the likelihood that 4 points will match on 2 randomly chosen sheets of torn paper is extremely small, namely on the order of 1 chance in 1.399×10^{20}

This analysis neglects the fact that the tear is not allowed access to all possible directions at each point and thereby overestimates the possible number of outcomes. To take into account the restrictions upon the tear propagation, we considered several possible approaches. The 1st approach would be empirical by employing a simple reduction in the area available to the tear. Data indicated a 20% reduction in the number

Paper of Type	Sheet #	Meas. #1 [cm]	Meas. #2 [cm]	Meas. #3 [cm]	Meas. #4 [cm]	Mass of weight, grams	Mass of paper, grams
Ream #1	1	4.5	12	23	27	330	4.59
Boise	2	8	18	22.5	27	290	4.60
Aspen	3	9	23	34	44	330	4.53
	4	7	16	24	34.5	290	4.56
	5	6	11	16.5	21	270	4.59
Ream #2	1	6	22.5	31	42	350	4.60
Staples	2	4	13	20.5	31.5	410	4.55
Copy	3	5	12	18.5	21	330	4.57
	4	6	15	22	34	350	4.60
	5	11	29	42	51	330	4.56
Ream #3	1	10	24	35	47	370	5.05
HP	2	5.5	16.5	27	38	370	5.11
Printing	3	8	23.5	41.5	57	510	5.08
	4	14	31	43	60	350	5.02
	5	5.5	18	29	34.5	370	5.09
Ream #4	1	8.5	24	39	47	390	5.44
Staples	2	9.5	21	32	41	470	5.49
Inkjet	3	9	15	28	37	430	5.39
	4	9	24	36	45	470	5.48
	5	5	19.5	33	47	450	5.46
Ream #5	1	7	23	24	35	370	5.44
Staples	2	5	12.5	20	27	390	5.44
Laser	3	6.5	20.5	31	42	430	5.47
	4	5	14	20	24	370	5.51
	5	6	19	29.5	37.5	430	5.47
Ream #6	1	3	9.5	12	16	410	4.57
Office	2	4	10	13	19	410	4.61
Depot	3	5.5	13.5	19.5	26	410	4.58
Copy	4	6	12	18	24	330	4.61
	5	8.5	17	26	29	270	4.56

Table 1 Paper Fracture Match Data.

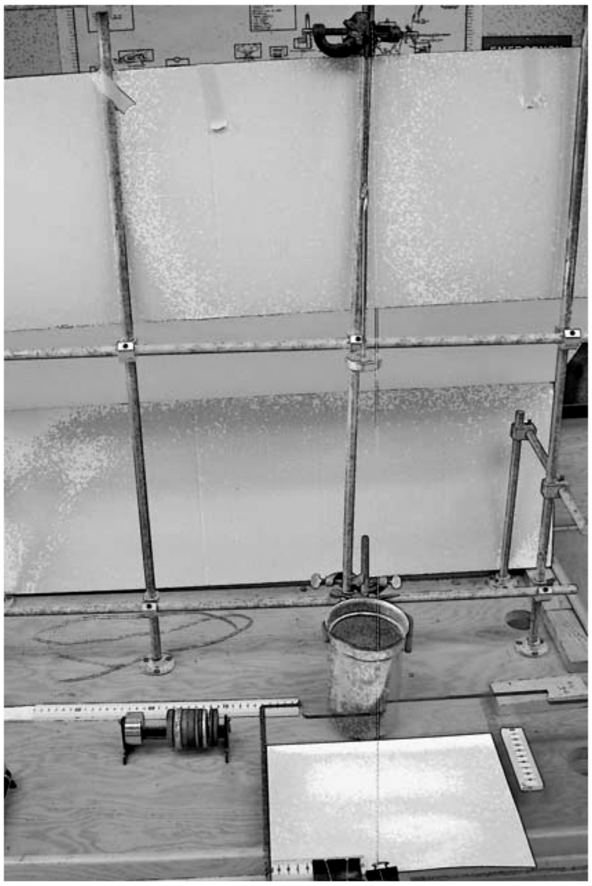


Figure 1 Experimental setup.

of accessible points for tear propagation. This reduces the probability of a match to 1 part in 2.38 x 10^{17}, still extremely unlikely.

Based on the data collected, a restricted random walk was examined where fiber angle and inaccessible sheet area were accounted for to reduce the number of points accessible to a propagating tear. Figure 3 shows that the tears were definitely confined within specified boundaries within the paper.

The analysis of data in this study can be further improved by taking a thermodynamic approach modeled on the study of polymer chain length by Flory. The analogy here is to consider the tear as equivalent to a random polymer chain growing along a 2-dimensional surface. Flory's development takes into account the free energy of the polymer chain and then minimizes that free energy to arrive at a likely chain length which would correspond to the paper tear length. The final model accounted for fiber length and dimensionality (to allow for paper thickness and multi-sheet tears) in order to arrive at a best estimate of the probability of a match by using a free energy minimization approach. Free energy minimization for tear length takes into account the density of points and assumes an unspecified fiber-fiber repulsive interaction that restricts fracture direction from 1 fiber to the next. In general, the free energy is defined as

$$F = U - TS$$

where F is a function of volume V and temperature T; and for this application we assumed an isothermal system. Within this regime, the change in free energy, ΔF, is equated with the work done by the system to relieve the stress buildup at the fracture front. Two terms in F arise naturally. The 1st term is associated with the potential energy stored in the fracture front, analogous to spring potential energy, U = 1/2 kx2. The 2nd term is the entropy contribution which mediates towards more order and a decrease in free energy. Each term can be qualitatively related to the tear length, R, as follows:

$$F \sim \underbrace{R^2 / M}_{\text{Elastic energy}} - \underbrace{M^2/R^d}_{\text{Entropic excluded volume}}$$

By minimizing F with respect to R we can get an expression for the length of tear, R = L.

$$L = a\, M^{3/(d+2)}$$

Where "a" is the step length (fiber length = 1 mm), M is the number of possible steps within the tear length, and "d" is the dimensionality of the tear. Single sheet data yielded tear lengths that, when incorporated into the equation, gave a value of d = 2.2980. In other words, the tear behaved as a 2-dimensional construct with fractional 3-dimensional characteristic due to the non-zero paper thickness. Based upon a fiber length of 1 mm and an average measured tear length of 206 m, the number of data points, M, accessible along the tear length was 2011. The probability that 2 sheets match, according to the 4-point correspondence principle, was P(2011,4,4,4) = 4!(2011-4)!/2011!, which equals 2.7 x 10-12. This represents 1 chance in 370 billion trials that the tear profile of 1/2 of 1 sheet would match the 4 points on another 1/2 of a 2nd sheet.

In order to arrive at a reasonable number of points along the tear line (M), we developed the thermodynamic approach. The modified random walk probability calculation P(M, m, n, p) requires a value for M. The thermodynamic derivation provides a scientifically valid basis for reducing the possible values of M from simple random walk values, which are very large, to more reasonable values.

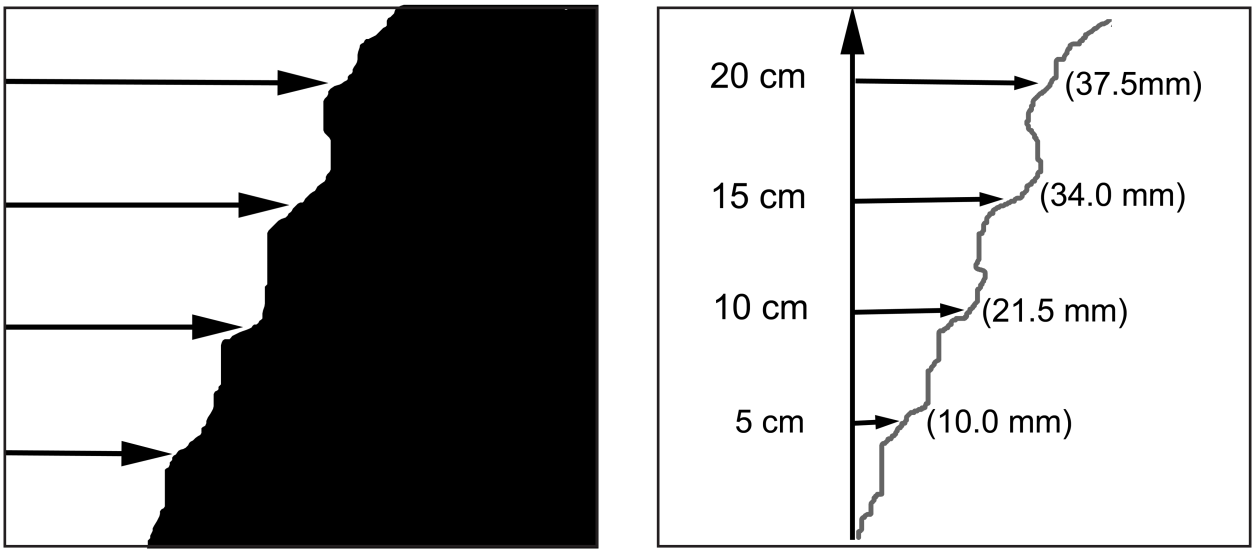


Figure 2 Paper tear with measurement positions indicated, and representation.

Temperature is not a variable in the calculation, since we were doing isothermal analysis.

Fiber length is included because the most likely mode of tear propagation is interfacial, i.e., along the boundary between a fiber and matrix.

Paper thickness is incorporated as a dimensional quantity to try to allow for the actual thickness of the paper playing some role as the tear attempts to find a path through the material.

Discussion

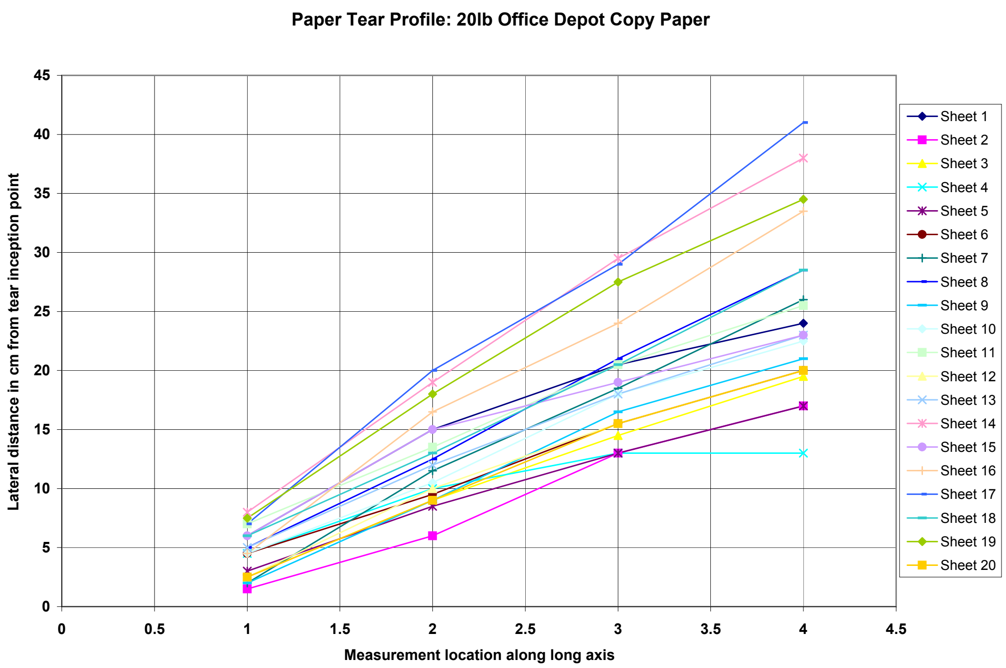
The data collected from single sheet tears under controlled conditions yielded results that indicate the tears are unique. Although the number of measured points, m and n, was set to 4 as an initial protocol, data shows that 4 points seem sufficient. However, it is beyond the scope of this study to determine the optimal number of measured points.

The determination of accessible points, M, along the tear is critical for arriving at calculations of the probability for a correspondence between the 4 measured points. The paper tear data provided tear lengths, L, measured by the 4-point protocol. The measured tear lengths, L, were used to arrive at the number of accessible points. Using this approach reduced the number of accessible points, M, from a large value based on a simple random walk model to a much more moderate value based on thermodynamic principles. Even with the substantial reduction in accessible points with the thermodynamic model, which would lead to the largest probability calculation, the probability determination was that single paper tears between papers torn at different times under similar conditions were extremely unlikely to yield a match.

The calculation of accessible points depends upon the tear length, fiber length, and dimensionality. A question remains as to whether the 4-point protocol must be modified to scale for different tear lengths, L. An approximate scale would be a simple ratio whereby $L/m = y$, where $m = 4$ and y is the longitudinal length measurement parallel to the length of the paper. All measurements in this study were taken without the aid of magnification, so if magnification were to be employed, this same ratio could apply to the length of the tear being imaged.

With respect to class characteristics in the paper tear profiles, the study revealed that the tears consistently propagated from the bottom left to the top right when torn in the portrait position. It is believed that the tear mechanism influenced this characteristic.

This validation study showed that for the conditions imposed it would be highly unlikely to see 2 matching tears from separate tear events. The conditions for this study were single-sheet tears in portrait mode and felt side up. Further studies involving multiple sheets, landscape orientation, and felt side down should be undertaken to determine whether these results are universally applicable. Additional considerations for study



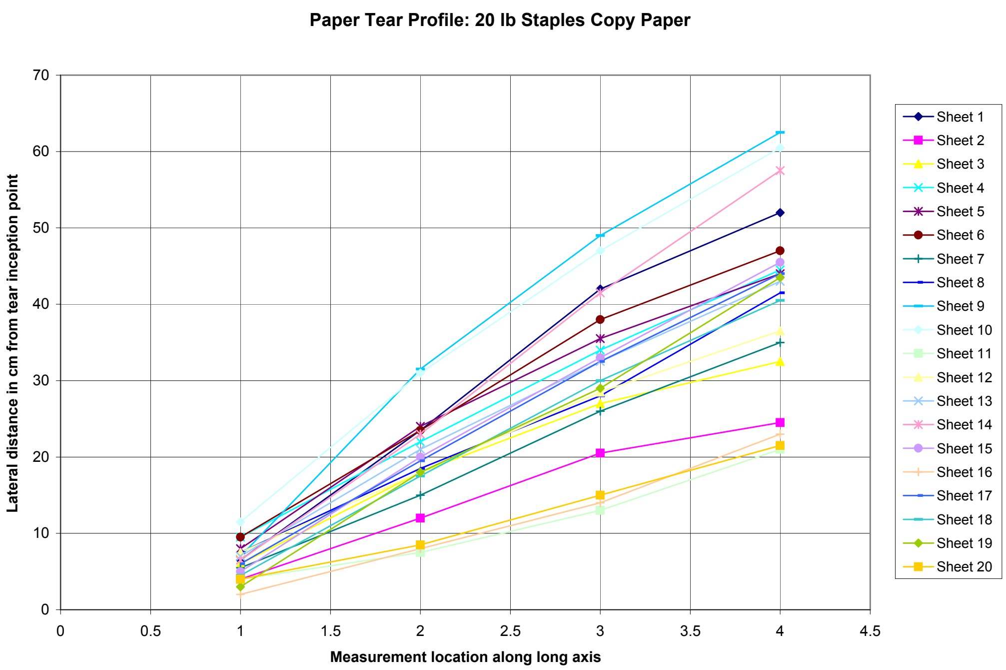


Table 2 Paper Tear Profiles for 2 representative sets of data.

are the impact of different numbers of measured points on the probability determination.

Finally, the degree of influence of paper thickness is an avenue of future investigation which could add support to the dimensional scaling arguments used in the calculation of accessible points. While scaling exponent arguments are seen widely in areas such as condensed matter physics and polymer physics, the application of these arguments to paper tears should be tested further to validate the use of the dimensionality factor as a way of accounting for paper thickness in the calculation of tear statistics.

Conclusion

On the basis of the research conducted, and controlling for the above mentioned variables, paper tears are unique. Concerning the points of measurement needed to identify a match, our study determined that 4 points of measurement were sufficient. However, we cannot determine without further study how many points are necessary. In conclusion, our research revealed that the chances of 2 sheets of paper tearing the exact same way twice with a tear profile at least 20 cm in length is 1 in 370 billion.

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Suggested Readings

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