ABSTRACT

DEVELOPMENT OF THE TEAR-PEEL TEST FOR PAPER TOWELS

by Samir El-Darazi

A novel Tear-Peel test apparatus and method was developed to evaluate the durability of paper towels. The new method was used to investigate the relationship of a towel’s tear-peel resistance to the dry scrub resistance. The tear-peel apparatus can be used to determine force and energy required to induce separate or combined modes of intra-ply tear and inter-ply peel. Effects of structural features such as embossing on peel energy are demonstrated. Sixteen towels, 1 ply and 2ply were evaluated by the new method.
THE DEVELOPMENT OF THE TEAR-PEEL TEST FOR PAPER TOWELS

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1 Introduction

1.1 Impetus for Research of Paper Towel

Today, over ninety percent of all households in the United States use paper towel for multipurpose end uses. These end uses range from wiping spills on surfaces to absorbing grease from fried foods [1]. When wiping spills, however, paper towels have a limitation to their re-use because they can fall apart. An example of a torn towel is illustrated by Sample A in Figure 1-1.

![De-cohered towel](image)

**Figure 1-1**: Cohesive durability comparison between two paper towel samples [2]

Sample A is shown to have a hole due to the fact that the towel sheet came apart as it was used to wipe a spill. In comparison to Sample A, Sample B’s sheet appears intact even though it underwent the same end use condition as Sample A. The term, cohesive durability, has been adapted in this thesis to describe the performance of a towel to stay intact during a wiping, rubbing, or scrubbing end use. Cohesiveness describes the act of “sticking together”, while durability is the “ability to withstand wear or decay” [3].

Figure 1-1 is actually a type of visual marketing tool used by towel manufacturers to prove that their towel’s last longer than the others. The situation in Figure 1 suggests that the durability of paper towels varies from towel to towel, but no scientific evidence can be found in the literature to support the claims made in the commercials. There is no
understanding of what makes a towel durable to scrubbing or any science-based testing available to quantify durability in a repeatable and non-biased manner.

There are subjective tests, but they are time consuming and do not provide a scientific understanding of how a towel design affects its cohesive durability [4]. This lack of scientific understanding is a problem to towel manufacturers because they do not know how towel design scientifically relates to cohesive durability. If the physical relationship of a towel’s design to its cohesive durability is understood, then towel manufactures may be able to gain more insight on improving cohesive durability performance or optimizing manufacturing cost of towel with desired cohesive durability performance [5, 6].

In response to the problems with current subjective evaluation of towels’ cohesive durability, a novel tear-peel test was developed to provide quantitative and systematic results believed to relate to cohesive durability for 1 and 2 ply dry towels.

1.2 Introduction to Paper Towel

To understand how the design of paper towels affects their end use properties, an introduction to paper towel is presented. Paper towels fall under the grade classification tissue paper. Paper is defined as a “network made mostly of natural cellulosic fibers” [7]. This network of cellulosic fibers on a paper’s surface is shown in Figure 1-2 from an image acquired by a Scanning Electron Microscope [8].

Figure 1-2: A network of fibers that makeup paper
It is this network structure that is adjusted to meet the consumer’s end-use requirements [9]. For example, some of the main properties consumers look for in a paper towel, other than its cohesive durability, include: its absorption rate, absorption capacity, and softness [10, 11]. In addition, the cost of manufacture needs to be aligned with what consumers are willing to pay. Cost and quality are primary reasons why towels have low grammage, less than 50 g/m², and sheet structures have large void volumes [10].

If one were to shop for paper towels, many design variations can be found – all to satisfy the consumers need. The brief illustration in Figure 1-3 shows examples of towels features that are designed to meet the consumers need, whether it is functional or aesthetic. These features include an embossing pattern (a), towel ply (b), and graphics(c).

![Figure 1-3: An example of paper towel embossment patterns](a) (b) (c)

A paper towel’s durability is influenced by its design. If the failure mechanism of cohesive durability is identified, towel manufacturers can adjust their towel design for improved cohesive durability performance. The work presented in this thesis does not suggest how towel design affects cohesive durability, but provides a means of quantitatively characterizing cohesive durability.
2 Background

2.1 Limitation of Current Methods

Despite the 80 year legacy of paper towel in the open market [1], no objective method is found in literature to test a towel’s cohesive durability. Typically with consumer tissue products, subjective panel rankings are used to evaluate the cohesive durability of towels. However, the main limitations of the “ranking” results, is that it does not inform the manufacturer, from a fundamental level, how to specifically target structural and material adjustments to improve cohesive durability performance.

For example, typical subjective evaluation methods such as ASTM3511-96 to 3514-96, involve a panel that judge the degree of piling, from a ranking scale of 1 to 5 [4]. This type of subjective evaluation can only give an indication of what degree manufacturing processes may affect the towels cohesive performance, but it does not inform the manufacturer of how the towel structure and material selection physically influences its durability. This can be costly for the manufacturer because who must rely on statistical data to control a towel’s cohesive durability [5, 6].

2.2 The Search for an Objective Test Method

Numerous literature sources were searched to provide a guide toward a test that objectively characterizes the cohesive durability of paper towel. This section details some of the work found on paper towels - no work was specifically found on objectively characterizing cohesive durability of towel.

In the latest edition of the Handbook of Physical Testing of Paper [10], a dedicated chapter was given to the physical and mechanical properties of paper towels. However, no literature was cited on the objective testing of towel’s cohesive durability. Instead, the topics addressed ranged from how towel properties are influenced by manufacturing processes to specialized physical tests that measured properties such as mass distribution, tensile strength and flexibility among others.

An interesting topic presented, analogous to the objective of this thesis, deals with using an objective test to incorporate physical quantities of paper towel to perceived softness. For example, in the Bulk Softness Measurement two sheet parameters are measured and incorporated into a model that relates to the perceived softness a user feels
when towel is crumpled between his/her hands. Specifically, the geometric mean stiffness (Equation 2-1) of towel is incorporated into a power law model (Equation 2-2) which is related to perceived bulk softness.

\[ S_T = \sqrt{S_{MD}S_{CD}} \]  
\[ R_1 = aS_T^m \]

\( S_{MD} \) and \( S_{CD} \) from Equation 2-1 are stiffness values for the machine direction and cross direction of the towel sheet. In Equation 2-2, \( R_1 \) is the perceived bulk softness. For a particular set of products, the constants \( a=99 \) and \( m=0.36 \) gave a coefficient of correlation of \( R^2 = 0.86 \). By using this evaluation technique, the towel manufacturer can effectively control the towel’s level of perceived softness by controlling the geometric mean of the towel’s stiffness.

A previous study by Coffin [14], researched several testers for their capability to objectively measure the cohesive durability of towel. None however, were found suitable for objectively characterizing towel durability. Figure 2-1, shows an example of two testers that were examined; the Taber abrasion tester and Martindale abrasion tester.

![Figure 2-1: (a) The Martindale Abrasion Tester and (b) the Taber Tester [14]](image)

The problem with these abrasion tests is that they measure the resistance of wear on a surface caused by textile or paper not the wear on the surface of the towel. The Martindale Abrasion Tester was primarily designed to determine the abrasion resistance
of textile fabrics. The Taber Abrasion tester, on the other hand is used in the paper industry. TAPPI T 476 “Abrasion Loss of Paper and Paperboard” describes the standard test using this equipment. No other scientific literature was found to link abrasion resistance to durability paper.

2.3 Towel Durability Study at Miami University

At Miami University, some progress toward developing objective tests of cohesive durability was made. First, a less subjective “scrub tester” by Coffin, compared to the panel ranking method, was developed to measure cohesive durability of towel. Secondly, a series of observational studies were performed to understand the physics of towel failure in scrubbing conditions. Both outcomes of these studies are used within this thesis, and therefore shall be discussed in more detail.

2.3.1 The Scrub Test

As a result of the previous work [14], the scrub tester, shown in Figure 5, was developed at Miami to evaluate cohesive durability of towel. A description of this method is presented to illustrate that it is more objective and the panel ranking test.

(a) Towel sample sandwiched between carpet and rubber backing
(b) Mount where added weight to be placed upon
(c) Rotor
(d) Shaft; linking the rotor to the mount, to drive linear oscillations

Figure 2-2: View of Scrub Tester (Developed by Miami University)
To measure the durability of a dry towel, a sample of towel is fitted on the base of the mount. Weights may be added on the mount as well, so that the normal force between the towel and the carpet surface is increased. Once the sample is prepared, the shaft that connects the rotor to the mount drags the attached towel sample across a carpet in a linear oscillatory motion. Carpet was used as the rubbing surface because it is a household substrate that offers substantial resistance to the towel.

The towel surface is checked for failure by simply stopping the motor and visually inspecting the surface of the base. Once failure has been detected, durability is measured by the number of oscillations taken before towel failure. While the scrub test is a good method of quantifying towel durability, its measurement still does not provide insight on the physics involved in towel failure. Meaning, it does not provide any fundamental measures of the forces involved in the action. This test however, was used in this thesis to compare to the Tear-Peel method.

2.3.2 Observations on the Mechanisms of Towel Cohesive Failure

The work of Coffin [14] was used to formulate the hypothesis that was tested in this thesis. Coffin hypothesized that peeling and tear strength in both wet and dry states may contribute to the durability of rubbing with paper towel. He explained that when a towel is rubbed on surface, failure is initiated by the liberation of its Free Fiber Ends (FFE) liberate. Figure 2-3 shows protruding FFES that extend out of plane when the towel was rubbed on a carpet surface. As rubbing continued the FFES liberate and roll among each other, as shown in Figure 2-4.

Figure 2-3: View of free fiber end on towel surface[14]
As the FFEs roll between the surface and paper towel, Coffin observed that they clumped. As rubbing continued, the liberated fibers pull adjacent fibers within the ply to simultaneously initiate inter-ply peeling and intra-ply tearing, illustrated by Figure 2-5.

Finally, once the roping on the first ply occurred, the second ply became exposed to the same conditions as the first ply, resulting in total failure of the two plied paper towel.

Based on the cohesive failure progression observed by Coffin, it is arguable that the combination of peeling and tear resistance has a dominant effect on the cohesive durability of towels when they are wiped. To prove how much the tear-peel resistance has an effect to towel’s cohesive durability, an objective tear-peel test method would be required. The next section reviewed literature for a tester that mimics the tear-peel phenomenon.
2.4 The Search for a Tear-Peel Test

The need for a simultaneous tear-peel tester became evident in order to test paper towel, however no such testers were found. There are many tests that either measure peel strength or tear strength, but not both. Hence, this work developed a tear-peel tester. A brief review on the state of art for peel and tear testers is presented because they provide insight to the development and measurement technique used in the tear-peel test that this thesis proposes.

2.4.1 Peel Test Setup and Measurement

The peel test measures the strength required to pull apart a bonded surface [15]. There are three modes of peel failure, as illustrated by Figure 2-6.

![Figure 2-6: Modes of ply failure][16]

Out-of-plane mode I peel failure was of particular interest in this thesis because it mimicked the type of peel failure seen in roping. Therefore six of peel tests associated with mode I failure, as shown in (Figure 2-7) were examined.
During preliminary testing, three test rigs were built to understand their capabilities and limitations, in terms of convenience and potential to be modified for tear testing. The first rig was built to emulate the fixed arm peel, the second a T-Peel and, the third a climbing drum peel, shown in Figure 2-7. They were all mounted on a Universal Tester [30]. The fixed arm peel test showed promise because of its relative simplicity in test setup compared to the climbing drum. The climbing drum peel proved inconvenient to set up samples because of its geometric nature. The T-peel was arguably the easiest test to perform, but similarly to the climbing drum test, its capability to simultaneously measure tear resistance was deemed unfeasible. The fixed peel arm test was the only test that was later modified so that peel and tear strength measurements could be evaluated.

An explanation of the fixed arm peel test and characterization of peel strength is presented. In a study by Zhao [17], the fixed arm peel test was used to study peel the behavior of peeling Pressure Sensitive Adhesives (PSA) from paper. Typically, the peeled substrate is peeled from a hard surface. However in this case, the tape substrate was peeled from a paper sample. Figure 2-8 illustrates the fixed arm peel test setup.
In this test setup, Zhao investigated the peel behavior from peeling a test tape from a paper sample. The paper sample was stuck onto a double sided tape, which was stuck to a hard backing metal plate. A universal tester was used to induce peeling from the tape-paper system at a fixed angle, $\theta$ (shown in Figure 2-8).

The test setup in Figure 2-8 produced the following idealized peel load-peel distance curve when it was tested.

The main characteristic of the peel for curve was explained in the following way. The peak force, $F_p$, is the force required to initiate peeling. The steady-state peel force, $F_{ss}$, corresponds to the mean force value to continue peeling propagation. $F_{ss}$ is the typical...
parameter used to characterized peel strength [7]. The other parameters such as $D_i$ and $D_t$ were typically ignored from the analysis because initial peel was not examined.

2.4.2 Peel Models

Over the years, mathematical [18-22] models have been developed to present how several factors such as peel angle, peel rate, and elastic modulus of the peeled material affect the peel strength measurements [17]. Rivlin [23] was first to document the relationship of fixed peel angle to peel strength at a given peel velocity by:

$$\frac{P}{b} = \frac{G_c}{1 - \cos \theta}$$  \hspace{1cm} (2-3)

Where $P$ is the mean steady state force as peeling propagates, $G_c$ is the surface energy, which is the energy required to de-cohere a unit area of the bonded surface. $b$ is the fixed width of the tape. Recall, $\theta$ is the peel angle illustrated in Figure 2-8. $G_c$ is found empirically by varying peel angle as shown in Figure 2-10 (b) and depending on the adhesive properties of the peel bond, $G_c$ varies as the rate of peeling changes. This is shown in Figure 2-10 (a).
Figure 2-10: (a) Plot illustrating that peel strength varies with peel rate, (b) Master curve illustrating peel strength as a function of peel rate and peel angle [24, 25]

Figure 2-10 (b) shows that $G_c$ can be determined by varying several peel angles. Both plots also indicate that $G_c$ increases with peeling rate at a fixed angle, see Figure 2-10 (a). Notice that as the peel angle increases, the peel strength decreases, however the $G_c$ of the adhesive remains constant.

Another factor that influences peel strength is the elastic modulus of the peel arm. When using Equation (2-3) with the $180^\circ$ peel test, the crosshead extension should be monitored so that it is twice as long at the peel extension for it to agree with Equation (2-3). If the peel arm length is longer than the peeled length, an extra energy contribution from stretching the peel arm must be accounted to the total peel energy. This phenomenon was noticed by Kendall when the peel strength deviated from Equation (2-2) with lower peel angle. Kendall modified Equation (2-3) to account for the elastic effect of the peel arm. The plot below shows that the model compares well to experimental results [30].
Figure 2-11: Plot illustrating the influence of stretch in the peel arm to peel strength [25]

In Figure 2-11, the experimental curve shows that as the \((1 - \cos \theta)\) term decreases, so does the peel strength, but it deviates from the Equation (2-2). The model used to represent the physical relationship of the peel system to the measured peel strength is given by [25]:

\[
G_c = (1 - \cos \theta) \frac{P}{b} + \frac{P^2}{2b^2 \varepsilon}
\]

(2-4)

Where \(E\) is the elastic modulus of the tape and \(h\) is its caliper.

There are several other models that account for the influence of other variables, (ie pre-stress of the tape). However, the information presented in this background was the most important for the experiments conducted in this thesis. The next section reviews the tests available for tear test and how they are analyzed.

2.4.3 Tear Test and Analysis

The tear test measures the strength required to tear paper. Similarly to the peel test, several tear tests exist to measure the end-use failure modes of the sample [26, 27]. Common tests for out-of-plane tear failure, known as mode III failure, include the Elmendorf and the Brecht-Imset tester.
Particular attention was paid to the Tensile Tear developed by Yamauchi and Tanaka [28] because of its ability to keep a constant tear angle and allow for monitoring of the crack tip status. Figure 2-12 shows its similarity to a Trouser test, except that a backboard is used to maintain a $180^\circ$ angle. Results of the Tensile Tear test correlates well with the industry accepted Elmendorf tester.

![Figure 2-12: Sample setup for Tearing Tensile Test](image)

Figure 2-13: Tear load-time curve and correlation of Elmendorf [29]

Figure 2-13 (a) shows the typical load extension curve of tearing paper that was setup in (b) Shows the correlation between tearing paper using the universal tester versus an Elmendorf tear test [29].
Yan [29] reviewed existing models for the tearing of paper [29] and found most were statistically derived. Yan developed a mechanistic model to describe the results obtained from the Elmendorf tester [29]. His results yielded that tear index is a function of three dimensionless parameters of a sheet of random network of fibers. These include fiber strain, the ratio of frictional resistance to debond strength, and the ratio of fiber length to critical length (which are dependent on bond strength and sheet density).
3 Problem Statement

3.1 Problem Summary

Simple quantitative test methods are needed to better understand paper towel durability. Direct scrub testing does not easily allow one to attribute the contribution of various towel features to durability. Observations of towel failure during rubbing indicate that intra-ply tearing and inter-ply peeling both occur. Peel and tear resistance of a towel may play a significant role to the dry cohesive durability of towel. Investigation of the tear and peel behavior of paper towels may lead to better insights into durability and ultimately lead to improved product design. Currently no adequate test methods for tearing and peeling of paper towels exist.

3.2 Objective

This work will investigate the hypothesis that tear-peel resistance is correlated to cohesive durability. Before this hypothesis can be tested, a method to measure the tear-peel resistance of paper towels needs to be developed since no such test exists to the author’s knowledge. The scope of this work was limited to evaluating the cohesive durability for 1 ply and 2 ply dry towels. Therefore, the objective of this thesis is as follows

Objective: Develop a tear-peel tester capable of quantifying the resistance of a paper towel to combined or separate actions of intra-ply tear and inter-ply peel.

3.3 Approach

The approach taken to meet the objective was as follows:

- Two tear-peel testers were developed in this work – a prototype and a final tear-peel tester. The prototype tear-peel tester was built to determine if the approach taken was feasible and allow for a parametric study of test variables. (Chapter 5). The final tear-peel tester was developed to provide a
simple apparatus that can be used to evaluate different towels and determine peel, tear, and tear-peel energies.

- Based on the results of the parametric evaluation, a suggested standard method was determined for the sake testing towel at the most convenient means for the user. The standard method was then used to compare the tear-peel resistance to scrub resistance of six different towel types. The correlation was between the two test methods was strong, indicating that tear-peel resistance may lead to insights into cohesive durability and justified developing the final prototype. (Chapter 0).

- The final tear-peel apparatus was built to set up easier test runs for the user. A statistical T-test was then conducted to validate that the results of the standard method using the prototype tester was similar to the results of the final tear-peel tester. Lastly, twenty-three commercial towels were evaluated using the standard method against the results of the scrub tester.
4 Development of the Tear-peel Test Apparatus and Method

4.1 The Prototype Test Apparatus

The main design objective of the tear-peel tester was to capture similar peel and tear failure modes to that of the macro roping feature discussed in Section 2.3.2. After considering various designs for tear-peel, including mounting the sample to a rotating cylinder or flat plates, it was decided that 180 degree pulls of a section of the towel mounted to a flat plate could be used to simultaneously induce tear and peel in the towel. Figure 4-1 shows the prototype design used to simultaneously capture inter-ply peel and intra-ply tear failure on a 2-ply towel sample. The apparatus is used in a universal testing machine (Instron).

Figure 4-1: View of the prototype apparatus as it peel and tears a towel sample

A sample of towel is attached to a flat plate using double-sided tape. As shown in Figure 4-1, two guides are used so that only the middle section of the towel can be deformed. The peel arm is attached to the top ply of the towel at the bottom edge and then gripped to the Instron’s top grip at the other end. As the crosshead of the Instron rises, the connecting peel arm moves upward. The towel and sample holder are held fixed in the lower grip of the Instron. The action causes the top-ply of the towel to both peel and tear. The two guides in conjunction with the peel arm promote tearing at the edge of the guide.
The basic dimensions and specifications of the prototype tear-peel tester are given in the schematic shown in Figure 18.

![Illustration of tear-peel tester dimensions and examples of 1" and 2" tear-peel widths]

(a) Holes on the base for setting 1” tear-peel widths

(b) Holes for alignment of the tear-peel widths

Edge where peel arm edge is placed adjacent to towel edge

Edge for placement of peel arm

Figure 4-2: Dimension of tear-peel tester and example of 1” (a) and 2” (b) tear-peel widths

The prototype allows flexibility in sample mounting and test parameters. For example, the width test parameter of the peel-section can be varied. This is illustrated in Figure 4-2 (a) and (b), which depict how the guides can be aligned with the holes on the base so that 2” and 1” tear-peel widths can be set. The speed of movement can be varied. The peel-arm can be varied. In addition, the sample can be mounted with different orientations of the machine direction of the paper with respect to the tear direction. The next section outlines the sample mounting for the prototype tester.
4.2 Sample Preparation

The suggested procedure for performing the tear-peel test, for one and two-ply dry towel, on the prototype tear-peel apparatus is presented. The suggested procedure is described first to aid as a reference for method adjustments made in the parametric evaluations. The specification of this method (i.e peel extension rate, tear-peel width etc) is justified in Chapter 0. The suggested procedure is shown in Table 4.1.

Table 4-1 : Standard Procedure to evaluate cohesive durability of dry towel

<table>
<thead>
<tr>
<th>Step</th>
<th>Explanation</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A 2.5 inch wide double-sided tape was applied onto the base plate surface (Figure 4-3) and then the towel sample was applied onto the upper surface of the two-sided tape (Figure 4-4).</td>
<td>Holes placed for exact tear peel width dimensions</td>
</tr>
</tbody>
</table>

Figure 4-3: Placement of the double sided tape

Figure 4-4: Placement of two ply towel sample on double sided tape
The two guides were placed to allow a 1” tear-peel section to be exposed (Figure 4-5). The guides were fastened by wing nuts and screws so that the towel is sandwiched. The wingnuts were fastened from protruding screws.

5” of one sided tape was attached to the top ply of towel sample. 4” of the tape was laid up the towel sample and 1” of the tape was attached to the edge of the metal bar (Figure 4-6).

A weight was used to press the tape to the towel sample. By pressing the tape onto the towel ply, adequate adhesion could be obtained to the towel’s top ply (Figure 4-6).
The metal bar was folded back along the top surface of the towel. The top end of the peel arm was then attached to the Instron’s top grip.

In the mounting procedure given in Table 4-1, the towel sample width is shown as one inch. It is important that the towel lay flat against the tape. The adhesion between the bottom-ply of the towel and the tape must be sufficient that peel is induced between the two plies. To evaluate a 1-ply towel, only a tear test was conducted since it does not have a second ply to peel off from. The only modification to the standard method for a 1 ply was to skip step 1, where the double sided tape is applied. This is done because the double sided tape is not need to hold the sample to the base. All that would be left to do is to lay the single ply towel and sandwich it against the backing with the guides.

For the prototype tester, the peel arm was chosen to be a one sided tape. Its purpose was to connect the top ply of the towel sample to a metal bar that drove the towel to peel and tear (see Figure 4-1). The metal bar was also attached the top grip of the Instron, which controlled the peel extension and extension rate. The metal bar (plate) was chosen primarily because of its fixed length, reducing the complexities of slack once its top end is attached to the universal tester’s grip. Other materials like a rope would slack, which adds complexities when analyzing results. The next section presents how the standard test is run to capture data from the tear-peel setup.
4.3 Execution of the Tear-peel Test

After the sample was mounted into the Instron, the tear-peel test was ready to be run for the collection of load-extension curves and their corresponding energy calculation. To run the test and collect data, a subprogram within the Merlin Software Application was used. The subprogram named “Tear-Peel Test” was a customized version of a standard peel test (ASTM D903), a preinstalled program part of Merlin Software suite. Among the customized features of the Tear-Peel Test was its ability to vary crosshead extension rates, vary crosshead extension, and calculate energy from different limits of the load-extension curve.

The standard test settings, determined after conducting the parametric study given in Chapter 6 are as follows: a crosshead extension rate of 100mm/min up to a crosshead extension of 200 mm and a one inch peel width. The procedure to adjust these test settings can be found in Merlin’s Operator’s guide [30]. While no controlled adjustments were made to the humidity and temperature of the test lab, they were recorded because papers typically have a dependency to environmental temperature and humidity.

Figure 4-8 captures an instance during a tear-peel test run for a three-inch wide peel width. As the Instron’s crosshead extends, so does the peel and tear extension.

Figure 4-8: Front view
Observations are made during the tear-peel test to note if the tear is along the guide edge and if the leading edge of the peel is perpendicular to the direction of motion. The desired result is that the tear stays along the edge and the peel is uniform (see 4.4 Data Analysis). During the test both the cross-head extension and the force on the load cell are collected. The rate of data collection is 60 data points/minute. This allows for 60 data points for the 100 mm peel extension at a rate of 100 mm/min. The force and peel extension data is saved for later analysis.

4.4 Data Analysis

After the test was run, a visual inspection of the sample was made similar to that shown in Figure 4-9. This sample was deemed as ideal because it had negligible wiggle-like tear paths, which means most of the desired tear-peel mode was captured. In rare cases, severe wiggle tear paths occurred. Data from those cases were excluded from the results.

![Clean tear and peel](image1)

![Imperfect tear-peel](image2)

(a) Clean tear and peel
(b) Imperfect tear-peel

Figure 4-9: Tear and Peel paths (a) An ideal test sample that is cleanly torn at the edges
(b) a wet sample showing a very uneven tear and peel path

The procedure for data collection and analysis for the good test sample follows. At the end of the test run, the data was exported to MS Excel and load-extension curves were produce in order to appreciate the nature of the samples tear-peel behavior. A mean and coefficient of variation curve was then produced from the result of 5 runs, shown in Figure 4-10.
In this example, the mean curve and coefficient of variation curve were appreciated in the following way. The mean curve had somewhat of an oscillation around a constant average load. The average coefficient of variation for this sample was around 20%, was relatively high, but not unexpected for tissue products.

The energy consumed during the tear-peel test, from crosshead extension 10mm to 200mm was also calculated as the area under the load-extension curve. The reason energy was calculated from 10mm to 200mm is discussed in Chapter 6. It was this energy measurement that was correlated with the scrub test to determine if tear-peal resistance had a relationship with cohesive durability for dry paper towels.
5 Results: Parametric Evaluations

5.1 Experimental Objectives

In this chapter, the experimental results of a tear-peel parametric evaluation are presented. The aim of the parametric evaluation was to determine the relevance of measured quantities, the influence of variables, and the uncertainties of tear-peel measurements. Instead of parametrically evaluating many towels, only two control towels (with durability performance at two extremes) were used. By using only two towel samples, one with the highest and one lowest subjective scrub durability, then the results of the parametric studies were thought to accommodate all the other towels that fall within two extremes of scrub durability for dry towels.

Table 5-1 lists the parameters tested to investigate a variable’s influence on peel tear results. As shown in the table, the tests are broken down into three categories: test setup, end-use operation influence, and towel structure influence. The test parameters specific to the method include number of tape layers, crosshead rate, width of section, initial tear length, and whether the test is peel, tear, or both. The tests that pertain to the structure of the towel involve MD/CD direction or top or bottom side of towel being rubbed. The detailed motivation for their investigation is addressed in their corresponding sections.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameters</th>
<th>Standard</th>
<th>Test Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of tape</td>
<td>5-25 @ 5” intervals</td>
<td>5”</td>
<td>Test Setup</td>
</tr>
<tr>
<td>Layer or Tape Setup</td>
<td>1-5 tape @ 1 tape intervals</td>
<td>1</td>
<td>Test Setup</td>
</tr>
<tr>
<td>Sample width</td>
<td>1”-5” @ 1” intervals</td>
<td>1”</td>
<td>Test Setup</td>
</tr>
<tr>
<td>Crosshead rate</td>
<td>100 – 500 min @ 100mm/min intervals</td>
<td>100mm/min</td>
<td>Operation</td>
</tr>
<tr>
<td>Tear-peel crack initiation</td>
<td>0 – 4” @ 1” interval</td>
<td>0</td>
<td>Operation</td>
</tr>
</tbody>
</table>
The test setup variables were investigated to determine how they affect the force measurements during the peel-tear test. The length of tape was varied so that its weight can be accounted for as the peel arm length increases during the test. The layers of tape were varied to account for the tapes bending stiffness. Operational variables attempted to mimic the end-use operations a towel goes through during wiping and scrubbing. The crosshead extension rate mimics the speed of scrubbing, and the tear-peel crack simulates the mechanical response of a towel that already has a degree of tear-peel failure. Towel manufacturers adjust the structure for optimized performance. Therefore, the sample orientation and both plies were tested to see how the affected tear-peel measurements.

### 5.2 Calibration of Instron Universal Tester Measurements and Settings

The parametric tests in Table 5-1 required the Instron to vary its crosshead extension, crosshead rate, and measure load. Calibration tests of the Instron were therefore conducted to assess the accuracy and precision of its test settings and measured load data. The calibration experiments were performed on the Instron’s: extension setting, extension rate, force measurements, data collection rate. The calibration tests and analysis are presented in the Appendix. The results from the calibration experiments suggest that the Instron Universal tester had sound accuracy and precision suitable for the required experiments. The most important information about the uncertainty of the Instron tester is that the load measurements had an 95% confidence interval uncertainty of 20mN. Other measurements such as extension and extension rate were so much more precise than the tools used to calibrate them, that their uncertainties were unaccounted. It was fair to conclude that the extension and extension rate settings were very precise and accurate since this equipment is a standard in industry tests. Experiments in the following
section were performed to identify how the components of the tear-peel apparatus affect measurements.

5.3 Apparatus Influence on Tear-Peel Measurements

One of the most important apparatus used in the tear-peel test was the front tape. As the front tape assists the towel to peel and tear it adds weight to the load cell, the front end peel bends, and it undergoes strain from the tension between the towel sample and universal tester’s grips. In this section tests were performed to determine how much different aspects of the tape influences tear –peel measurements.

5.3.1 Length of Tape

As the Instron’s crosshead extends the peel front, it has to carry the weight of the tape. Experiments were performed to assess how much the load of the tape influences the tear-peel measurements. A balance was used to measure the load of the tape. The relationship between the tape’s load and its length was obtained, as shown in Figure 5-1.

![Figure 5-1: Weight curve of front tape length using mass balance.](image)

As seen in Figure 5-1, at a length of 600mm the tape’s load of 14.1mN will have a negligible effect to the Instron’s load measurement since the Instron has an uncertainty of 20mN (from the calibration tests in Section 5.2). The plot however does provide
information on the good uniformity of the tape because it had a linear dependency of mass on tape length ($R^2=0.99$).

This study provided evidence that the tape’s weight contribution in the standard method was insignificant compared to the towel tear-peel measurement. The data collected was useful in determining the tape’s load in other experiments, such as Section 5.5, where tape lengths were varied.

5.3.2 Elastic Energy Contribution

Recalling Equation (2) where,

$$G_c = (1 - \cos \theta) \frac{P}{b} + \frac{P^2}{2b^2 Eh}$$

It shows that apparent peel energy $G_c$ can be contributed by the tape-towel elastic energy (the second term). For the peel results to truly represent the energy required to break peel bonds, the second term of the equation must be much smaller than the first. This translates to the fact that the elastic modulus of the tape-towel composite must be very large. Therefore, the stiffness of the towel-tape composite was investigated.

The elastic stiffness was determined by using a standardized tensile test for paper (ASTM D828 – 93), which was pre-loaded from the Merlin software. Figure 5-2 shows the tensile load-extension curves of the two towel samples alone (a and b) and when they are adhered to the tape (c and d).
Stiffness values were calculated from the slopes of the load extension curve, before the yield point. Although the stiffness of plots a and b show that the two samples differ quite considerably, c and d show that the stiffness of the tape-towel sample have a small percent difference of 1.5%. It appeared that the tape’s stiffness dominated that of the towel. Upon evaluating the slopes of c and d, the mean stiffness of the towel-tape composites was $16.95 \pm 1.42$ N/mm. By employing equation 2, the average peel strength values (obtained from section 5.5.2) and the stiffness value of the tape-towel were used to
compare the energy contribution for the first and second term. The second term was found to be only 0.24% of the first term in Sample A and 1.27% in sample B. Therefore, because the differences were less than 5% for both samples, the elastic component can be ignored in the interpretation of measured energy.

5.4 Parametric Evaluation I – Related to Rubbing Operation

5.4.1 Effect of Towel Orientation

The effect of the towel’s orientation on tear-peel resistance was tested to investigate if rubbing in a particular direction affects tear-peel resistance. As shown in Figure 5-3 the towel’s orientation was referenced to the CD direction of the towel. Note, CD was considered as the side that did not have towel perforations.

Figure 5-3: Reference angle used for orientation variation (where CD=0 and MD=90)

The plot in Figure 5-4 was used to infer that orientation of towel does not significantly affect its tear-peel resistance.
The plot in Figure 5-4 illustrates the tear-peel resistance of the two towels orientation is varied. This conclusion was inferred because for both samples, the slopes were relatively low. This suggested that towel orientation does not have a significant effect on its tear-peel resistance.

5.4.2 Effect of Velocity

Users can rub towels at varied velocities, and the test setup allows for different rates of extension. Therefore, the influence of velocity parameters on tear-peel resistance was investigated. To carry out this investigation, most of steps of the standard method were followed with one exception of changing the crosshead extension rate. The parameters of extension rate effect on tear-peel energy, ranged from 100mm/min to 500mm/min. The particular velocity parameters were chosen for several reasons. First, to
match the velocity ranges a user might rub towel, to complement the velocity ranges of
the scrub test, and because of the limitation of the universal tester. The velocity affect on
tear peel is shown in Figure 5-5.

The results in Figure 5-5 showed that both samples had very small slopes and low $R^2$
values to make an inference that peel velocity had no effect on peel-tear strength. This
result appears contradictory to the peel results shown in Chapter 2.4.2. This apparent
contradiction may be because in this test, all the velocities were at the same magnitude,
whereas Figure 2-10 (a) was for different magnitudes.

In hindsight, collecting more amounts of velocity data for a full range of velocity
magnitudes (ie 0.001mm/min, 0.1mm/min to 10000mm/min) might have been beneficial
for gaining insight on the nature of tear-peel force-velocity relationship of the ply bonds.
Nonetheless, the velocity ranges tested are still useful because they relate to the typical
velocities a towel is scrubbed at by an end user. Therefore, one can conclude that tear-
peel rates at the chosen ranges are insensitive to tear-peel strength.
5.5 Parametric Evaluation II – Influence of Towel Structure

5.5.1 Influence from varying tear-peel width

In this section, the response of the tear-peel resistance to towel width was investigated. The widths were varied in one-inch increments by simply applying the 1” wide tape adjacent to one another. Figure 5-6 illustrates an example of a 1 inch and 3 inch tear-peel width.

![Figure 5-6: Example of tape setup for varied widths. In this case (a) is 1” and (b) is 3”](image)

For setting up tear-peel widths larger than one inch, an example to setup a 3 inch tear-peel width is presented. In the case of a 3 inch width set up, the first step was to cut one strip of tape to a length of three inches. It was placed under the peel arm, as shown in Figure 5-7.

![Figure 5-7: Prior step before placing front tapes in Figure 36 b on top of towels](image)
The next step was to lay 5” long strips of tape adjacent to one another as shown in Figure 5-6 b. Recall from the standard test that 1” of the 5” long tape is overlapped with the tape in Figure 5-7. This would leave 4” of tape applied on the towel surface. Figure 5-8 shows the effect of adjusting tear-peel width on peel tear resistance.

![Figure 5-8: Effect of Width Variation on Tear-peel Energy](image)

The plot in Figure 5-8 relates the total energy absorbed for the 100mm tear-peel length to the tear-peel width variation. There are three arguments were produced from this plot. First, the slopes were argued to provide information of the sample’s peel energy per width, because the only variables varied were peel width and the number of tapes adjacent to one another. Secondly, the same slope values were argued to possibly account for energy contribution provided by the tape, particularly in bending. Lastly, the intercept of the curve implied that it should be the tear energy of the sample. The answers to these argument were further investigated the next section.
5.5.2 Influence of Peel Only Resistance

To test the first argument provided from the tear-peel energy tests in Section 5.5.1, a peel only test with varied width was conducted. To perform the peel only test, the general procedure was followed from section 5.5.1 except the sample width was pre cut for a length of 100mm so no tear failure was observed. The following response was obtained.

![Graph showing the effect of width variation on Peel Only Energy.](image)

**Figure 5-9: Effect of width variation on Peel Only Energy**

Figure 5-9 validates the first question of section 5.5.2. The slopes of the curves are in fact similar to the peel energy /width of the samples tested in this peel only experiment. Table 5-2 summarizes the slopes are considered similar based on the small level of percent difference between the two parametric evaluations.

**Table 5-2: Percent Difference of Peel Energy obtained from Section 5.5.1 and 5.5.2**

<table>
<thead>
<tr>
<th>Sample</th>
<th>From Ch 5.5.2 (mJ)</th>
<th>From Ch 5.5.1 (mJ)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>29.2</td>
<td>29.073</td>
<td>0.45%</td>
</tr>
<tr>
<td>Sample B</td>
<td>4.764</td>
<td>4.965</td>
<td>-4.2%</td>
</tr>
</tbody>
</table>
However, this plot does not answer what percentage of tape-towel bending contributes to the peel only and tear-peel results. This question is answered by the experiment performed in section 5.5.4. The last question from section 5.5.1 is answered next.

5.5.3 Tear Only Influence

The plot in Section 5.5.1 implied that the intercept of tear-peel curves were the tear energy (for two tear paths) of the towel samples. To validate that claim, towels were un-plied so that they could be tested for only their tear energies. The same procedure of the standard method was followed except that no double-sided tape was used to adhere the base plate to the towel sample. The following tear only energy results were obtained.

![Figure 5-10: Effect of width variation on tear only resistance of ply](image)

As shown by Figure 5-10, the slopes for both samples were relatively small, thus indicating the tear resistance is not affected by width variations. Furthermore, the implication of the intercept from the tear-peel test was validated by the measurement made by the tear only test as observed in the small differences shown in Table 5-3.

Table 5-3: % Difference of tear energy form tear-peel curve and tear only curve
<table>
<thead>
<tr>
<th>Sample</th>
<th>Tear Energy from Section 5.5.3 (mJ)</th>
<th>Tear Energy from Section 5.5.1 (mJ)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>59.99</td>
<td>57.54</td>
<td>-4.26%</td>
</tr>
<tr>
<td>Sample B</td>
<td>30.09</td>
<td>30.19</td>
<td>-0.33%</td>
</tr>
</tbody>
</table>

5.5.4 Tear-Peel Crack Initiation

To determine the bending energy of the tape and sample on tear-pel resistance, the following procedures were carried out. Peel and tear cracks were initiated at various lengths, such as the one shown in Figure 5-11.

The peel-tear crack was initiated at various intervals within 100mm of the sample. The energy determined from the data was for the whole 100mm section, regardless of the peel-tear initiation crack. The results shown in Figure 5-12 were obtained from the experiment.
The x-axis is the length of the 1” wide sample strip that was pre-fractured for both peel and tear. As the pre-fracture length increases, the tear-peel energies reduce as one would expect because there is a reduction in resistance area. At 0 in, it appears no energy was absorbed. That means that there is insignificant energy that is contributed by tape bending. The slopes of the curve reveal the value of peel and tear resistances per length of the sample with a tear-peel width of 1 inch. This tests tear-peel per length energy values were compared to the added tear and peel only energies determined from the other tests (in section 5.5.1, 5.5.2 and 5.5.3).
Table 5-4: Comparison of additive tear and peel energy per length

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tear energy (mJ/mm)</th>
<th>Peel energy (mJ/mm)</th>
<th>Peel + Tear Energy (mJ/mm²)</th>
<th>Crack initiation (mJ/mm²)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A</td>
<td>14.3</td>
<td>7.45</td>
<td>21.8</td>
<td>21.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Sample B</td>
<td>7.5</td>
<td>1.18</td>
<td>8.7</td>
<td>8.1</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The percent difference column shows that there is a small percentage difference with the compared values. This small percentage difference suggests that the additive of results of separate peel and tear energy correspond equally to the results of a peel-tear test.
6 Discussion: Determination of Final Tear-peel Apparatus and Method Specifications

In this discussion, the reasons for the specification of the standard tear-peel test method and final tear apparatus are justified. Abiding by the objective to develop a test that is objective and convenient to the user when comparing many towels, the information gathered from the parametric studies were used to determine the standard methodology and specification for final tear-peel apparatus.

Once the tear-peel standard method was determined (i.e. tear-peel width and peel rate), in Chapter 4, it was used with the prototype to obtain tear-peel results for 6 towel samples. The same samples were tested by the scrub test. Both test results were correlated to prove the relationship of tear-peel to cohesive durability. As shown by Figure 6-1, the correlation results from the prototype tear-peel tester and the scrub test showed a good agreement because they had a $R^2 = 0.9$.

![Absorbed Energy vs Number of Rubs to Ply-Failure](image)

$y = 5.5217x + 13.178$
$R^2 = 0.9009$

Figure 6-1: Correlation between standard tear-peel test method and Scrub Test
Because of the good correlation results, this set the green light to build a final tear-peel test with modified specifications from the prototype test, so that could be easier to test many towel samples. The reasoning behind the determined specifications for the final Tear-peel tester is discussed below.

6.1 **Data collection rate**

A suitable data collection rate was set to 1 second intervals; this was set for convenience in two aspects. First, it recorded the load at every millimeter so that one can look back at the sample and notice how the load corresponded to the state of towel structure at that particular point. Secondly, 50 data points were deemed reasonable enough to appreciate the resolution of the load curve yet small enough for MS Excel to handle without any processing retardation.

6.2 **Crosshead Extension and rate**

The crosshead extension of 200mm and rate of 100mm/min were chosen as the parameters of the standard test. The 200mm extension line was chosen because it allowed for a relative large tested area relative to the space constraints of the Instron tester.

The results in 5.4.2 show that tear-peel energy results do not vary with velocity. 500mm/min should therefore have been an ideal test setting because it would help finish tests faster. Instead, 100mm/min was chosen as the standard rate because there was more information about its affect with other variables than there was with 500mm/min. For example, the orientation experiments and the width variation experiments were all tested with the 100mm/min extension rate since it was deemed as the default rate in the experimental program.

6.3 **Tear-peel width**

A 1 inch wide tear peel width was chosen as the parameter for the standard method primarily because of convenience. It was easier to apply one tape over the towel than two or more. The justification of using the 1” tear-peel width is also based from the parametric results. In section 5.5.1, the tear peel width of towel was varied and thus the energy results responded linearly width. This meant that the 1” parameter was a reliable parameter for capturing towel tear-peel energy results.
6.4 Tear-Peel Orientation

Towels can be rubbed in different directions, however the tear-peel resistance was found to be insensitive to orientation. Therefore, the MD direction was set as the orientation of the standard tear-peel method. Other orientation would have suited equally, but MD was picked arbitrarily.

In summary, a standard method for the tear-peel test was developed for convenient tear-peel testing of towels. Parameters such as tear-peel width, speed, and orientation of were suggested for testing towel. The tear peel width was set to 1”, the speed 100mm/min, and orientation at the MD direction.
7 The Final Apparatus and Procedure

The final design and fabrication of a tear-peel tester was carried out based on discussion presented in Chapters 6. The goal was to have a set-up that was sturdy and simple to use. Like the prototype it was designed to be used with the Instron universal tester. Unlike the prototype it conducts peel-tear test of only one width.

Figure 7-1: Overview of Equipment and Setup for Tear-peel tests

7.1 Equipment Introduction and their specifications for the Tear-peel Test

As shown in Figure 8-2, tear-peel mount was fitted on to the Instron Universal tester’s base. The base provided the ability of placing the mount at the same placement. The Instron Universal tester was used to set up test conditions, measure of load, and calculate tear-peel energy. The Instron’s load cell measurements were captured from the Merlin software that operated on a PC console. Towels can be affected by environmental temperature and humidity. Therefore the Acurite tool was used to monitor the conditions of the room. Detailed tear-peel tester standardized method was determined from results of a parametric evaluation conducted with a prototype tear-peel tester (Chapter 5).
However, for now, the standardized procedure developed to measure tear-peel resistance using the final apparatus, is presented.

7.2 Test Setup

Step 1: Installation of Tester’s Base

The area of the universal tester (1) supports the base (2) of the tear-peel apparatus. Four of the screws were screwed in by an Allen key in the appropriate holes as shown in (2).

Step 2: Mounting the towel sample for Tear-peel Testing

First, a double stick tape is laid upon the surface (1), of which a 4” X 4” towel is stuck upon it (2).

The two guides are then laid on top of the towel sample (3) and clamped down by using the four hinges (4).
Scotch tape is placed over the towel sample (5) and the peel arm, which is then folded back (6).

The body of the tear-peel tester is then slid across the channel of its base (7), until the two holes are aligned and secured by the push pins (8).
The string is secured by the universal test’s grip (9) with minimal slack.

![The sample is ready to be tested for its tear-peel resistance. The results of using the final tear-peel tester are presented in the next chapter.](image)

9.

The sample is ready to be tested for its tear-peel resistance. The results of using the final tear-peel tester are presented in the next chapter.
8 Results: Correlation of Final Tear-Peel Tester

There are three main results that were provided by the tear-peel test apparatus. First, sixteen towel samples were evaluated and ranked in order of their tear-peel energy. Second, the influence of towel embossment bonds was measured by the tester. Lastly, the tear and peel energies of towel can be separated to develop better insight of which component provides the most resistance to tear-peel energy.

8.1 Tear-Peel Evaluation

Sixteen commercial towels were evaluated by the final tear-peel test apparatus. Their evaluation technique was followed by the standard method that was presented in Chapter 7. Figure 8-1 shows the tear–peel resistances of the towel sample in descending order.

![Figure 8-1: Tear-peel energy of commercial towels (in descending order) 5 runs per sample](image)

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Important inferences were gained from this chart. First, the bar chart shows that towels can vary significantly from their tear-peel energies. Such is the case with sample 10 and sample 1, which had mean tear-peel energies from 42.96mJ to 388.97mJ respectively. This suggests the capability of the tear peel tester to measure a wide range of towels. The global perspective of the chart indicates that the tear peel of the towels is very close to one another (especially from sample 3 to 14).

In terms of the uncertainty of the energy data, one can see that the tear-peel energies of towel can vary widely also. For example the standard deviation for sample 10 and 5 compare significantly different from samples 1 and 15. An investigation to the cause of this contribution is discussed in Section 8.2.

8.2 Ability to evaluate peel peaks

In Figure 8-1, it was found that some towels, such as sample 1, 7, 12, and 15 have unusually high variances compared to other towels. These uncertainties were found to be a contribution from the towel not the apparatus, specifically from the embossing of the towel. This conclusion was found by investigating the resistances of tear and peel separately. The investigation yielded information that suggested that peel energy is contributed by resistance from the embossing. It was found that in all towels, the embossing were used to bond plies of two-ply towel are bonded.

To measure the force contribution of the embossed patterns, the data collection rate of the Instron was set so that it collects data just as the embossed area is peeled. Figure 8-2 is an example of a chart that corresponds to the peel force of the embossment.
Figure 8-2: Force Contribution of Embossing

The peaks of the chart correspond to the resistance of the embossment pattern highlighted in red. The blue line indicates the critical force that most of the embossing peel. Another test was conducted to evaluate the influence of a set of embossment, such as that in Figure 8-3.

Figure 8-3: Superposition of small peaks
The peaks in the load-extension plot correspond to the row of embossment in the towel. One can see how the three-peak series correspond to the three rows of embossment. This phenomenon provided added evidence that embossments play a significant role to the peel energy of towel. They also play significant role to the variance in energy data. Towels with complex embossing patterns produced varied energy measurements – some more than others. This was the case with samples such as sample 15. It was a challenge to test exact replicates of a sample with the same embossing. Therefore some runs of a sample may have had more embossed areas while other may have had less embossed area. This inconsistency was inferred to be the cause of the variances in tear-peel energy.

8.3 Separation and Superposition of Tear and Peel Energies

The last contribution of this thesis was to prove that tear only and peel only resistances can be superimposed to tear-peel measurements. Figure 8-4 shows and example of superimposed tear and peel only energies compared to tear-peel energies for width of 1” and 5”.

![Figure 8-4: Peel & Tear Energy Contribution for 2 samples of 1" & 5" (mean of 5 trials)](image-url)
The data from this plot suggests that tear and peel only tests can be added together and compared to the tear-peel results. One can see that for each sample, the tear energies remain constant, regardless of tear-peel widths. The peel energies on the other hand, increase with added area. The dependency of peel energy to increased width corresponds to the slopes obtained in the parametric evaluation.

The separation of tear-peel energy is the most unique feature of the tear-peel tester. At the present time, tester either measure peel energy or tear energy but not both. This all-in-one feature of the tear-peel test makes it easier for the evaluation of many towel samples. But it also provides more full information of a towels peel and tear resistance.
9 Conclusion

9.1 Main Summary

- A novel, fully working tear-peel test apparatus was developed in this study. The apparatus can be utilized to determine the energy required to propagate either intra-ply tear, inter-ply peel, or a combined mode of failure. Other features of the tear-peel tester offer the flexibility of testing towel at varied orientations and tear-peel speed.

- For embossed paper towels, the resistance to peeling is provided at the embossed locations, which is where the two plies are bonded together.

- Results for peel and tear measured individually could be added to yield very similar results to a test where peel and tear were combined together.

- By varying the width of the tear-peel test and plotting energy versus width, the slope of the line provides a measure of peel durability and the y-intercept provides a measure of tear durability.

- With the use of a single layer of tape, bending and stretching energies are likely to be negligible for most towel samples.

- The results of combined tear and peel correlated to the scrub durability for several paper towels. Therefore, the tear-peel tester may be useful in studying the scrub durability of paper towels. More testing needs to be carried out to confirm this.

9.2 Future work

- Perform tear-peel resistance studies on wet towel samples. In this thesis, a trial for the tear-peel evaluation of wet towel was investigated; however, no meaningful results were obtained.

- The tape-towel system effectively made the samples stiff. Parametric studies showed that towel stretches easily. More investigation should be conducted to determine the influence of towel’s elasticity to tear-peel results.

- The tear-peel resistance of only 6 towels was correlated with the scrub tester. The scrub tester results should be correlated with the 16 other towels evaluated. Furthermore, correlating parametric results of the tear-peel tester to the results of
the scrub test may provide added evidence of the role tear-peel resistance has to cohesive durability. For example, tear-peel resistance in this study was found to be insensitive to velocity variation from 100mm/min to 500mm/min. More studies should be conducted to conclude if the same phenomenon occurs by varying the velocities of the scrub tester. The same correlation should be performed for orientation and tear-peel width parameters.
References


