ABSTRACT

Z-DIRECTIONAL COMpressIBILITY OF PAPER TOWEL STRUCTURAL FEATURES

by Daniel William Knettel

There is minimal published research on the physical properties of structural modifications that are used in tissue and towel products for the development of end use properties including bulk and absorptivity. This investigation was conducted in order to determine the compressive elasticity of retail paper towel structural features, as well as to develop a relationship between the micro-compressive response of single structural features and the macro-compressive response of paper towels in bulk. The modified micro-compression instrument and an Instron Universal Testing Unit were used to make compressive loading measurements on four retail paper towel samples. Compression experiments consisted of single feature micro-compressions for a single cycle and multiple cycles, multi-feature single cycle micro-compressions, and multi-ply compressions. A compressive scalability model was developed to relate the results of single and multiple feature compressions to those of the multi-ply compression experiments. Relevant physical properties including limiting load and stiffness were determined, and an effective compressive scalability was exhibited by both the CWP-embossments and TAD features.
Z-DIRECTIONAL COMPRESSIBILITY OF PAPER TOWEL STRUCTURAL FEATURES

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1. Introduction

As far as historians are aware, paper was first introduced roughly 2000 years ago for its usefulness for writing and record-keeping. Since then, the use of paper has expanded far beyond that of just a medium for writing. The paper industry now encompasses paper for writing as well as printing, packaging, tissue products, and many specialized industrial applications. With the advent of modern technology, specifically computing and the internet, there were concerns that the need for paper will vanish due to online news, e-books, computerized record-keeping, and personal computer and tablet note-taking, among others. While this might still occur for certain paper grades, an example of which is the decline in newsprint grade production, the continued growth of the market for tissue and packaging products can allay this concern.

Tissue paper, which includes paper towels, toilet paper, facial tissues, napkins, among others, is a multi-billion-dollar market globally. The size and distribution of the global tissue and towel market is illustrated in Figure 1-1. Based on global production, it is apparent that these products are used on a daily basis by millions, if not billions, of consumers. With the rise of the standard of

![Figure 1-1. Global tissue and towel production capacity in finished metric tons by region (Courtesy of Fisher International, 2018).](image-url)
living in countries like China and India, it is expected that there will be immense opportunity for even further growth in the tissue industry in the coming decades. Even in the U.S., significant investments have been made in tissue paper production in the past decade. From 2012 to 2015, the U.S. tissue production capacity increased by almost 9% [1]. Due to the current size of the industry and the recognized potential for significant growth in the near future, there is an interest within the industry to improve the manufacturing processes for efficiency, energy use and raw material consumption, as well as improvements in the products themselves in order to reduce cost, while increasing end use performance.

A large portion of hygienic tissue papermaking is directly related to the development of structural features that will benefit sheet strength, softness, absorptivity, and bulk. This investigation focused on two structural features common in paper towels, specifically: embossments and through-air-drying features. The manner in which these features are created in their respective manufacturing processes, and characteristics of their structure will be covered in the sections that follow.

1.1. Background
This section addresses in detail the manufacturing of tissue paper, with a specific focus on paper towels. Softness and bulk are critically important properties of tissue, both of which can be optimized through structural design. The methods used to impart tissue structural enhancements, and the characteristics of such modifications, will be discussed. Furthermore, previous work related to z-directional compressibility and research into the elasticity of paper will also be discussed, followed by a brief overview of the methods utilized to quantify paper formation.

1.2. Tissue Manufacturing
In the papermaking process, there are typically three main sections to a paper machine, the piece of machinery that converts a fiber and water slurry to a finished paper material that is ready for converting into a consumer product, an example for the manufacture of tissue and towel products is shown in Figure 1-2. These three sections are forming, pressing, and drying. An important consideration with respect to tissue production is the relatively low grammage (mass per unit area) of each ply. Because of this, many commercial tissue products are composed of multiple
plies to achieve a desired thickness and bulk for end use performance. The specific processes and the types of changes that are translated to the finished product in each of these sections will be discussed specifically through the lens of tissue papermaking in the sections that follow.

1.2.1. Forming

With regard to forming in general, the purpose of the forming section is the rapid removal of water from an initial pulp slurry, or stock. From pre to post, the forming section typically converts a <1% solids content stock into a wet web of anywhere from 10-25% solids content. To achieve such effective dewatering of the developing wet web, there have been numerous developments of the forming section specifically addressing the manufacture of tissue. As far as current tissue papermaking goes, there are three main types of formers: suction breast roll, twin-wire, and crescent. A comparison of the formers by Atkins [2] included a side-by-side comparison of the machines, shown in Figure 1-3. The first of these, the suction breast roll former, is an older style former that uses only a single wire and a specially designed headbox and suction roll configuration to force water through the wire. Following suction breast roll machines, twin-wire formers were developed for the sake of improved dewatering. With twin-wire formers, stock from the headbox is sprayed into the gap between two moving wires. From there, the majority of the water is removed due to a compression of the developing sheet caused by the tension of the wires wrapping around a forming roll. Additionally, twin-wire formers can be further separated into
two types: “S-wrap” and “C-wrap”. The difference between the two types of twin-formers can be attributed to the conveying wire. For “S-wrap” formers, the outer wire takes the sheet to the next section of production while the inner wire conveys the sheet in a “C-wrap” former. Finally, the most recent development in tissue formers, a crescent former is similar to a twin-wire in that the stock is sprayed in between two opposing surfaces. However, with a crescent former, the difference is that rather than two wires, the stock is sprayed in between a wire and a felt. The benefit of this arrangement is such that the sheet does not need to be transferred to a press felt later on, as is the case with twin-wire formers.

1.2.2. Conventional Wet Pressing (CWP) and Yankee Drying

In conventional wet pressing (CWP), following the forming section, the tissue sheet passes through one or more press nips for further dewatering, typically taking the sheet from around 10-20% solids to 40-50% solids content. The presses are typically nipped against the Yankee Dryer, which will be discussed next, so that the dewatering from pressing occurs as the sheet is transferred to the dryer, or just following transfer to the dryer. There are a variety of press combinations and types of presses used in industry to achieve effective dewatering as well as to prevent over-densification of the sheet. In a presentation by Christiansen [3], he compares the selection of either a single, double, or shoe press configuration based on the end-product qualities that each setup will help to produce; a comparison of the three setups is shown in Figure 1-4. According to Christiansen, a single press would be used for a high bulk, a double press for high dryness,
and a shoe press would be used to isolate a specific interplay of bulk and dryness [3]. After pressing in a CWP setup, the wet web has already been pressed onto a Yankee Dryer for the drying section. In the drying section, the sheet is dewatered from around 45% solids to a final solids content of roughly 95%. In this process, shown in Figure 1-5, the tissue wet web is pressed onto a Yankee Dryer, a large heated drum of roughly 10-20 feet in diameter. At the same time, chemicals are sprayed onto the dryer to cause the wet web to adhere to the dryer surface for effective heat transfer. The web is dried by conductive heat transfer from the drum, resulting in a flat and relatively dense sheet with significant inter-fiber bonding potential. As the tissue leaves the Yankee Dryer, a “crepe blade”, or doctor blade as it is commonly known, unsticks the tissue from the dryer and imparts bulkiness via an accordion-fold-like modification known as creping. The web undergoes internal debonding to an extent, which promotes flexibility, softness, and absorptivity. Thus, Yankee drying and creping are responsibility for a significant part of the end use material properties.

Figure 1-5. Illustration of tissue moving across a Yankee Dryer [4]
1.2.3. Through-Air-Drying (TAD)

In contrast to conventional wet pressing, the other popular tissue-drying method is known as through-air-drying (TAD). The actual through-air-drying process involves sending heated, dry air through the sheet which provides significant heat transfer and pulls out moisture from the sheet [5]. Typically, in a process involving through-air-drying, a press section is not employed so the layout of the paper machine consists of a forming section and a drying section. The elimination of pressing from the drying processes allows the tissue to maintain greater end product bulk and absorbency. The obvious drawback to TAD from a manufacturing standpoint is the energy cost to heat the extra water out of the sheet that normally would have been mechanically removed by pressing. On the other hand, due to the extra bulk that results from TAD processes, fiber costs can typically be somewhat reduced, enabling a slightly lower basis weight ply that gives equal absorption and strength performance. Depending on the specific product being made, the full drying process, following the forming section, may include a through-air-dryer followed by a Yankee Dryer to crepe the product. Regardless, the use of through-air-drying results in the production of a unique morphological feature in the structure of the finished tissue product that mimics the patterning of the wire through which the hot air is passed. This pattern can be formed by a felt, fabric, or belt with a characteristic pattern that has both densified and bulked regions.

![Illustration of through air drying](image)

Figure 1-6. Illustration of through air drying [4].
1.2.4. Embossing

Tissue made in both the CWP and TAD processes is often impressed with an embossed pattern when separate webs are combined into two or three plies. The purpose of embossing includes potential improvements in bulk, absorbency and flexibility, the ability to bond different plies, as well as for the production of aesthetic patterns or decorations. In paper production, where the paper is supplied continuously, rotary embossing, in which a rotating embossing roll is used, is the preferred embossing method, as it is much faster than intermittent embossing methods [6]. The embossing nips and processes that are utilized ultimately determine the final embossed finish.

The typical ply bonding of embossed tissues has different configurations, including traditional, nested, and foot-to-foot, as shown in Figure 1-7. For traditional embossing, all the plies of the paper are embossed at once, while both nested and foot-to-foot emboss each ply separately and then bond the plies together afterwards. The difference between nested and foot-to-foot is related to how the plies are glued together. Nested is an arrangement of the plies such that the peaks from the first ply fit exactly into the recessed space of the embossments of the second ply. Foot-to-foot, on the other hand, aligns the plies opposite of the nested method such that the plies are joined together at each peak [7].

Figure 1-7. Illustration of traditional (A), nested (B), and foot-to-foot (C) embossing types.
1.2.5. Embossed and TAD Features

The structural characteristics of embossed and TAD features arise from the manufacturing processes used to create the features. With embossed features being imparted to tissue via patterned embossing rolls, the structures can be adjusted to match a desired outcome by simply modifying the embossing roll. In many commercial paper towel products, embossed features are typically introduced for increased bulk in multi-ply products, or for creating aesthetic patterns or designs. The “height”, or out-of-plane deformation of embossed features can be as great as 0.6 or 0.7 mm, while the feature diameters generally range from 1-3 mm. TAD features, on the other hand, arise from the through-air-drying process with their structure being determined by the wire pattern and the amount of dewatering occurring at the through-air-dryer. Since TAD features essentially mimic the pattern of the wire, their spatial arrangement in the web tends to be much more of a continuous distribution than most embossed feature arrangements. Additionally, TAD features typically have lesser out-of-plane deformations than embossed features, around 0.5 mm or less, and also tend to have smaller diameters, roughly between 0.5 and 2 mm.

Investigation of towel and tissue structure by mapping the local thickness has led to increased understanding of the spatial characteristics of embossed and TAD features. Sung [9] introduced and developed thickness mapping using twin-laser profilometry (TLP). This is a non-contact method of measuring thickness by using laser triangulation to measure the relative distance to both surfaces of a paper sample. This method enables the mapping of the out-of-plane deformation using the center surface and thickness of tissue paper, among other thin materials. In Sung’s and similar works [9,10,11,12], the lasers were mounted on movable platforms so that the thickness distribution of a selected area of the specimen could be mapped. In the work by Sung et al. [10], the difference between multiple thickness measurement techniques, including hard and soft platen caliper as well as TLP, was illustrated on various paper samples. The results showed that TLP provided a good approximation of the intrinsic thickness due to its ability to capture the fine scale asperities of the non-uniform paper surfaces. In a work by Keller et al. [11], it was found that TLP, as a non-contact measurement, was a suitable method for measuring creping patterns along with embossments and TAD structural features. Furthermore, that study focused on separating the thickness of the web from the out-of-plane deformations that charac-
terize creping, embossments, and TAD features. To add to this, Branca [12], through the combined use of TLP and grammage mapping, was able to calculate local apparent density maps of tissue paper. The results confirmed the fact that embossing of the sheet causes out-of-plane deformation as well as an increase in the local density of the web. Additionally, the results also confirmed that creping causes a reduction in apparent density, or an increase in bulk. Overall, it has been shown that advances in thickness measurement have led to the ability to differentiate between thickness and out-of-plane deformation of tissue paper. Furthermore, specific analysis of tissue structural modifications like embossments and TAD features have been successful.

Further demonstration of the value of structural features in tissue paper can be seen in the research of tissue paper softness. Although the relative importance of structural features in tissue paper with regard to softness development is not well understood. A three-parameter model of CD-to-MD tensile index ratio, surface roughness, and mean elastic modulus developed by Liu and Hsieh [13] could predict the subjective softness of simple creped tissue paper to a high degree. However, the model was unable to accurately predict the subjective softness of tissue samples that included TAD-induced features. Furthermore, as explained by Hollmark [14] in a literature review, no single instrument or model based upon physical properties has been able to successfully predict tissue paper subjective softness over a wide range of tissue samples with variations in structural features. Based on this, it is evident that embossed and TAD structural features play a complex role in softness development, even though the specific reasoning may be unclear at this time. Additionally, other tissue softness modelling efforts were able to achieve a fairly high (75-85%) degree of accuracy in predicting subjective softness with the inclusion of a measure of the Z-directional compressibility in the modeling parameters [15,16]. Again, these models only achieved such accuracy when limited to simple creped tissue papers. But the proof of a relationship between ZD compressibility and softness provides further argument for the value of studying ZD compressibility of tissue paper and its structural features.

1.3. Z-Directional Compressibility

While it is understood that the development of bulk in tissue via structural modification lends itself to greater absorbency and softness, the strength and physical properties of the individual modifications are not well documented in the literature. Significant capital and energy goes into
the creation of both embossed and TAD features, so it is therefore important that these structures remain intact post-manufacture - such as during winding, converting, packing, shipping, and in storage. During these intervals, there is a possibility that the tissue product will be exposed to external stresses, notably compression, that could cause permanent deformation in the web structure, which could adversely impact the end use performance or perceived quality. For example, if the feel or appearance of a towel product were to differ between the outermost and innermost layers of a roll, a product could be perceived as defective. Thus, if the web is being compressed at multiple stages during its lifecycle, it is necessary to determine the inherent stiffness and elasticity of the structural features to ensure that they have sufficient resiliency to withstand the repeated stresses, and not exhibit a detectible permanent deformation. For these reasons, the Z-directional compressibility of features in paper towels is the subject of this investigation. Yet, the focus on these features comes after a long history of paper compressibility modeling and basic paper testing found in the literature, especially for more dense papers such as printing and writing grades.

When it comes down to it, the TAPPI standardized methods of measuring caliper, i.e. thickness, are in reality just compressibility tests to a set pressure of 50 kPa [17,18]. In most cases, the determination of thickness is the distance measurement between two planar surfaces, outside of perhaps effective thickness relationships based upon physical properties [19] or the calculation of thickness from apparent volume and buoyancy relationships [20]. Thus, the simplest methods involve the compression of a sheet between two hard outer surfaces, as is the case for the TAPPI T411 standard [17] which uses two hard metal platens to measure thickness at a 50 kPa load. However, the hard platen method does not account for surface roughness. To address this, soft rubber platen methods for caliper measurement were developed by Wink and Baum [18,21].

With respect to thickness distributions, early work in this area was conducted by Schultz-Eklund et al. [22] in which the thickness of paper sheets was measured in steps of 150 microns over a 77 mm² area of paper; the thickness was recorded as the distance between spherical probes loaded to 35 mN against the sample. However, these works in thickness measurement were limited to the scope of setting thickness standards and also attempting to account for thickness variations due to surface roughness. For further understanding of paper compressibility, the next step is to look towards extensive compressibility modeling found in the literature.
Early work on the Z-directional compressibility of paper centered on relating elastic-plastic models of polymeric foams to paper [23,24,25]. For example, Rodal’s [23] work in which he assigns the three stages of compression found in foams to the compressive response of paper. However, much of the work done with polymeric foams [24,25] assumes that the material is isotropic. Thus, application of these models to paper, which due to the hydrodynamic forces encountered in the forming of the fibrous structure is anisotropic, is not ideally suitable. The work by van Wyk [26] took into account the randomness of paper by modeling the compression of a 3D, stochastic fiber network based on a few parameters including: mean contacts per fiber, mean contacts per volume, and mean distance between contacts. Following Van Wyk’s work, many researchers expanded his equations and methodology. For example, Komori and Makishima [27] worked on generalizing equations for the determination of fiber contacts, while Neckar [28] introduced the concept of a contact volume in relation to packing density from the Van Wyk equation. With these works as a basis, Pawlak and Keller [29] derived a model for the prediction of paper compressibility based upon relevant characteristics including fiber length, elasticity, and coarseness. These models are generally suitable for planar fibrous structures, and not those with significant out of plane deformation, such as encountered with embossments, TAD features, or creping lines. These are localized structures superimposed on the underlying structure of the formed fibrous web. For these reasons, this research will focus specifically on experimental analysis of structural feature compressive properties.

Two prior works made progress in understanding the compressibility of paper towels and, more specifically, the compressibility and elastic nature of paper towel structural features. Work done by Feng [30] highlighted the differences in compressibility between TAD and embossed features and the bulk towel structure. His experiments were conducted at high loads, up to 400 kPa, using two 2 N load cells, in opposition, compressing the paper from two sides. Feng performed micro-compression tests on a variety of paper towel samples, focusing on the difference between embossed features and non-embossed regions and TAD features and non-TAD regions. The results indicated that embossed and TAD features did not require as much load as non-structurally-modified regions of the paper towel to achieve a given thickness. In other words, for a given load, the embossed and TAD features experienced significantly more deformation than a non-modified region of the same sample, especially at lower loadings (50 kPa). Based on the compressive
curves generated by Feng, it seemed that further testing of compressive responses at lower loadings (<50 kPa) could provide further insight into the compressive properties when the webs are deformed in handling or winding, where structural collapse does not occur. To illustrate this point, as seen in Figure 1-8, a significant portion of the deformation of paper towels due to compression occurs at loads less than 50 kPa. At these lower loading levels, the material stiffness is an essential part of the tactile properties such as softness or crumple. The work by Feng set the foundation for Wang [8] to focus in on the compressive deformation that occurs as the structures are initially deformed at lower loadings between 10 and 50 kPa. Wang modified the experimental apparatus used by Feng, by replacing the back force probe with a fixed flat plate, and adding a higher sensitivity load cell to the front sensing apparatus, which provided a wider dynamic range with maximum loads of 0.3 N and 2 N, affixed in tandem. This modified setup provided greater resolution to record the small-scale compressive response, especially for TAD features that are more compliant than CWP embossments.
Wang demonstrated the relationship between structural features to the classic three phase compression exhibited by solid foams. The three phases he describes are (1) the initial elastic region, followed by (2) collapse of the feature, and finally (3) the bulk compaction of the sheet. His work then focused on two initial regions, (1) and (2). For the elastic region, Wang determined what he identified as the tangent moduli, which was in effect the Young’s moduli in this case, for TAD and embossed features. The results showed comparable normalized Young’s moduli values, normalized for grammage (g/m²), between embossed features and TAD features respectively. The other property Wang examined was the yield stress, or the stress at which feature collapse occurred. Values of yield stress varied more widely than the Young’s moduli within a given sample, which might be attributed to heterogeneity in grammage or apparent density, or the mode of failure of the features, i.e. twisting, tipping or bursting outwards, among other things [8]. Wang’s research shed more light onto the finer details of feature compressibility through stress-strain analysis and determination of the Young’s modulus, however this investigation will instead simplify the compressive response analyses to force-displacement relationships. In this way, the stiffness, which is a structural property, of paper towel structural features can be examined. Additionally, Wang’s analyses of elasticity were limited to singular compressions, without recording the decompression behavior, or how the feature responds to cycled loading. To further understand the elastic-plastic characteristics of TAD and embossed features, cycling of stresses would provide a more complete understanding of the elastic response, the transition between

Figure 1-9. Comparison of Feng [30] (left) and Wang [8] (right) compression setups.
elastic and permanent deformation, and thereby the resilience of the structures. Furthermore, the compression of multiple features at once more accurately represents a real-world compressive event. Thus, examination of the scalability of compressive loading to larger regions with multiple features is essential to relating the results of this work to realistic compressive events.

1.3.1. Cycling of Z-Directional Loading of Paper

In recent years, cycled loading tests have been used to study the elastic response of paper, specifically to determine resiliency and the resistance to permanent deformation under compressive loading. Tensile and compression testing utilizing repeated loads can be used to discern some of the finer aspects of the elastic and plastic behavior of different paper grades. Although the published research involving the cycled loading of tissue and towel papers is sparse, similar experimental procedures have been used for paperboard, although at much higher loadings, to study the pressing and calendering processes. Work with repeated ZD compressive testing of paperboard has produced interesting results. Nygards’ [32] work on the subject revealed that the stress in repeated ZD compressive load tests could be fit to an exponential function dependent only on the elastic strain and material properties. The major difference to consider is that the compressive loads utilized in paperboard studies are typically up to several MPa, one or two orders of magnitude greater than the loads required for typical paper towel feature collapse. A relevant work by Coffin [33] used the efficiency factor to illustrate the changes in the tensile response of various paper grades through repeated straining. The efficiency factor, previously explored by Seth and Page [34], is defined as $\phi = E_i/E_0$, where $E_i$ is the elastic modulus after (repeated) straining and $E_0$ is the initial elastic modulus. In the work by Coffin [33], a variety of repeated tensile tests were conducted on various board grades, flat papers, and market pulp: immediate repeated reloading, cycled tensile loading to a set stress, as well as stress-relaxation and recovery tests. The results indicate that the stress-strain curves from repeated and increasing tensile loads can be superimposed upon one another quite well by shifting the strain values and scaling the stress values by a factor of the inverse of the efficiency factor, which was defined previously. Additionally, comparison of the efficiency factor with the plastic strain showed that all the papers tested exhibited a regular decrease in efficiency as the plastic strain increased. Using these methods, the recoverable and plastic deformation of nominally dense papers could be separated by determining the shape of the recoverable curve. In this case, one of the final curves from a repeated loading
test could be defined as the recoverable curve and could then be multiplied by the efficiency factor to scale it to some level of straining or loss of efficiency [33]. In relation to this work, the change in efficiency factor across cycled compressive loadings will have different properties than that of cycled tensile loadings. This is due to the difference in the stress-strain relationships for compression and tension: compressive stress will tend towards infinity as the strain approaches a value of 1, while the tensile stress will level off to a defined value. Similarly, unrecoverable deformation from compression will affect the shape of the resultant stress-strain curve differently than as a result of tension. Furthermore, since stress-strain relationships and the elastic modulus will not be used in this work, direct analysis of a compressive efficiency factor cannot be made. However, there may be similar trends related to changes in structural stiffness over cycled compressive loadings.

1.4. Grammage Maps Using Radiographic Analysis

With respect to compressive response, the amount of fibers within the compression zone, the distribution and arrangement of those fibers, and the geometric structure of the feature will be significant variables. Increases in the local grammage will likely lead to an increased compressive stiffness, as well as the limiting compressed thickness of the web. For this reason, the grammage of each individual structural feature that undergoes compression should be considered and determined, if possible, to account for any variation that is observed for a given sample. A non-destructive method to determine the grammage distribution within a sheet of paper is required. What follows is a brief description of the methods that have been developed to measure in-plane grammage distribution or formation.

Formation, which is a measurement of the distribution of grammage within paper, was originally evaluated using the unaided eye; holding a sheet in backlighting and interpreting the light and dark areas to get an impression of the opacity distribution that is presumed to be closely related to the grammage distribution. Advances in this area led to the creation of optical formation measuring devices which rely on light transmission through the fibrous web. However, methods utilizing light transmission become ineffective at high grammages (around 100-150 g/m²), are prone to inaccuracies due to the scattering of light within and between fibers, and any variation
in scattering coefficients that might exist within the structure. A development in formation measurement came with the introduction of β-radiography and its usefulness in the characterization of the mass density distribution, a term used by Corte [35] in his work on the subject. Several early works [36,37] were focused on developing a standardized and effective mass density distribution, or formation, measurement via β-radiography. The later introduction of film and high-precision image scanning and analysis allowed for the translation of β-transmission films to electronically stored datasets. Keller and Pawlak’s work [38] found that increases in the stand-off distance significantly limit the spatial accuracy of the final formation distribution. This is especially a problem for bulkier papers including tissue and towel with out of plane features, and higher grammage paperboards. Farrington [39] attempted to map formation with soft X-ray transmission methods over a wide grammage range; his samples were lab-made handsheets that had grammages in the range of 60-200 g/m². However, he had difficulty with spatial variation of the incident radiation intensity, so-called vignetting, and also the processing of final formation images. Feng’s [30] work with soft X-ray radiography for paper towel formation analysis proved quite successful. By applying an inverse cosine to the 4th function in addition to other first principles models, the spatial non-uniformity of the X-ray distribution was addressed so that accurate, high resolution formation maps could be obtained. By applying the techniques that have been developed by previous researchers, as described above, formation maps for the paper towel samples used in this study were obtained. Furthermore, the compressive responses, or specific characteristics of the compressive responses, of individual structural features were then normalized based upon the grammage variation.
2. Statement of Problem and Objectives

2.1 Statement of Problem
The prior works by Feng [30] and Wang [8] on the compressibility of paper towels shed some light on the compressive characteristics of out of plane structural features, such as those created by embossing or TAD drying. However, both of these works were limited to compressive testing of single towel features. In practice, the paper product will be exposed to compressive loads over larger areas involving multiple contact points at various times during converting, transport, and end use. Scaling of the compressive response of single feature to multiple feature and multilayer (plies) has not yet been explored. Two methods of scaling could be applied to test scalability: increased number of features, or an increased number of plies. Furthermore, improvements to the testing machine and data processing methods were necessary in order to efficiently analyze cycled loading with the instrument used in the earlier investigations [8,30]. To this point, the prior use of a dual strain gauge system (0.3 N gauge connected in tandem to a 2 N gauge) caused uncertainty in the data collected at the transition point where the smaller strain gauge reached a maximum, and load transferred to the larger load cell.

2.2 Objectives
Since paper towel structural (embossments and TAD) features play an important role in end use property development, determination of the physical characteristics of these features can be useful for understanding the types and amount of deformations that may occur between production and consumer use. For this reason, the first objective of this investigation is to determine the limiting loads at which feature collapses occur as well as to measure the structural stiffness, k, as it relates to the cycled compressive loading of a feature. However, realistic compressive events will likely not involve only a single feature. Furthermore, an understanding of the relationship between single feature and bulk paper towel compressive responses could be used to make informed feature design modifications and potentially improve bulk towel performance. For this reason, the second objective of this work is the development of a compressive scalability model that effectively relates increased area and increased ply compressive responses back to the compressive response of an individual structural feature.
3. Experimental Methods

3.1. Materials

Four retail paper towel brands were selected for micro-compression analysis: two conventional wet pressed (CWP) samples, and two through-air-dried (TAD) samples. Three of these samples, the two CWP samples and one of the TAD samples, were the subject of the previous study by Wang [8]. His results will serve as a reference point during initial qualification of the modified micro-compression instrument before continuing the investigation of cycled and multiple-feature compressions. An overview of the samples is provided in Table 3-1.

Table 3-1. List of paper towel samples and their relationship to Wang’s [8] identification of samples.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Feature Type</th>
<th>Wang Comparison</th>
<th>Gravimetric Grammage (g·m⁻²)</th>
<th>Soft X-ray Grammage (g·m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWP-1</td>
<td>Embossed</td>
<td>CWP-1</td>
<td>22.8</td>
<td>26.7</td>
</tr>
<tr>
<td>CWP-2</td>
<td>Embossed</td>
<td>CWP-2</td>
<td>24.8</td>
<td>36.5</td>
</tr>
<tr>
<td>TAD-1</td>
<td>TAD</td>
<td>TAD-1</td>
<td>27.2</td>
<td>32.7</td>
</tr>
<tr>
<td>TAD-2</td>
<td>TAD</td>
<td>N/A</td>
<td>30.3</td>
<td>32.4</td>
</tr>
</tbody>
</table>

In Wang’s work, the assumption was made that the area of compression was the surface area of the probe tip [8]. However, the actual area would more accurately be represented by the size of the feature being compressed, which can vary from sample-to-sample and feature-to-feature. A more realistic approach will be used in this study, where the system will be considered a complex geometric shape, rather than an isotropic material. The displacement as a function of compressive load will be used in place of stress and strain.

3.1.1. Material Characterization – Grammage Maps

To eliminate uncertainty related to the variation of grammage affecting micro-compression results, radiographic methods were used to collect formation maps for each of the four samples prior to micro-compression testing. Formation was determined prior to compression tests so that potential mass-redistribution that might occur during those tests could be avoided. What follows then is a description of the radiographic testing and post-processing methodology.
For the determination of sample grammage distributions, soft X-ray imaging was performed using an AXR Minishot X-ray cabinet. Following the procedures used by Wang [8] and Feng [30], wooden guides were placed within the cabinet to ensure that the sample and sample holder would be fixed in the center of the cabinet for each exposure. A metal template that fit within the guides was used to hold the sample. The template had an opening in the center with dimensions of 7.5 cm by 7.5 cm for the sample to be exposed. Additionally, a 1.5 cm by 7.5 cm opening was made below the sample opening for the placement of a Mylar calibration strip of known grammages. For each exposure, the sample and Mylar strip were affixed to the metal template and the X-ray film was placed beneath the template and within the guides in the cabinet. All films were exposed using an X-ray tube acceleration voltage of 6.5 kV for 30 minutes.

Following exposure of the X-ray films, films were developed, scanned and converted to grammage maps using the methods described by Wang [8]. From these grammage maps, the individual features that later underwent compression were identified and had their individual grammages calculated. The samples used in this study are shown as photographs and corresponding grammage maps in Figure 3-1. As can be seen in Figure 3-1, some structural features, like in CWP-2 and TAD-1, have defined grammage variations from the rest of the web making their outline visible in a formation map. In other cases, like CWP-1 and TAD-2, the structural features are essentially indistinguishable within the grammage map. Nonetheless, even in this case, variation in grammage throughout the sheet will lead to variations in the compressive response of individual features. Thus, it is important to determine how much compressive variation can be expected based upon the grammage variation of the individual features that are tested. In the appendix, the individual features from each sample that were compressed are marked on their respective grammage maps. An example of this is provided in Figure 3-2.
Figure 3-1. Sample photographs (left) versus grammage maps (right) in order from top to bottom: CWP-1, CWP-2, TAD-1, TAD-2. Formation maps are brightness adjusted for visual clarity.
3.2. Compression Testing

3.2.1. Micro-Compression Instrument

All micro-compression testing was conducted using the micro-compression instrument setup shown in Figure 3-3. The instrument consisted of (A) two Aerotech Accudex (model ATS100-050-20P) positioning stages for the Z-directional control of the (B) front probe and (C) back plate. The stages have a step resolution of 0.5 µm, allowing for accurate measurement of probe and back plate position during the loading process. The system also utilizes two more positioning stages used to control X and Y position. These stages are used to simultaneously position the front probe and back plate to exact placement above a structural feature at the start of a test. In the middle of the two Z-directional positioning stages, (D) there is a metal frame with which a paper towel sample is held vertically, between the back plate (left) and front probe (right). The paper towel samples were first separated into single-ply sheets from which a 7x8 cm² section was cut out and used for testing. Three different front probe sizes, as shown in Figure 3-4, were used in this research, to analyze compressive responses of single features (probe tip A) and multiple features (probe tip B and C). Probe tip A had a circular contact surface that was 2.37 mm in diameter. Probe tip B was rectangular (5x4 mm²), as was probe tip C (7x6 mm²). Compression testing was
Figure 3-3. A picture of the micro-compression instrument setup

Figure 3-4. Left: A close-up image of the front probe and sample holder, prior to the compression of a CWP-2 embossed feature. Right: Comparison of the three probe tips.
conducted using a custom LabView application that controlled the positioning stages and recorded the signal from the load cell. Raw position and force data was saved as a dataset and was next transferred to MS Excel and MATLAB for subsequent analysis.

3.2.2. Micro-Compression Calibration and Testing Procedure

In this investigation, three forms of micro-compression tests were performed: single feature single cycle, single feature multi-cycled, and multi-feature single-cycle. While certain aspects of these experiments are different, the basic calibration and test procedures remain the same across all tests. All micro-compressive tests used a single strain gauge (Strain Measurement Devices S256 30g Low Range Overload Protected Force Sensor) with probes of varying size and shape attached to the front. The strain gauge calibrations for both the determination of the relationship between actual force (mN) and strain gauge output (mV) and for the deflection correlation, were carried out using the procedure outlined by Wang [8]. However, since this research study used only single sided measurements, only one force calibration curve was needed. Verification of the force to voltage relationship was conducted by applying known loads to the strain gauge within its operating range. The relationship between the transmitted signal (mV) and actual force (mN) follows the equation \( mV = -0.0344mN + 0.4214 \) with ideal linearity. Strain gauge calibration also involved the Hooke’s law spring constant for the load cell, so that a correction for load displacement could be used to determine the Z-position of the probe tip during a compression test. The method for deflection calibration used by Wang was applied here, where the front probe and back plate are first brought into contact, then the front probe is stepped into the back plate at a rate of 1 \( \mu \)m/s [8]. Deflection calibration was carried out using the three probe tips, where the deflection coefficients are given in Table 3-2. The spring constant across the three tests remained roughly constant, as is expected. The main difference between the three calibrations was a change in the offset. This shift of the offset is likely a result of the different weights of the probes exerting a small amount of torque that is detected by the load cell.

Table 3-2. A list of the deflection coefficients for each of the front probes used.

<table>
<thead>
<tr>
<th>Probe</th>
<th>Description</th>
<th>Spring Constant (mV/mN)</th>
<th>Offset (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.37 mm cylinder</td>
<td>0.0576</td>
<td>0.678</td>
</tr>
<tr>
<td>B</td>
<td>5x4 mm²</td>
<td>0.0586</td>
<td>0.5405</td>
</tr>
<tr>
<td>C</td>
<td>7x6 mm²</td>
<td>0.0582</td>
<td>0.9294</td>
</tr>
</tbody>
</table>
A final consideration of note is related to the resting potential (mV) of the strain gauge. Each dataset was normalized based upon the first 20 values (prior to compression) of strain gauge voltage in relation to the original force-to-voltage calibration. This calibration accounted for small changes in the resting potential that may have been due to changes in temperature, humidity, or electrical noise, for example.

Following calibration of the instrument, compression tests were performed by first moving the back plate inward to make contact with the sample. The front probe was then stepped inward in steps of 0.5 µm at a rate of 3 µm/s. Once the recorded values from load cell reached a maximum voltage limit, the probe movement was then reversed, and stepped outward at the same rate until no force was measured. Strain gauge voltage and the stage position were recorded at 1 Hz using LabView software.

3.2.2.1. Single Cycle Compression Testing

Single cycle compression tests were performed on each of the samples for two reasons. First, to verify the compressive responses recorded by the modified single load cell configuration of the micro-compression instrument. This verification was achieved by replicating the results of the earlier work by Wang [8]. Second, the single cycle experiments were carried out to study the elastic region of compression for each sample included in this study. This would provide a basis from which the cycled compression experiments could be designed. Thus, for each sample, five structural features were subjected to single cycle compressions to the maximum force limit of the strain gauge. For all single cycle experiments, probe tip A (2.37 mm dia.) was used.

3.2.2.2. Cycled Compression Testing

More detail about the transition from the elastic to plastic deformation of features was possible using cycled loadings over successively increasing maximum loads. The purpose of these experiments was to fully characterize the elastic region of structural feature compression for each of the samples used in this work, and to determine the reproducible coefficients that are characteristic of each sample. From the results of the single cycle compressions described above, ranges for cycled compression tests were selected based on the relevant force range of the feature compression, i.e. prior to localized web compression. These ranges were then divided into ten sub-ranges
of compression. For cycled compressions, structural features were then subjected to ten success-
sive cycles of compression, with increasing maximum loads at each cycle up to the limit deter-
mined from the single cycle experiments. For the cycled compression experiments, three struc-
tural features from each sample were tested. Since only single features were tested, probe tip A
(2.37 mm dia.) was used.

3.2.2.3. Multi-Feature Compression
To examine the relationship between the compressive response of single features and the bulk
compressibility, multi-feature compression tests were conducted. Samples CWP-2 and TAD-1
were chosen as the test samples for multi-feature compression based on the arrangement of their
structural features. CWP-2 has shorter inter-embossment distances than CWP-1, thus making it
easier to compress multiple embossments under a relatively small front probe size. TAD-2 was
excluded from multi-feature compression due to the interweaving of both TAD and embossed
features in the structure of the paper towel, effectively making larger area compressions of only
TAD features unfeasible. TAD-1, on the other hand, only has TAD features present in the bottom
ply of the towel, with a regular distribution of those features, making it an effective multi-TAD
test sample. In multi-feature tests, probe tip B (5x4 mm²) and C (7x6 mm²) were used. These two
probe tips enabled the compression of a greater numbers of features for these tests. Also, the
method of compression for multi-features followed that of the single cycle compression tests.
Each area of structural features was compressed over a single compressive cycle up to the maxi-
mum force limit of the load cell. For both CWP-2 and TAD-1, five multi-feature tests were con-
ducted, for each probe size, with a varying number of structural features in each test.

3.2.3. Tissue Paper Bulking Thickness
An important aspect of this investigation is to examine the scalability of compression analysis
from single feature to bulk compression response. Therefore, tests were conducted on various
stack compositions to determine if a relationship does indeed exist. These tests included not only
structural features in single plane parallel, as with multi-feature, but also in Z-directional series
due to the stacking of the plies. These experiments provide an essential link between singular
structural feature compression and realistic bulk-towel compression.
For these experiments, the larger area within the compression zone, at a given compression required the measurement of loads larger than what could be measured on the micro-compression instrument. Therefore, an Instron 3300 Single Column Universal Testing unit was used for the collection of z-displacement and compressive load values for compression. The testing instrument, shown in Figure 3-5, uses a 5 kN load cell connected to a 45 mm diameter platen. Prior to testing, the load transducer was electronically calibrated, and the platen deflection under load was recorded for use in correcting displacement values. For the deflection calibration, the platen was stepped downward into the base platen at a rate of 100 µm/s until just prior to reaching the maximum load of the force transducer (5 kN), at which point the test was stopped. The data from the calibration was then plotted as the deflection calibration curve, shown in Figure 3-6.

Figure 3-5. An image of the Instron tester setup for ZD-compression.
The results of the deflection calibration indicate that the Instron tester reaches a maximum deflection of roughly 700 µm at the maximum load; a deflection this great was a necessary consideration with respect to the thickness of a stack of paper towel plies under load.

Industry standards for the measurement of bulk tissue thickness, apparent density, and bulk are typically conducted following the methods outlined in ISO 12625-3 [40], and TAPPI T580 [41] which is identical to the ISO method. In these testing methods, a single tissue sheet is subjected to a pressure of 2 kPa to determine a measure of the bulking thickness of the sheet. The methods only describe the bulking thickness measurement for a single sheet, however it is generally accepted within industry to perform the same, or similar, test method with multiple stacked sheets to arrive at a better approximation of the bulking thickness. In this investigation, stacks composed of eights sheets, as per an industry standard, were tested. Additionally, since this work is focused on the elastic and collapse compressive responses of tissue structural features, much greater stresses, up to several hundred kPa, were applied rather than the standard 2 kPa loading.
Prior to testing, the samples were prepared for stacked compression as follows. For both samples, eight two-ply sheets, i.e. 16 plies, were stacked. For CWP-2, eight sheets were separated into 16 individual plies in which the embossments of each ply were oriented such that they were all facing upwards (towards the top platen). For TAD-1, since the top-ply of each sheet contained other surface modifications other than TAD features, 16 sheets were separated, and only the bottom ply (without embossment) was stacked, facing upward, into a stack of 16 layers. For each experiment, the stack was placed on the bottom platen, and the top platen was stepped downward at a rate of 0.1 mm/s. Load and position were sampled at 10 Hz, until just prior to reaching the maximum load of the system. This test was performed three different times over a new area of each sample. After each test, the paper towel areas that underwent compression were separated from the rest of the towel material and had their grammages measured, which are listed in the table below.

Table 3.3. Grammage averages over 16 plies from the three tested areas of each stacked towel sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Feature Type</th>
<th>Grammage (g·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWP-2</td>
<td>Embossed</td>
<td>24.2 (±0.8)</td>
</tr>
<tr>
<td>TAD-1</td>
<td>TAD</td>
<td>26.6 (±0.5)</td>
</tr>
</tbody>
</table>

Due to the relative uniformity of the grammages across the three tested regions from both CWP-2 and TAD-1 in the stacked compression tests, it was determined that the effect of grammage variation on the stacked compressive results was minimal.

3.3. Compression Analysis

For the analysis of the compressive response of paper towel structural features, it is convenient to relate this behavior to the compressive response of solid foams. While it is obvious that the geometric features in paper towels are primarily out-of-plane deformations, and are not isotropic materials, as are solid foams, the transitions observed for these structures do exhibit similarities to the pattern observed with solid foams. The compressive responses of both solid foams and paper towel structural features exhibit three phases of deformation. These are shown in Figure 3-7, (1) the material initially exhibits a linear elastic response phase, followed by (2) collapse of the
structure, ending with (3) bulk structural compression in which the material is heavily compacted. For this investigation, the main focus is on the (1) linear elastic phase, and also the transition between the elastic (1) and collapse (2) phases. Within the elastic phase (1), it is known that the tangent modulus of the compressive response is equivalent to the elastic modulus which is the main characteristic of this compressive phase. However, in this investigation, since compression analysis was conducted via force-displacement relationship, and the structural characteristics such as contact area were not determined, calculation of the elastic modulus is not feasible. However, the stiffness of the features, which is dependent on the elastic modulus, was observed in force and displacement plots, and may also exhibit specific characteristics within the linear elastic phase (1).

3.3.1. Development of Displacement

The separation distance between the surface of the probe tip and the backing plate may be related to the displacement of a tissue feature once a force is sensed by initially contacting both sides of the material. Separation distance is determined using the front and back stage positions (D_z, D_{zz}).
front probe deflection ($D_d$), and the initial distance between the front probe and back plate ($D_0$). The equation used for determining separation distance, $D_s$, is as follows:

$$D_s = D_0 - D_z - D_{zz} + D_d$$  \hspace{1cm} (3.1)

The separation distance between the front probe and the back plate is effectively the sample thickness under a given load and will be referred to as such in the analysis of the single feature, single cycle compression results. $D_z$ and $D_{zz}$ are controlled during the experiment. The deflection of the probe, $D_d$, is calculated from the calibration curve for deflection from the load cell output (mV), and $D_0$ is determined just prior to the start of each experiment or anytime the probe or back plate are adjusted. $D_0$ is determined by stepping the front probe and back plate together until initial contact is made, as indicated by the first nonzero signal from the load cell.

From the separation distance ($D_s$), the deformation of the material can then be quantified. The displacement, $\delta$, is determined from the separation distance as follows:

$$\delta = D_{s0} - D_s$$  \hspace{1cm} (3.2)

where $D_{s0}$ is the initial separation distance, when initial contact with a feature has been made, and $D_s$ is the separation distance for any given load.

### 3.3.2. Stiffness

The stiffness is a valuable characteristic of the compressive response due to its dependence on both material and structural properties. For example, embossments and TAD features might have different stiffnesses due to their differences in surface area and out of plane deformation, even if made from the same materials. The determination of stiffness is therefore important in the study of structural feature compressive responses since structural variation will lead to different resulting stiffnesses. From the force-displacement relationship, the stiffness is defined as the slope of the curve at any given point. The equation for stiffness, $k$, can thus be defined as follows:

$$k = \frac{\Delta F}{\Delta \delta}$$  \hspace{1cm} (3.3)

### 3.3.3. Compressive Scalability

In this investigation, two forms of compressive scalability are considered. These will be introduced as structural features in parallel, for compression over wider areas that include multiple
features, and in series, which involves stacked plies where several layers of features span the gap between platens. The multi-feature compression experiments are representative of parallel feature compression, while the compression of stacked plies includes both parallel and series feature organization. In order to achieve the goal of developing a relationship between singular structural feature compressions and multi-feature and multi-ply compressions, models based upon the principles of Hooke’s law for elastic materials will be developed.

3.3.4. Compressive Scalability Model

For the creation of a model to develop continuity between the behavior of a single feature and the assembly of many features in a towel product, an analysis based on simple elastic springs and Hooke’s law will be applied. The three scenarios experienced in the single feature, multi-feature, and stacked compressions are illustrated in Figure 3-8.

![Figure 3-8](image)

Figure 3-8. Graphic comparison of (1) single feature compression, (2) multi-feature compression, and (3) stacked ply compression with structural features represented by springs.

For all cases, a unit spring is used to represent the compressive response of a structural feature. For case (1), a single spring or feature, the compressive force is represented by equation 3.4.

\[ F = -k\delta \]  

(3.4)
where $F$ is force in Newtons, $k$ is the spring constant in N/m, and $\delta$ is the displacement in meters.

To relate the expression for case (1) to case (2), the number of springs, $N$, is incorporated into Equation 3.4 for parallel compression of springs as follows:

$$F = \sum_{n=1}^{N} -k\delta$$  \hspace{1cm} (3.5)

Using these two relationships, modelling the compressive response of multiple features such that it is equivalent to the compressive response of a single feature, the force must account for the number of structural features, $N$, as shown in Equation 3.6.

$$\bar{F}_{\text{single}} = \frac{F_{\text{multi}}}{N}$$  \hspace{1cm} (3.6)

where $\bar{F}_{\text{single}}$ is an average force over repetitive single feature compression tests, and $F_{\text{multi}}$ is the compressive force over multiple features. The relationship assumes that all structural features have the same stiffness, $k$. However, this is addressed by the use of an average single feature force over several tests, which should account for some of this variation. Equation 3.6 is used as the model relationship between single and multi-feature compressive responses.

A model is also proposed for stacked ply compressions which incorporate both parallel and series elastic spring relationships, based on case (3) from Figure 3-8. By using Equation 3, which accounts for the action of multiple features under compression, the mechanics of multiple structural features compressed in series are then accounted for. The compressive force over multiple springs in series is described by Equation 3.7.

$$F = -kp\delta$$  \hspace{1cm} (3.7)

where $p$ is the number of springs in series, determined from the number of plies, or layers, for the stacked compression experiments. From this relationship, it is clear that the number of plies, $p$, must be incorporated into the displacement, as shown in Equation 3.8.

$$\delta_{\text{single}} = \frac{\delta_{\text{stack}}}{p}$$  \hspace{1cm} (3.8)

where $\delta_{\text{single}}$ is the displacement of a single ply and $\delta_{\text{stack}}$ is the displacement of a stack of multiple plies. Furthermore, it is known that the compressive force for multiple springs in series is equivalent. Thus, by incorporating Equation 3.6 and 3.8 into Equation 3.4, the model for the relation of stacked compression reduces to the relationship in Equation 3.9.

32
\[
\overline{F}_{single} = \frac{F_{stack}}{N} = -k \frac{\delta_{stack}}{p}
\] (3.9)

The force-displacement relationship developed in Equation 6 takes into account both the effect of multiple features in a given area, as well as the stacking of multiple plies on top of one another. This model can then be used to compare the compressive responses recorded in stacked towel compression experiments to both the singular feature compressions, and the multi-feature compressions. These compressive scalability models ultimately provide a means of determining to what extent structural features play in the bulk compression of paper towels.
4. Results and Discussion

4.1. Single Cycle Compression

In the earlier work by Wang [8] on paper towel structural feature compressibility, micro-compression tests were performed on two embossed and two TAD paper towel samples using similar apparatus as used in this research, except for the use of two load cells connected in tandem versus the single load cell configuration used in this work. Since the micro-compression instrument was modified, it was important to demonstrate consistency between the results from this study and those presented in the earlier work by Wang [8]. For this, three of the samples in this study were the same retail paper towel products as those used by Wang [8]. It is also important to note that Wang [8] used the area of the probe tip (2.37 mm), regardless of the actual area that is directly in contact with the feature. However, in this work, rather than expressing the compressive response as a stress-strain relationship, that might be appropriate in the study of a planar web structure, a force-displacement relationship is preferred as it is more useful in describing the deformation of more complex assemblies that involve geometric structures formed within a heterogeneous fibrous web. For the sake of comparison to Wang’s [8] results, all stress values presented in this section have been calculated based on the cylindrical front probe (2.37 mm dia.) area. Consider also that in later sections, force, not stress, will be used in the analysis of compressive response. The single cycle compression results for sample CWP-1 are provided first, as shown in Figure 4-1.
Figure 4-1. Top: 5 Single cycle compressive responses of CWP-1 embossed features, a single representative decompression curve is shown. Bottom: 10 compressive response curves of CWP-1 embossed features by Wang [8].

For CWP-1, it can be seen in Figure 4-1 that the compressive response curves of the embossed features have been successfully replicated using the modified micro-compression instrument. The characteristic shape of the curves and load ranges in which feature collapses occur have been reproduced. However, there is a difference in the measured thickness of the sample throughout the compressive loadings. The results for CWP-2 are provided in Figure 4-2.
Figure 4-2. Top: 5 Single cycle compressive responses of CWP-2 embossed features, a single representative decompression curve is shown. Bottom: 10 compressive response curves of CWP-2 embossed features by Wang [8].

As was the case with CWP-1, there was a successful replication of the CWP-2 compressive response curves with the modified compression instrument. In this case, some of the limiting thickness values seen in Wang’s [8] results are reproduced in this work’s single cycle compressions of CWP-2. Not all of the scatter captured in Wang’s [8] was seen in this investigation’s single cycle compressions on CWP-2, however fewer tests were performed in this work. The results of TAD-1 are provided in Figure 4-3.
Figure 4-3. Top: 5 Single cycle compressive responses of TAD-1 features, a single representative decompression curve is shown. Bottom: 10 compressive response curves of TAD-1 features by Wang [8].

The compressive response curves and stress ranges in which elastic responses were seen were reproduced in this investigation’s single cycle compression experiments on TAD-1. However, the calculated thicknesses of TAD-1 in this work were double those seen by Wang [8].
Overall, comparing the stress values from all three samples, the results were very similar; limiting loads were essentially within the same ranges. However, there were differences in limiting thickness for all three samples. For CWP-1, the limiting thicknesses were about 20 μm greater in this work. For CWP-2, only the largest two of the three limiting thicknesses seen by Wang [8] were reproduced in this work. Lastly, for TAD-1, the limiting apparent thicknesses were essentially double in this work. An important point is that for the embossed samples, the towels used were from the exact same rolls used in Wang’s [8] original study. However, TAD-1 was the same brand of towel, but was sourced from a new roll of the product. It is possible that recent changes to the manufacturing process of this product resulted in the differences seen in the apparent thickness. Moreover, additional compression tests could be completed to potentially recreate all of the scatter seen by Wang [8]. The similarity of the results supports the validity of the new micro-compression instrument modification. The final sample studied in this work, TAD-2, was not included in the work by Wang [8]. The single cycle compression results on this sample are shown in Figure 4-4.

![Figure 4-4](https://www.example.com/figure44.png)

Figure 4-4. 5 Single cycle compressive responses of TAD-1 features, a single representative decompression curve is shown.
TAD-2 responded quite differently to the single cycle compression experiments than the other samples in this investigation. For TAD-2, all of the compressive response curves line up quite nicely in the elastic region, but then see significant scatter at higher loads once the bulk towel compaction phase of compression is entered. The limiting thicknesses across the five single cycle tests on TAD-2 had much greater scatter than all of the previous samples. This result may be due to the irregular shape of TAD-2’s structural features. Rather than having a relatively homogeneous cylindrical or half-spherical shape, the TAD structural features seen on TAD-2 appeared to be more of a continuous zigzag pattern. Variations in this zigzag pattern may have contributed to the differences seen in the limiting thicknesses from single cycle compression.

These single cycle compression experiments also measured the decompressive response. A single representative decompression curve for each sample was provided earlier in each of the figures from this section. It appears that the observed decompressive response of all samples, both CWP and TAD produced, was quite similar. After the peak compressive load was reached, decompression began. There appear to be two regions of the decompressive response curves: (1) a relatively constant thickness region followed by (2) a relatively constant compressive stress region. The decompressive response across all experiments conducted in this work exhibited the same characteristic shape as seen in the single cycle results.

4.2. Cycled Compression Results

Cycled compression tests throughout the elastic and feature collapse phases of compression are the next point of interest for this work. These specific regions were identified using the limiting loads determined from the earlier single cycle compressions and then divided into ten separate cycles. The cycled tests provide greater insight into the compressive elasticity of the embossed and TAD features. In the sections that follow, embossed feature cycled responses will first be examined, followed by the cycle responses of TAD samples. Also note that the compressive responses will be presented as force-displacement curves, rather than the stress-thickness curves shown in the single cycle compression results.
4.2.1. Cycled Compression of CWP-Embossed Features

In this section, the results of the cycled compression tests on embossed features from the CWP samples are presented. Starting with CWP-1, the ten steps of a complete cycled compression test are presented in Figure 4-5. From the progression of the curves in Figure 4-5, is it evident that previously loaded regions experience some level of deformation from each loading step due to the decreased loads seen in later cycles at a given displacement. Moreover, there appears to be a gradual flattening of the curves over each cycle, with large decreases in the linear phase slope near feature collapse. However, it also appears that upon entering a non-previously-loaded region, the force values continue from the upper terminus of the previous cycle. In other words, it appears that the non-previously-loaded region of each cyclic curve makes up a portion of what could be a typical full compression curve. To better illustrate this, the newly loaded, or non-previously-loaded, portion of each cyclic curve can be spliced together into a single curve, as shown in Figure 4-6.

![Figure 4-5. Complete set of 10 cycles from cycled compression of a CWP-1 feature.](image-url)
Figure 4-6. Spliced cycled compression curve vs. a regular single cycle compression of a CWP-1 feature.

Here it can be seen that the combination of all the newly loaded portions of the individual cyclic curves come together to create a single, continuous compression curve. Additionally, for sake of comparison, a single fully-loaded compression curve for CWP-1 is shown alongside the “spliced” curve in Figure 4-6. The comparison of these curves demonstrates the fact that repeated compressive loading does not affect the ultimate compressive curve of the embossed feature. However, the spliced curve shown here, and in most of the other cycled results in this investigation, appears to exhibit a significantly decreased total displacement over the ten cycles. This could be due to a difference in feature thickness (or web thickness plus out of plane deformation) since displacement increases from zero once first contact is made.

As described previously, the previously loaded regions of each cyclic curve experience some level of deformation and appear to show some decrease in slope over a given displacement range. Identifying the elastic portion of each cyclic curve can further demonstrate the deformation occurring, as well as the changing of the slope, or stiffness. This is shown in Figure 4-7.
Figure 4-7. Section of elastic region from cycles two through ten on a CWP-1 feature; stiffness, $k$, for each cycle is provided.

The results of cycled compressive loading can be seen by visual inspection of the elastic sections of the cyclic curves as well as the stiffness values provided in Figure 4-7. Notice that, following the third cycle, the stiffness decreases fairly regularly throughout the rest of the ten cycles. At the seventh cycle, collapse of the embossed feature occurs, as shown previously in Figure 4-6, and a much greater displacement difference between steps is observed before and after the seventh cycle. It appears that the feature stiffness begins at a given value, then quickly increases to some maximum stiffness before gradually decreasing upon greater and further cycled loadings.

Following CWP-1 cycled compression, it is expected that the cycled compression of embossed features from CWP-2 should exhibit similar relationships to full compression and should also exhibit similar changes in stiffness and deformation with each cycle. The results of CWP-2 cycled compression are provided next, beginning with Figure 4-8. For CWP-2’s features as well, splicing together the newly-loaded portion of each cycle from all ten cycled loadings, as shown in Figure 4-8, a typical single cycle compression curve is reproduced, as shown in Figure 4-9.
Figure 4-8. Complete set of 10 cycles from cycled compression of a CWP-2 feature.

Figure 4-9. Spliced cycled compression curve vs. a regular single cycle compression of a CWP-2 feature.
A similar thinning effect was seen in the spliced cycled versus single cycle compression curves for CWP-2 features. This result is likely due to similar reasons described for CWP-1, such as varying feature thickness and the data sample rate. However, the shape of the compressive curve is still effectively reproduced, so the attention shifts again towards the changes in stiffness and displacement over each cycle. This is illustrated in Figure 4-10. For the cycled compressive response of CWP-2, there is a similar trend seen in the stiffness changes at each cycle to what was seen for CWP-1. The stiffness begins at some initial value, then increases to a maximum, then gradually decreases upon further cycling over greater loads.

Overall, the analysis of cycled compression curves for embossed features can provide insight into some specific details related to deformation and feature collapse. The first valuable piece of information gained from cycled compressions is the determination of when significant deformation begins to take place. Previous work with feature compressibility focused heavily on the loads to cause feature collapse. However, the cycled compression results of the CWP samples further illustrate that the majority of feature deformation occurs near the collapse phase as well,
as would be expected. To further analyze the deformation, the compression cycles could be made over shorter load intervals to further identify specific load ranges in which major deformations occur. It was also shown that changes in the stiffness of these features follows a somewhat regular pattern in which they increase to some maximum value and then gradually decrease over further cycled loadings. The maximum stiffness for both samples was experienced fairly early in the cyclic loadings, occurring well before feature collapse. As such, the loads at which maximum stiffness are reached could be further studied to essentially determine optimum compressive operating ranges for a given feature geometry.

Table 4-1. Grammage normalized limiting load averages prior to embossed feature collapse over three cycled compression tests on CWP-1 and CWP-2. Average sample grammages also given.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Normalized Limiting Load (mN)</th>
<th>Grammage Average (g∙m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CWP-1</td>
<td>94.9 (±4)</td>
<td>27.0 (±1)</td>
</tr>
<tr>
<td>CWP-2</td>
<td>97.6 (±20)</td>
<td>34.6 (±2)</td>
</tr>
</tbody>
</table>

As a summary of the cycled compression results for embossed features, the maximum stiffness and limiting loads prior to feature collapse from the spliced cycled compression curves (Figure 4-6 and Figure 4-8) are presented in Table 4-1. Both CWP samples experienced feature collapse at similar load values, see Table 4-1, however CWP-1 had much less variation in its limiting loads. This could be a result of greater geometric and grammage uniformity across CWP-1’s embossments.

**4.2.2. Cycled Compression of TAD Features**

In this section, the results of the cycled compression tests on TAD features are presented. Compared to embossed features, TAD compressions do not typically exhibit a distinct feature collapse phase, as shown previously by Wang and Feng [8,30]. Furthermore, TAD compressions may also lack a typical linear elastic phase, instead exhibiting a regularly increasing slope for the entire compressive loading. For this reason, only cycled compressions that yielded regular linear elastic phases are presented in this section. Starting with TAD-1, ten cycled compressions are provided in Figure 4-11.
Figure 4-11. Complete set of 10 cycles from cycled compression of a TAD-1 feature.

Figure 4-12. Spliced cycled compression vs. single cycle compression of a TAD-1 feature.
As was done previously for the CWP samples, the newly loaded portion of each cyclic curve from Figure 4-11 can be spliced together to reproduce a regular single cycle compression curve, as shown in Figure 4-12. As shown in Figure 4-12, the spliced cycled compressive curve derived from cycled compressions matches the response of a full compression test on TAD-1 features. These two curves matched up quite well, contrasting the “thinner” spliced curves seen for the CWP samples. This might be due to greater uniformity of feature thickness for TAD features compared to embossments. Next, the stiffness of each cycle can be compared across the linear elastic region of each cycled compression curve, as shown in Figure 4-13. The trend for stiffness changes over cycled loadings seen in TAD-1 follow the trend exhibited by the CWP samples, shown in Figure 4-13. In the case of TAD-1, however, the maximum stiffness value occurs in the fourth cycle, just prior to the transfer between linear elastic and bulk web compression phases in the fifth cycle. The deformations of TAD-1 features from cycle-to-cycle were rather spread out, rather than being concentrated around a single cycle as was the case for the CWP samples. TAD-2 will be discussed next, beginning with the results shown in Figure 4-14.
Figure 4-14. Complete set of 10 cycles from cycled compression of a TAD-2 feature.

Figure 4-15. Spliced cycled compression vs. single cycle compression of a TAD-2 feature.
Using the results in Figure 4-14, a spliced curve can then be created to reproduce the characteristic shape of a single cycled compressive loading, as shown in Figure 4-15. The spliced curve for TAD-2 in Figure 4-15 appeared to exhibit a similar “thinning” result as was seen with the CWP spliced curves. In the case of TAD-2 specifically, the TAD patterning of this sample was not radially uniform, so compression under a cylindrical probe tip could have led to the compression of various portions of what was previously described as a zigzag patterning. Again, though, the spliced curve for TAD-2 effectively reproduces the characteristic shape seen in a single cycle compression of the structural feature. The next step is to then examine the change in stiffness over each cycle, shown in Figure 4-16. Since the TAD-2 feature in this cycled compression exhibited a collapse phase, the majority of the deformation occurred between cycles following the collapse, i.e. cycles six and seven, as can be seen in Figure 4-16. Additionally, a fair amount of deformation occurred in each cycle following collapse. For this TAD-2 feature, the maximum stiffness within the linear elastic region was observed during the sixth cycle in which feature collapse occurred.
Compared to embossed features, it appears that TAD features exhibit a greater spread of deformation from cycled compressive loads. The embossed features discussed in the previous section experienced the majority of their deformation during the feature collapse cycle and nearby cycles. Although the TAD features also saw their greatest deformations during feature collapse, or during the transition from the linear elastic phase to the bulk web compression phase, they also exhibited a greater spread of deformations across the entire range of steps. For TAD feature cycled compressions, the maximum stiffness within the linear elastic compression phase was observed in, or once cycle prior to, the cycle in which the elastic to web compression transition or feature collapse occurred. This is much different from the embossment cycled compression results, in which the maximum stiffness was seen in much earlier cycles, well before feature collapse occurred. This difference in stiffness across cycled loadings might be a result of general structural differences between embossments and TAD features.

Table 4-2. Grammage normalized limiting load averages prior to the transfer from linear elastic region to bulk web compression over three cycled compression tests from TAD-1 and TAD-2. Grammage averages for each sample also provided.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Normalized Limiting Load (mN)</th>
<th>Grammage Average (g·m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAD-1</td>
<td>70.9 (±1)</td>
<td>36.2 (±10)</td>
</tr>
<tr>
<td>TAD-2</td>
<td>52.5 (±1)</td>
<td>34.0 (±2)</td>
</tr>
</tbody>
</table>

The limiting loads for TAD-1 and TAD-2 had very little scatter, with TAD-1 having greater limiting loads than TAD-2 overall.

4.3. Multi-Feature Compression Results

As explained previously, two different rectangular front probe tips (5x4 mm² and 7x6 mm²) were used for multiple feature compression. Varying numbers of features were compressed from test to test in order to analyze the scalability of the single feature compression curves over increased area with greater numbers of features. The multi-feature compression data were modeled as single-feature compressions by using Equation 3 that was derived previously for the compression of multiple springs, or features, in parallel.

\[
\bar{F}_{\text{single}} = \frac{F_{\text{multi}}}{N} \quad (3.6)
\]
CWP-2 was used as a representative sample for embossed features, while TAD-1 was used for TAD features. The two samples and their results are covered in depth in the following sections, beginning with the multi-feature compression of CWP-2 under the 5x4 mm² probe tip.

For this probe tip, CWP-2 was limited to a maximum of two features due to the spacing of the embossed features within the sheet. Unfortunately, due to the increase in features under compression, the requisite loads in order to reach equivalent loads as seen in single feature compression were doubled as well. Because of this, and the natural load limit of the strain gauge, the two-feature compressions did not fully reach their expected feature collapse phases. However, the linear elastic regions of each two-feature curve match quite well to the single feature compression curves, except for the single curve that had a significantly lower overall total displacement. This result could be from compressing two features with less than average out-of-plane deformations or might also be the result of a structural defect in one or both of the compressed features leading to a greater than expected load for a given displacement. These initial tests establish a relationship between single and multi-feature compressions. Following these tests, greater numbers of CWP-2 embossed features were compressed using the 7x6 mm² probe.

![Figure 4-17. Five two-point compressions vs. two single-point (feature) compressions of CWP-2 embossed features using 5x4 mm² probe tip.](image_url)
Figure 4-18. Multiple versus single-point (feature) compression of CWP-2 features using 7x6 mm² probe tip.

With the 7x6 mm² probe tip, as many as four embossed features from CWP-2 were able to be compressed at once. The test results shown in Figure 4-18 included three and four-feature compressions. Overall, all of the multi-feature test results seen in Figure 4-18 matched quite well to the original single feature compression curves.

All of the CWP-2 multi-feature compressions replicated the typical single feature compressive response in the linear elastic region fairly well. It is unclear whether or not the multi-feature compressions would have yielded a collapse phase as is typically seen in single feature compression if the load cell had a greater maximum load. Following these results, the next focus is then the multi-feature scalability of the TAD features from TAD-1. The results of those tests are presented next, beginning with Figure 4-19. All of the tests with the 5x4 mm² probe captured exactly four TAD features due to the regular spacing of features on TAD-1. At low loads, the four-feature compressions on TAD-1 had less than expected loads, which might be a result of not all of the features being in contact with the probe yet. Ultimately, though, the multi-feature com-
Figure 4-19. Four-point versus single-point (feature) compression of TAD-1 features using 5x4 mm² probe tip.

Figure 4-20. Nine-feature versus single-feature compression of TAD-1 features using 7x6 mm² probe tip.
pressive curves align fairly well with the single-feature curves once this initial low-load phase is exceeded. For further insight into the trends seen with four features, the next set of results covers the compression of nine features with the 7x6 mm² probe tip, as shown in Figure 4-20. The nine-feature compression curves shown in Figure 4-20 exhibited a similar response to the four-feature curves with lower-than-expected loads in comparison to the single-feature compressions at low displacement. At greater displacements, it appears that the nine-feature curves gradually begin to match up with the single-feature curves. Again, this could be a result of not all of the features making full contact with the probe in the lower displacement range.

The multi-TAD compression curves appeared to match the single-TAD compression curves quite well, except at low displacement. Along with the multi-embossment compression on CWP-2, it appears that the model relationship between single and multiple feature compressions scales fairly well. Following these multi-feature compression results, the next section will discuss the results of the stacked ply compressions on CWP-2 and TAD-1.

4.4 Stacked Compression Results

The final portion of this investigation is focused on relating the compression of singular structural features to the compression of a stack of paper towel plies. The ability to predict the compressive response of stacked paper towels based on the compressive response of single structural features could lead the way for end use property improvements solely based on changes in the design of embossed and TAD features. For the stacked compression tests, three tests on both CWP-2 and TAD-1 were conducted. The results of those tests are then compared to the single and multi-feature compressions presented earlier. In this case, the model developed to relate a single feature compression to the stacked compression experiments made use of the force-displacement relationship and accounted for the number of features and the number of piles in the stack, as shown in Equation 3.9 which was derived previously.

\[
\overline{F}_{\text{single}} = \frac{F_{\text{stack}}}{N} = -k \frac{\delta_{\text{stack}}}{p} \tag{3.9}
\]

The application of this model to the stacked compression test results from TAD-1 is provided in Figure 4-21.
Figure 4-21. Three stacked compression tests and two single-feature compression tests from TAD-1.

Figure 4-22. Three stacked compressions, as well as a one and three-feature compression on CWP-2.
The TAD-1 stacked (16) ply compression curves lined up right in the middle of the two representative single-feature compression curves, as shown in Figure 4-21. The shape of the stack compressive curves also matches quite well to the characteristic shape of the single-feature compressions. Following this, the stacked compression results for CWP-2 are shown in Figure 4-22. The stacked compression versus single feature compression comparison for CWP-2 shown in Figure 4-22 is quite a different scenario than the stacked results for TAD-1. The stacked compression curves appear to start at greater loads than the micro-compression curves due to setting the initial contact point as the point at which the load began to regularly increase. This was done to remove the compression of void space between plies from the force-displacement curves. The stacked compressive responses appear to only match up with the initial linear elastic phase of the single feature compressive response curve. However, this result is not unexpected. To observe such a significant collapse phase as seen in single feature compressive curves, it would have to be that all, or a large majority, of the features within the stacked paper towel sample collapse over the same compressive load range. The fact that a collapse phase is not exhibited by the stacked compressive response curves seems to indicate that the collapse of features within the paper towel stack is being averaged out due to the much greater number of features and plies involved in the experiment. Yet, comparison of the stacked results to a three-feature compressive response shows an effective scalability. While the response of a single embossed feature compression is not approximated well by a stacked compression, it seems that compressions of multiple embossed features respond quite similarly to the stacked compressions.

Overall, the model developed for the compressive scalability of paper towel structural features appears to be effective at relating single feature to stacked compressions in the case of TAD-1, and multiple features to stacked compression in the case of CWP-2. The difference seems to lie in the fact that compression of singular TAD features does not result in the significant collapse phase observed in embossed feature compression. Other factors may have been at play in the relation of these compression experiments. For example, the spacing and dimensions of the structural features, as well as variations in the stiffness of individual features. Ultimately, the experimental results of these compression tests in combination with the scalability model demonstrate the relationship between small and large scale compression of paper towels.
5. Conclusions and Future Work

5.1. Conclusions

1. The micro-compression instrument used in a previous work by Wang [8] was modified to be used with only one load cell rather than two load cells arranged in tandem. Single-feature compressions of three of the samples used in Wang’s work showed similar yield stresses and limiting thicknesses, suggesting that the switch to the single load cell was successful. Additionally, load ranges for cycled compression experiments were determined based on the single cycle compressive results.

2. Cycled compression tests of two embossed and two TAD samples revealed that single, full compression curves can be recreated by splicing together the newly loaded portions of each successive cycled curve from an entire cycled compression experiment. Furthermore, the stiffness and feature deformation could be analyzed cycle-by-cycle, providing further information about repeated loading of the features. The results showed that embossed features typically underwent the majority of their deformation near the feature collapse point, while the TAD features had a more varied spread of deformation over compression cycles.

3. Multi-feature compression tests on one embossed sample and one TAD sample demonstrated a relationship between single-feature and larger-scale compression of structural features. Both the embossment and TAD multi-feature compression curves matched fairly well to the characteristic single-feature compressive response curves. For TAD features, however, less-than-expected loads at low displacement were exhibited in the multi-feature curves.

4. Finally, stacked compression of 16 plies of the embossed and TAD paper towels used in multi-feature compression successfully illustrated the relationship between single feature and bulk paper towel compression via the use of a force-displacement scalability model. The stacked compression curves for TAD features matched fairly well to the characteristic compressive response of single features, while for embossments the stacked compres-
sion curves did not exhibit feature collapses as seen in typical single-feature compressions. However, the multi-feature and stacked compressive responses of embossed features appeared to match quite well.

5.2. Future Work

1. Continue to improve upon automated data processing via programs such as MATLAB. Editing the script used in this study to perform the spliced and cycle-by-cycle analyses of cycled compressions could eliminate hours of work in future research.

2. The opportunity to conduct more focused cycled compressions by performing a greater number of smaller steps in load could lead to increasingly well-defined limiting loads for feature collapse as well as deformation distributions. Additionally, repeated loadings to the same stress levels could be analyzed specifically for feature deformation and recovery, perhaps with respect to time.

3. The re-introduction of a greater maximum load strain gauge could open up opportunities for further investigation of multi-feature compression. In this study, the maximum attainable loads were limited by the number of features being compressed. With a 100 or 200-gram strain gauge, multi-feature compressions could be taken up to the load levels at which feature collapse occurs in single-feature compression to make further comparisons.

4. In relation to the stacked compression experiments, performing a greater number of these stacked tests on samples with varied feature geometries and distributions as well as varying the number of plies under compression is a necessary next step. Conducting single-feature compressions in concert with stacked compressions of many different paper towel brands could lead to further connections between feature geometry and compressive response.
References


Appendix

A. Formation Maps

Figure A-1. CWP-1 grammage map with compressed features from single cycle and cycled compression experiments circled.
Figure A-2. CWP-2 grammage map with features compressed in single cycle and cycled experiments circled.
Figure A-3. CWP-2 grammage map with multi-feature areas compressed with probe tip B (5x4 mm²) marked.
Figure A-4. CWP-2 grammage map with multi-feature areas compressed with probe tip C (7x6 mm$^2$) marked.
Figure A-5. TAD-1 grammage map with features compressed during single cycle and cycled experiments circled.
Figure A-6. TAD-1 grammage map with multi-feature areas compressed with probe tip B (5x4 mm$^2$) marked.
Figure A-7. TAD-1 grammage map with multi-feature areas compressed with probe tip C (7x6 mm²) marked.
Figure A-8. TAD-2 grammage map with features compressed during single cycle and cycled experiments circled.
B. Cycled Compression

Figure B-1. Ten cycled compressions on a CWP-1 embossed feature.

Figure B-2. Spliced compression curve on a CWP-1 feature, created from Figure B-1 curves.
Figure B-3. Linear elastic region from each cycled curve from Figure B-1. Stiffness for each cycle provided.

Figure B-4. Ten cycled compressions on a CWP-2 embossed feature.
Figure B-5. Spliced curve created from cycled compression curves in Figure B-4.

Figure B-6. Linear elastic region from each cycled curve in Figure B-4; stiffness values shown.
Figure B-7. Ten cycled compressions on a CWP-2 embossed feature.

Figure B-8. Spliced compression curve created from Figure B-7 curves.
Figure B-9. Linear elastic region from each cycled curve in Figure B-7; stiffness values shown.

Figure B-10. Ten cycled compressions on a TAD-1 feature.
Figure B-11. Spliced compression curve created from Figure B-10 curves.

Figure B-12. Linear elastic region from each cycled curve in Figure B-10; stiffness values given.
Figure B-13. Ten cycled compressions on a TAD-1 feature.

Figure B-14. Spliced compression curve created from Figure B-13 curves.
Figure B-15. Linear elastic region from each cycled curve in Figure B-13; stiffness values given.

Figure B-16. Ten cycled compressions on a TAD-2 feature.
Figure B-17. Spliced compression curve created from Figure B-16 curves.

Figure B-18. Linear elastic region from each cycled curve in Figure B-16; stiffness values given.
Figure B-19. Ten cycled compressions on a TAD-2 feature.

Figure B-20. Spliced compression curve created from Figure B-19 curves.
Figure B-21. Linear elastic region from each cycled curve in Figure B-19; stiffness values given.