THE EFFECT OF STRETCH WRAP PRE-STRETCH ON
UNITIZED LOAD CONTAINMENT

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ABSTRACT

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There are three main factors affecting the stability of a palletized load that is unitized by a stretch wrapping mechanism. These factors include the type of unitized load, wrapping configuration and shipping method. The wrapping configuration is determined on the basis of the type of unitized load and shipping method. For this study, the aforementioned components were referred to as the package, the product, and the distribution environment. These components come together to make up a stretch wrapping system. The package corresponds to the stretch wrap film that is packaging the unitized load and pallet. The product corresponds to the goods placed on the pallet to be packaged by the stretch wrapper. The distribution environment corresponds to the hazards that the packaged product will encounter in transit. This study was designed to observe and understand the interactions between each of the components of the stretch wrap system. Prior to stretch wrapping a pallet of product, the film is elongated or pre-stretched. The elastic nature of the stretch wrap forces the film to conform around the palletized load. It is hypothesized that the film force that the stretch wrap applies to the palletized load contributes to improved load containment. Hence, the objective of this study was to determine the existence of a correlation between percentage pre-stretch to change in film force and load containment. For the study, a range of pre-stretched unitized loads were subjected to ISTA 3E distribution testing. Simultaneously the film

force was monitored during the period of distribution testing. Subsequent to distribution testing, the load dispersion was quantified. The data obtained from this test suggested that there is no correlation between percentage pre-stretch and change in film force or load containment. The study also compared three methods of calculating pre-stretch: the marking wheel procedure, tapeless measure, and film cut and weigh. It was found that the most consistent method was the marking wheel procedure, followed by the cut and weigh procedure, and the tapeless measure procedure.

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1.0 Introduction

Every product is packaged and transported at one point during its lifetime. Packaging efficiency has drastically increased over the years as production volumes increase exponentially. Since many products are produced in such large volumes, improving the efficiency of processes or materials can save businesses valuable resources. Most products are unitized as a palletized load. The palletized load is often contained using stretch wrap. Businesses that produce in high volume demand stretch wrapping methods that have low material usage while maintaining optimum load containment. Film pre-stretch has been considered a large factor in load containment and material usage. This study will address the relation of film pre-stretch with unitized load containment.

2.0 Literature Review

2.1 Unitized Loads

Most products are shipped on pallets in a unitized orientation in order to maintain stability and provide product protection during transit. Unitizing a load can also increase packing and handling efficiency during distribution. There are multiple ways of unitizing a load including stretch wrap, stretch hood, stretch net, and strapping or banding. This study focuses on the most common method of load unitization: stretch wrapping.

2.2 Stretch Wrapping Unitizing Loads

The most common method of load unitization is stretch wrapping. In this method, a stretchable plastic film is wrapped around the pallet of product. Linear low-density polyethylene or LLDPE is a commonly used film for stretch wrapping. There are three automation levels in stretch wrapping: manual, semi-automatic, and automatic.

Manual stretch wrap application is performed by hand. It is a slow and labor intensive method. It is also difficult to obtain consistent wraps that tightly contain the load. An example of manual stretch wrap is shown in figure 1.

Figure 1: Manual Stretch Wrap Application

Semi-automatic stretch wrapping machines apply the film mechanically but still require manual labor to move and setup the loads. Automatic stretch wrapping machines do not require any physical labor. They move the load via conveyer, setup, and wrap the load automatically.

There are three types of stretch wrapping systems: turntable, rotary arm, and orbital.

A turntable stretch wrapping system uses a rotating base to spin the load as a film carriage applies the stretch wrap. The film carriage ascends and descends about a fixed mast. An example of a turntable stretch wrapping system is shown in figure 2.

Figure 2: Turntable Stretch Wrapping System

A rotary arm stretch wrapping system applies stretch wrap with a film carriage that rotates horizontally about a fixed load. This system is better suited for loads that are fragile, unstable, or too heavy for turntable systems. An example of a rotary arm stretch wrapping system is shown in figure 3.

Figure 3: Rotary Arm Stretch Wrapping System

Orbital stretch wrapping systems apply stretch wrap with a film carriage that rotates vertically about a fixed load. The load passes through the system horizontally. An example of an orbital stretch wrapping system is shown in figure 4.

Figure 4: Orbital Stretch Wrapping System

2.3 Stretch Wrap Load Containment Factors

Stretch wrap is applied to a unitized load in order to increase load containment. Load containment allows a load to be securely held in place so it can safely arrive intact at its desired destination. Proper stretch film application increases load containment. Stretch film is properly applied when the film is elongated, applied under tension, and elastic recovery conforms the film to the load. Additional wraps, heavier gauge film, and increased post-stretch can increase load containment.

In order to obtain the maximum load containment, three factors must be considered. These factors are the unitized load type, wrapping configuration, and distribution environment.

2.3.1 Unitized Load Type

Profile Load

The type of unitized load refers to the items that are being shipped. The type of product and the orientation that the product is unitized affect the ability of the load to be contained. The items may be packaged in corrugated, paperboard, or plastic containers. Unitized loads that are uniform in shape and have no protrusions or puncture hazards are considered “A-Profile Loads”. The A-Profile Load perimeter closely matches the pallet perimeter. These loads are the easiest to wrap and contain. Loads with puncture hazards fewer than 3 inches are considered “B-Profile Loads”. They are less uniform than A-Profile Loads and may have an irregular stacking pattern. B-Profile Loads are more difficult to wrap and contain than A-Profile Loads. Loads with puncture hazards over 3 inches are considered “C-Profile Loads”. This load type is the most difficult to contain.

Its size and shape vary significantly on each face of the load. A-Profile Loads tend to be composed of homogenous products while B and C-Profile Loads tend to contain mixed product. B-Profile Loads generally exist in smaller manufacturing and distribution warehouse locations. They contain two or three types of product destined for a single destination. C-Profile Loads are often assembled at distribution centers for retail store locations and contain many different types of product. Examples of A, B, and C-Profile loads are shown in figure 5. [8]

Figure 5: A, B, and C Profile Loads

Load Perimeter

Load perimeter may also affect the ability of a load to be contained. A load with a larger width and length is less dense than a load with a smaller width and length (assuming the height and weight are constant). The less dense a load, the easier it is to contain during transit. Thus, as load perimeter increases, load density decreases and the load becomes less difficult to contain.

Load Height

The effect of load height on containment is more difficult to define. As the height of the load increases, the density decreases and the load becomes easier to contain. However, as the height increases, so does the center of gravity. This causes the load to become unstable. Thus, an increase in load height can either increase or decrease ease of containment, depending on other load variables such as weight and perimeter.

2.3.2 Wrapping Configuration

There are many variables that can be altered when stretch wrapping a pallet. These variables affect the ability of stretch wrap to contain the load.

Wrap Pattern

One of the options is the wrap pattern. Wrap pattern refers to the location that the stretch film is applied. Commonly, the bottom wraps are applied first. Then the carriage spiral wraps while ascending and slightly overlaps the film until it reaches the top. The top wraps are then applied. The carriage then spiral wraps down until it reaches the bottom. The turntable then finds its home position, decelerates, and stops. Alternative wrap patterns are also used such as wrapping the top first and the bottom second. This wrap pattern can be used to secure multiple stacked pallets or bulk bin tops.

Film Force to Load

Film force to load is tension created due to the stretch films attempt to return to its original state after having been stretched. Film force is produced by creating tension between the load and the film carriage. This can be accomplished by reducing the film

feed. As the film feed decreases, the load demand pulls the film and creates film force between the film and the load. The tension can also be created by mechanically delaying the dancer bar arm. Delaying the dancer bar arm reduces the film feed leaving the carriage. [11] The dancer bar also supplies the varying film demand of the load during rotation. This occurrence is called corner demand. A 48" x 40" load creates three different distances from the film carriage: the corner, the short face, and the long face of the pallet. The progression of these distances during rotation requires a fluctuating supply of film by the carriage. The dancer bar compensates for the change in demand. It does this by accumulating a length of film using a roller and spring during a period of low film demand. When the film demand increases, the dancer bar extends, releasing the accumulated film. [1] Corner demand is illustrated in figure 6.

Figure 6: Corner Demand

Number of layers

Applying more layers to the top and bottom of a load can provide better load containment. Each additional layer increases the overall film force. This phenomenon is called benefit per layer and is illustrated in figure 7.

Figure 7: Benefit per Layer

Turntable and Carriage Speed

Turntable and carriage speed can also be adjusted on most stretch wrappers. Turntable speeds can range from 1-16 revolutions per minute. Increasing the turntable RPM can decrease wrap time. However, increasing the RPM also increases the centripetal force endured by the product and can cause the load to fall while in rotation. Higher RPM's can also lead to film breaks. Carriage speed is adjusted in order to compensate for a change in

turntable speed and provide the desired film overlap. Film overlap is necessary to strengthen the bonding of each layer of film in the center of the load.

Pre-stretch

Pre-stretch is the process of stretching film before it is applied to the load. The film is fed through a primary and secondary roller inside the film carriage. The primary and secondary rollers are shown in figure 8. The rollers rotate at different speeds, stretching the film to its desired length. The tension created by stretching the film is isolated between the two rollers. This force is referred to as F_1 . Since the force of F_1 is isolated between two rollers, the film can be stretched with a high force and applied with little force. This prevents the packaged units from being pulled from the load. For example, 200% stretch takes 1 inch of film and turns it into 3 inches of film. In order to obtain 200% stretch, the primary roller is rotated at 12 rpm and the secondary roller is rotated at 36 rpm. Most films can reach up to 400%. The average stretch level on new machine installations as of 2010 was 180% stretch. [1]

Figure 8: Primary and Secondary Rollers

Film Elongation

When film is elongated, it experiences an elastic region. In this region the film can deform, but when the force is removed it returns to its original shape. Once the elastic limit has been reached, the film begins to exhibit plastic behavior and permanent deformation. The film then undergoes strain hardening and its tensile strength increases significantly. Next, the film reaches its ultimate stress. It then begins to neck and will eventually fracture.

Film type

There are many different types of stretch film designed to address different stretch wrapping needs. The two most common types are blown stretch film and cast stretch film.

Blown stretch film is created by feeding beads of plastic resin through a heated die. After the resin is extruded through the die, it is blown vertically into a thin walled tubular bubble. An air ring is blown around the tube to cool the resin. The tube is pulled upwards and then fed through rollers that flatten the tube into two layers. The flattened tube is slit on each side to produce two sheets of film. The two sheets of film are then wound into a roll. [7] [12]

Cast stretch film is also created by extruding resin through a heated die. The slit shaped die creates sheets of extruded resin. The extruded sheet is then passed through chilled, polished rollers where it can solidify and reach its desired thickness. Finally, it passes a system of rollers that wind the sheet into a roll. [13]

Blown film has greater load retention than cast stretch film. Once applied, blown film's memory allows it to conform to the load and resist re-stretching as the load shifts. It can also be stretched further than cast films, yielding greater load coverage per foot of film. The blown film manufacturing process gives the film greater puncture resistance qualities. Cast film has better visual clarity than blown film. This increases reading and scanning ability. Cast film also creates less noise while unwinding. This reduces the decibel level in the workplace. [10]

2.3.3 Distribution Environment

The distribution environment refers to the dynamic and static stresses that a unitized load will endure during transit and warehousing. It often causes unitized load failure and is a critical factor when deciding what load type and wrapping configuration to use. The severity of the shipping environment and the intensity of the hazards that the load will endure are evaluated and used to determine what method of containment is necessary.

Unitized loads in less than truckload (LTL) shipments are subjected to a harsher environment than truckload shipments (TL). TL shipments utilize cabin space more efficiently than LTL shipments. This reduces void space in the cabin and decreases movement during transport. TL shipments commonly have one destination while LTL shipments have multiple stops and handling which results in rougher treatments and more load failures.

3.0 Objective

The objective of this study was to compare three methods of calculating pre-stretch: the marking wheel procedure, tapeless measure, and film cut and weigh. These are three standard procedures used for measuring film elongation. It is necessary to manually measure film elongation as stretch wrapping machines can often vary.

The study also intended to observe the interactions between the aforementioned factors of the stretch wrap system. It sought to determine the existence of a correlation between percentage pre-stretch to change in film force and load containment during simulated distribution. It is a common assumption in industry that higher film force correlates to better load containment. It is also hypothesized that higher pre-stretch values prevent film force from decreasing, and thus provide better load containment.

4.0 Materials and Methods

4.1 Experimental Design

In order to evaluate the relationship between percentage pre-stretch to change in film force and load containment, unit loads of stock boxes were stretch wrapped with a range of 5 pre-stretch levels: 100, 150, 200, 250, and 300 percent. The unitized loads were subjected to ISTA 3E standardized distribution testing in a certified packaging dynamics laboratory at California Polytechnic State University, California.

Film force was observed prior to, during, and subsequent to distribution testing with a wireless portable film force measurement system. Film force was measured at the top, middle and bottom locations of face 5 of the unitized load as per ASTM D 4649 [6]. Load dispersion was quantified subsequent to distribution testing. This included measurements to quantify load shifting, including overhang and change in perimeter.

4.2 Constant Variables

The following variables were held constant throughout the experiment:

Table 1: Constant Variables

Variable	Value
Wrap Pattern	Bottom to Top
Film Force	4.5
Turntable Speed	12 RPM
Carriage Speed	45%
Top and bottom wrap counts	2

Unitized Load	50 regular slotted containers (20 lbs ea) on a 48"x40" CHEP pallet
Film Type	MP2 0.7 Mil
Film Overlap	4"
Pallet Wrap	4"

4.3 Test Load Construction

The test load was composed of fifty 16"x12"x8" regular slotted containers. The dimensions of the regular slotted container are illustrated in figure 9. The load consisted of 10 containers per layer for a total of 5 layers. The containers were arranged in a ten down pattern. Each container was loaded with 20lbs of dead weight. The dead weight consisted of 20lb sand bags. Expanded polystyrene blocks were used to fill the headspace in the container so the dead weight could support the load. The containers were placed on a 48" x 40" x 5" CHEP pallet. The load had 0.5" of overhang on each side of the pallet.

Test Load Construction Procedure:

1. Erect ten 16"x12"x8" regular slotted containers (see RSC dimensions) and seal bottom with one strip of clear 2 mil industrial tape.
2. Insert an expanded polystyrene block into each erected container.
3. Place 20 lb sand bag on top of expanded polystyrene block, making sure that the sand is evenly dispersed about the surface of the block.
4. Seal top of containers with of clear 2 mil industrial tape.
5. Arrange containers in a 10 down pattern (see figure 10) on a 48" x 40" CHEP pallet.
6. Repeat steps 1-5 until the load measures 5 tiers high.

Figure 10: Pallet Pattern

4.4 Film Force Measurements

Portable Film Force System

The portable film force system used for this experiment consists of a primary load cell and two secondary load cells each attached to 6” diameter force plates. See figure 11. The load cells are designed to measure the containment force at the top, middle, and bottom of the unitized load. The load cells are attached to each other with a 2” strap and buckles. The three load cells are balanced on face 5 of the pallet with the support of counter weights on the opposite side of the pallet. The primary load cell is positioned so that its center is 18” from the left of the face and 10” from the top of the load as required by ASTM 4649 [6]. The three load cells are electrically connected via USB to a wireless transmitter located behind the primary load cell. The transmitter sends the data recorded by the load cells wirelessly to a computer.

Portable Film Force System Procedure:

1. Attach 6” diameter force plates to one primary and two secondary load cells.
2. Connect each load cell using 2” straps and buckles.
3. Plug each load cell USB cable into the primary load cell ports.
4. Attach three load cell counter weights with a 2” buckle.
5. Drape the three load cells over face 5. Arrange primary load cell so that it is 18” from the left and 10” from the top of the load. (See figure 12)
6. Drape attached counter weights over face 6.
7. Plug the battery charger into primary load cell and arrange charger as shown in figure 11.

8. Turn on primary load cell with toggle switch.
9. Using wireless laptop, connect software to load cells.
10. Tare each load cell.
11. Start test.

Figure 11: Portable Load Cell

Figure 12: Load Cell Placement

Pull plate

Pull plate is a destructive method used to measure film force. It uses a 6 inch diameter non-yielding plate with an attached eyelet and a fish type scale to measure the force that a film is exerting on a load at 4" from the face. The standard method was obtained from ASTM 4649 [6]. A 24" ruler with a 4" bolt attached was used to locate the pull plate in the correct orientation.

Pull Plate Procedure:

1. Place 6" pull plate between the film and the load at a measured location 10" from the top and 18" from the left side of the load on face 5.
2. Cut a 1" wide horizontal slit in the film to allow the pull plate eyelet to protrude through the film. See figure 13.
3. Attach the film scale hook to the eyelet of the film force plate.
4. Pull the scale 4" away from the load using the 4" bolt as reference.
5. Record the force (lbs) required to pull the plate 4" from the load was recorded.

Figure 13: Pull Plate Procedure

4.5 Stretch Wrapping

For the experiment, a Synergy 4 Semi-Automatic Stretch Wrapper was used to apply the stretch film to the load. The film used was 0.7 Mil MP2 manufactured by Berry Plastics.

Stretch Wrapping Procedure:

1. Plug the machine into a 120V, 20A receptacle. Turn the main disconnect switch clockwise. See figure 14.

Figure 14: Power Switch

2. Ensure the machine is powered up. Pull the Emergency Stop button fully out, then release to restore power to the machine. Ensure the film carriage door is closed.
3. Under the main navigation screen, make sure the system power is ON. Select OPERATOR CONTROL SCREEN. Press the SYSTEM RESET button on the OPERATOR SCREEN. See figure 15. The wrap cycle will be reset and the turn table will return to its home position.

Figure 15: Navigation and Operator Screens

4. Once the table has moved to home position, select the BOTTOM WRAPS FIRST – TOP WRAPS SECOND wrap pattern from the wrap pattern selector on the OPERATOR SCREEN.
5. Select desired package PRE-STRETCH.
6. Set film force to 4.5.
7. Select FILM ASSIST. Pressing the button will allow film to be fed out while the dancer bar is pulled. Ten seconds will be provided to attach the film to the home corner of the pallet. See figure 16.

Figure 16: Attaching Film to Pallet

8. Press the CYCLE START button to initiate a wrap cycle.
9. Record amount of film dispensed with tapeless measure according to tapeless measure procedure.
10. Mark film with marking wheel according to marking wheel procedure.
11. After cycle has ceased, cut film 6" past edge 4-5 and wipe to load.

4.6 Percentage Film Pre-Stretch Calculation Methods

Marking Wheel

The marking wheel procedure is a method for determining percentage stretch of a contained load. The marking wheel tool places marks of a known distance on the unstretched film. The distance between the marks changes as the film is stretched. The

new length is measured and compared to the original length to obtain the film stretch percentage. The film stretch percentage obtained from this procedure corresponds to one specific location on the load, not the average film stretch percentage of the load. [6]

Marking Wheel Procedure:

1. Begin stretch wrap cycle.
2. While film carriage is applying the bottom layers of film, press marking wheel to center of film roll. See figure 17.
3. Allow wheel to apply 2 marks.
4. Depress marking wheel.
5. While film carriage is rising towards the top of the load, press marking wheel to center of film roll.
6. Allow wheel to apply 2 marks.
7. Depress marking wheel.
8. While film carriage is applying the top layers of film, press marking wheel to center of film roll.
9. Allow wheel to apply 2 marks.
10. Depress marking wheel.
11. Measure the distance between the marks at the bottom, middle, and top of the load.
12. Use the values recorded in the calculation provided below. See figure 17.

Figure 17: Marking Wheel and Calculation

Since the marking wheel procedure corresponds to the percentage film stretch at one specific location on the load, three measurements were taken and an average was calculated. The three measurement locations were located at the top, middle, and bottom of the load.

Tapeless Measure

The tapeless measure procedure is another method for determining the percentage stretch of a contained load. In this procedure, the total perimeter of the load is measured. If the load is not uniform, the largest path of the wrap is recorded. As the load is being wrapped, a tapeless measure is used to measure the total film length that is applied to the load. The perimeter of the load is multiplied by the number of turntable revolutions to obtain the total wrapped length. The total wrapped length is compared to the total film length to calculate the percentage stretch of the load. The percentage film stretch obtained

from this procedure does not correspond to one specific location on the load, rather the average percentage film stretch of the load. [6]

Tapeless Measure Procedure:

1. Tare tapeless measure. See figure 18
2. Press tapeless measure to center of film roll. See figure 19
3. Begin stretch wrap cycle.
4. Once wrap cycle has ceased, record tapeless measure value.
5. Use the value recorded in the tapeless measure calculation. See figure 18.

Figure 18: Tapeless Measure and Calculation

Figure 19: Marking Wheel and Tapeless Measure Procedure

Film Cut and Weight

The cut and weight procedure is a destructive method for determining percentage film stretch of a contained load. In this procedure, the film is removed from the load after the wrap cycle has finished. The cut film is then weighed on a scale. The cut film weight is compared to the weight of the film if it were not pre-stretched in order to obtain the percentage film stretch of the load. Because this method is a destructive test, the procedure was conducted after the distribution test.

Cut and Weight Procedure:

1. Cut film from load after distribution sequence has ceased.
2. Roll film into a tight ball.

- [illegible]

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always secured together or restrained for distribution as a single load.” [9] The test challenges the capability of the product, package, and unitized load to withstand simulated transport hazards. These simulated hazards subject the unitized load to vibration, shock, compression and other stresses normally encountered during handling and transportation.

The faces are identified as single numbers (e.g. face 1), edges are identified by locations where 2 faces meet (e.g. edge 3-4) and corners are identified by the location at which the three faces meet (e.g. corner 3-4-5). See figure 21.

Figure 21: Pallet Labeling

The test sequence used to simulate distribution and storage is shown below (Table 2).

Table 2: ISTA 3E Test Procedure

Sequence #	Test Category	Test Type	Test Level
1	Atmospheric Conditioning	Temperature and Humidity	Ambient
2	Shock	Incline Impact (Conbur)	42 in/sec
3	Shock	Rotational Edge Drop	8 in
4	Compression	Machine Apply and Release	Calculated Test Force x 1.4
5	Vibration	Random	Overall Grms level of 0.54
6	Shock	Rotational Edge Drop	8 in

Sequence 1 - Atmospheric Conditioning Procedure (Temperature and Humidity):

The corrugated containers were stored prior to testing at laboratory ambient temperature and humidity for 12 hours [3].

Sequence 2 – Shock Procedure (Incline Impact):

The incline impact procedure tests a loads ability to withstand horizontal impacts. It is used to simulate manual and mechanical handling of palletized loads [5]. The apparatus uses a guided carriage to bring the load into contact with an impact surface called a backstop. The sequence for this test is provided in Table 3 and illustrated in Figure 22.

Incline Impact Procedure:

1. Center the unitized load on the carriage with the desired vertical face of the unitized load flat against the backstop and parallel to the leading edge of the carriage (Figure 22). Follow the sequence in Table 3.
2. Raise the pneumatic cylinder to a displacement of 10 inches.

3. Release and allow the carriage to impact the backstop.
4. Check to see if the unitized load reached the minimum impact velocity of 42 in/s.
5. Lower the pneumatic cylinder and allow carriage to return.
6. Repeat steps 1-5 for tests 2 and 3.

Figure 13: Incline Impact Test

Figure 22: Incline Impact Test Setup

Table 3: Incline Impact Test Sequence

Test #	Orientation	Specific Face	Face Tested
1	Face	One of the smallest vertical faces	2
2	Face	Opposite small vertical face	4
3	Face	One of the largest vertical faces	5

Sequence 3 – Shock Procedure (Rotational Edge Drop):

The rotational edge drop procedure tests a loads ability to withstand rotational impacts. It is used to simulate manual forklift handling in a warehouse environment. The sequence for this test is provided in Table 4 and illustrated in Figure 23.

Rotational Edge Drop Procedure:

1. Place unitized load onto a flat, rigid surface.
2. Support edge 3-2 with a wooden block 4" in height and width. See figure 232.
3. Lift the opposite face 3 edge 8" from the surface of the ground.
4. Support the edge with an 8" wooden block.
5. Release the edge so that it falls freely onto the surface (impact on edge 3-4).
6. Repeat step 1 so that the impact is on edge 3-6.

Figure 23: Rotational Edge Drop Test Setup

Table 4: Rotational Edge Drop Sequence

Sequence #	Orientation	Specific Edge	Edge Impacted
1	Edge	One of the smallest edges	3-4
2	Edge	One of the largest edges	3-6

Sequence 4 – Compression Test Procedure (Machine Apply & Release):

The compression test procedure tests a loads ability to resist external compressive forces applied to the top face. It is used to simulate stacking of multiple loads [4]. The test is illustrated in Figure 24. The warehouse compression calculation for the apply-and-release test force is determined by the following equation:

$$\text{Apply – and – release test force} = W_t \times (S - 1) \times F \times 1.4$$

$$\text{Apply – and – release test force} = 1000 \text{ lbs} \times (2 - 1) \times 3 \times 1.4$$

$$= 4,200 \text{ lbs}$$

Where:

$$W_t = \text{Gross weight of the unitized load (lbs)}$$

$$S = \text{Total number of potential unitized loads in a warehouse stack, including bottom load}$$

F = Compensating factor (accounts for effects such as temperature/humidity conditions, misalignments, long-duration loading, etc.)

1.4 = Factor to account for time of compression

The compensating factor, F, accounts for effects that may not be simulated in the laboratory test such as temperature/humidity conditions, misalignments, long-duration loading, etc. When using the apply and release method for compression testing, the larger of the two calculated test forces will always be the warehouse compression due to the lack of a stacking value in the vehicle compression formula. Therefore, the decision between the larger stacking values must be made prior to applying the 1.4 compensating factor.

Compression Test Procedure:

1. Centered the unitized load on the lower platen of the compression tester with face 5 towards the operator. See figure 24.
2. Lower the platen to 0.5" above the load
3. Set the moving platen to a speed of 0.5 in/minute.
4. Set load to 4,200 lbs
5. Apply load and immediately released.

Figure 24: Compression Test Setup

Sequence 5 – Vibration Test Procedure (Random):

This procedure tests a loads ability to withstand random vibration input. The procedure simultaneously excites the resonances of the product, container, and load [2]. It is used to simulate the vibration experienced on a truck in transit. The duration of the test correlates to the number of miles simulated. In this experiment, the unitized loads were subjected to random vibration for a duration of 1 hour, simulating a 300 mile trip. See formula. The sequence for this test is provided in Table 5 and illustrated in Figure 25.

$$60 \text{ min} = \frac{(\text{Transportation Miles})}{5}$$

Transportation Miles Simulated = 300 Miles

Random Vibration Test Procedure:

1. Place the unitized load on the vibration table with face 3 resting on the platform.
See figure 25.
2. Fasten restraining devices to prevent the specimen from moving off the platform and maintain the orientation of the packaged product. Make sure the restraining devices do not restrict the vertical motion of the specimen during the test.
3. Enter the power spectral density breakpoints (Table 5) into the vibration controller to produce the acceleration versus frequency profile in Figure 26, with an overall G_{rms} level of 0.54.
4. Set vibration duration to 1 hour.
5. Begin vibration test.

Figure 25: Vibration Test Setup

Table 5: PSD Breakpoints

Frequency (Hz)	PSD Level, g^2/Hz
1	0.00005
4	.01
16	.01
40	.001
80	.001
200	.00001

Figure 26: ASTM Truck II Random Vibration Spectrum

Sequence 6 – Shock Procedure (Rotational Edge Drop):

The rotational edge drop procedure tests a loads ability to withstand rotational impacts. It is used to simulate the manual forklift handling in a warehouse environment. The sequence for this test is provided in Table 6 and illustrated in Figure 27.

Rotational Edge Drop Procedure:

1. Place unitized load onto a flat, rigid surface
2. Support edge 3-4 with a wooden block 4" in height and width. See figure 27.
3. Lift the opposite face 3 edge 8" from the surface of the ground.
4. Support the edge with an 8" wooden block

5. Release the edge so that it falls freely onto the surface (impact on edge 3-2)
6. Repeat step 1 so that the impact is on edge 3-5

Figure 27: Rotational Edge Drop Test Setup

Table 6: Rotational Edge Drop Sequence

Sequence #	Orientation	Specific Edge	Edge Impacted
1	Edge	One of the smallest edges	3-2
2	Edge	One of the largest edges	3-5

4.8 Load Dispersion Quantification

Pallet Overhang Quantification

This procedure was designed to quantify the movement of a unitized load in relation to its pallet. A load that is overhanging significantly on one side can change the center of gravity and induce load failure. A procedure was created to quantify pallet overhang in order to compare the effect of pre-stretch on load dispersion. This test is illustrated in Figure 28.

Pallet Overhang Quantification Procedure:

1. Place an L-square ruler perpendicular to the edge of the pallet.
2. Drape a plumb bob suspended by string over the top edge of the load until it reaches the L-square ruler. See figure 28.
3. Use the vertical reference line to observe the distance that the load is overhanging at that particular point.
4. Observe overhang every 5 inches along the face and record the largest value observed.
5. Repeat steps 1-4 for remaining 3 faces of the load.

Figure 28: Pallet Overhang Test Setup

Load Perimeter Quantification

During transit, containers can migrate outwards from the center of the load. This creates overhang and produce voids within the load. The movement misaligns the walls of the corrugated containers, weakening the compression strength of the load. The movement also changes the center of gravity and weakens the containing stretch film. A procedure was created to quantify the load perimeter in order to compare the effect of pre-stretch on load dispersion. This test setup is illustrated in Figure 29.

Load Perimeter Quantification Procedure:

1. Attach one end of a 16' string to the center of the top load cell plate with a strong magnet.
2. Pull the string around the perimeter of the load making sure it is at the same height about the entire load. See Figure 29.
3. Mark string length where it reaches the starting end of the string.
4. Measure and record the string length.
5. Repeat steps 1-4 on the middle and bottom load cells.

Figure 29: Load Perimeter Test Setup

5.0 Results and Discussion

5.1 Comparison of Pre-Stretch Calculation Methods

Three methods were used to record the output percentage stretch of a semi-automatic stretch wrapper. These methods were tested on five different input stretch levels: 100%, 150%, 200%, 250%, and 300%. Three replicates were tested. The calculated output stretch percentage was converted to a percentage deviation from the input stretch percentage. For example, if the input stretch percentage is 100% and the marking wheel method measured a stretch percentage of 90%, then the percentage deviation would be negative10%.

The following table displays the percentage deviation of each pre-stretch calculation method:

Table 7: Percentage Deviation of Pre-stretch Calculation Method

Input Stretch %	Input vs. Mark Wheel	Input vs. Tapeless	Input vs. Cut and Weigh
100.00%	-7.08%	20.13%	-5.57%
100.00%	-11.25%	-17.77%	5.28%
100.00%	-2.08%	-11.01%	16.24%
150.00%	-10.50%	-28.96%	2.25%
150.00%	-9.47%	-28.96%	0.53%
150.00%	-1.33%	-18.25%	15.00%
200.00%	-2.08%	-28.46%	8.66%
200.00%	3.33%	-24.15%	10.23%
200.00%	-7.50%	-31.52%	-0.93%
250.00%	-10.83%	-45.71%	-4.99%
250.00%	-8.75%	-43.20%	4.28%
250.00%	-6.67%	-43.20%	-10.77%
300.00%	-15.00%	-58.88%	-23.20%
300.00%	-16.67%	-62.06%	-25.49%
300.00%	-10.83%	-60.16%	-20.74%

The following table displays the average percentage deviation of each pre-stretch calculation method:

Table 8: Average Percentage Deviation of Pre-stretch Calculation Method

Input Stretch %	Average Input vs. Mark Wheel	Average Input vs. Tapeless	Average Input vs. Cut and Weigh
100.00%	-6.81%	-2.88%	5.31%
150.00%	-7.10%	-25.39%	5.93%
200.00%	-2.08%	-28.04%	5.98%
250.00%	-8.75%	-44.04%	-3.82%
300.00%	-14.17%	-60.37%	-23.14%

In order to determine if there is a relationship between input percentage pre-stretch and calculation method, an analysis of variance was performed. An ANOVA 1 Way test was used with the following inputs:

- Factor: Desired Percentage Pre-Stretch
- Response: Calculation Method
- P-Value is < .05 reject null

H₀= Calculation method has no association with input percentage pre-stretch

H_a= Calculation method is associated with input percentage pre-stretch

The following P-Values were generated for the film force calculation methods:

Table 9 : Pre-Stretch Calculation Method P-Values

ANOVA	Mark Wheel Calculation	Tapeless Measure Calculation	Cut and Weigh Calculation
P-Value	0.062	0	0.003
R or FTR Ho	FTR	REJECT	REJECT

The P-Values generated from the ANOVA 1-Way test reject the null hypothesis in support of the alternative hypothesis for the tapeless measure and cut and weigh methods. The P-Value for the marking wheel method fails to reject the null hypothesis. There is no evidence suggesting that there is an association between the marking wheel procedure and input percentage pre-stretch. There is an inverse relationship with the input percentage pre-stretch and the deviation of the tapeless measure and cut and weigh methods. The tapeless measure and cut and weigh methods deviate in the negative direction as percentage pre-stretch increases. The marking wheel procedure deviation is not affected by percentage pre-stretch.

The following scatterplot compares the input percentage pre-stretch with the calculation methods:

Figure 30: Scatterplot of Pre-stretch Calculation Methods

The scatterplot of the data suggests that the marking wheel procedure is the most consistent and generates the closest values to the input percentage pre-stretch. The cut and weigh procedure is the second most consistent and is closer to the input percentage pre-stretch than the tapeless measure procedure. The tapeless measure procedure is the least most consistent and accurate method of determining percentage pre-stretch.

5.2 Relationship between Pre-Stretch and Film Force

Initial Film Force

The initial film force was defined as the film force observed by the portable film force system immediately after the wrap cycle has completed. The values were recorded before the first distribution sequence took place.

The following bar graphs depict the film force experienced by each individual load cell while being subjected to a range of input pre-stretch levels:

Figure 31: Individual Load Cell Initial Film Force

No obvious trend was observed by looking at the individual bar graphs. In order to visually compare the difference between the top, middle, and bottom film forces, the three individual bar graphs were overlaid on figure 32. The film forces observed by the middle load cell were consistently less than both the top and bottom load cells. This can be explained by the wrap cycle used. First, the cycle applied two layers of stretch wrap to the bottom of the load. The carriage then rose as the load continued to rotate, applying one layer to the middle. Next, the carriage applied two layers to the top. After the top layers were applied, the carriage returned to the bottom of the load. The middle of the

load experienced less film force because fewer layers were applied in this location than on the top and bottom of the load.

Figure 32: Overlaid Initial Film Force Values

In order to determine if there is a relationship between input percentage pre-stretch and initial film force, an analysis of variance was performed.

An ANOVA 1 Way test was used with the following inputs:

- Factor: Pre-Stretch
- Response: Initial Film Force
- P-Value is < .05 reject null

H_0 = Initial film force has no association with pre-stretch

H_a = Initial film force is associated with pre-stretch

The following P-Values were generated for initial film force:

Table 10: Initial Film Force P-Values

ANOVA	Bottom Film Force	Middle Film Force	Top Film Force
P-Value	0.513	0.848	0.735
R or FTR Ho	FTR	FTR	FTR

All P-Values generated for the initial film force failed to reject the null hypothesis. There is no evidence suggesting an association between initial film force and percentage pre-stretch.

Change in Film Force

In order to interpret the film force values recorded during distribution testing, the values were converted in two ways. The first method converted the values to a percentage deviation from the previous sequence film force values. This was called individual section film force value. For example, if the initial film force was recorded as 15 lbs, the film force recorded after sequence one was 14.25 lbs, and the film force recorded after sequence two was 13.5 lbs, then the individual section film force percentage deviation was calculated to be negative 5% for sequence two. The second converted the values to a percentage deviation from the initial film force values. This was called the cumulative film force value. For example, if the initial film force was recorded as 15 lbs, the film force recorded after sequence one was 14.25 lbs, and the film force recorded after sequence two was 13.5 lbs, then the cumulative film force percentage deviation was calculated to be negative 10% for sequence two. Figure 33 shows the film forces for the top, middle and bottom load cells plotted over time. The graph has been divided into

sections for each sequence of the distribution test. Figure 34 shows the difference between the individual section film force value and the cumulative film force value.

Figure 33 : Film Force Potted Over Time

Figure 34: Sectional vs. Cumulative Film Force Values

In order to determine if there is a relationship between input percentage pre-stretch and change in film force, an analysis of variance was performed.

An ANOVA 1 Way test was used with the following inputs:

- Factor: Pre-Stretch
- Response: Change Film Force
- P-Value is $< .05$ reject null

H_0 = Change in film force has no association with input pre-stretch

H_a = Change in film force is associated with input pre-stretch

The following P-Values were generated for the Individual Section Film Force Values:

Table 11: Individual Section P-Values

Sequence	TOP P-Value	MID P-Value	BOT P-Value
1: Incline Impact	0.317	0.036	0.768
2: Rotational Edge Drop	0.323	0.275	0.807
3: Compression	0.237	0.198	0.279
4: Vibration	0.679	0.52	0.414
5: Rotational Edge Drop	0.368	0.486	0.097
1 Hour Static	0.675	0.015	0.344

For the individual section film force values, the majority of the P-Values generated failed to reject the null. There was no evidence suggesting that there is an association between the change in film force of the individual section values with the input pre-stretch levels.

2 out of 18 P-Values were less than 0.05, however there is a very high possibility that

these were obtained by chance. It is not likely that there was any association for those two sequences.

The following P-Values were generated for the Cumulative Film Force Values:

Table 12: Cumulative P-Values

Sequence	TOP P-Value	MID P-Value	BOT P-Value
1: Incline Impact	0.317	0.036	0.768
2: Rotational Edge Drop	0.397	0.667	0.883
3: Compression	0.239	0.097	0.619
4: Vibration	0.555	0.555	0.403
5: Rotational Edge Drop	0.815	0.886	0.708
1 Hour Static	0.817	0.854	0.742

For the cumulative film force values, the majority of the P-Values generated failed to reject the null. There was no evidence suggesting that there is an association between the change in film force of cumulative values with the input pre-stretch levels. 1 out of 18 P-Values were less than 0.05, however there is a very high possibility that it was obtained by chance. It is not likely that there was any association for this sequence.

Traditional Pull Plate Method

The traditional pull plate method was also used to record the final film force values. This method was not used after the wrap cycle or during distribution because it is a destructive test.

In order to determine if there is a relationship between input percentage pre-stretch and pull plate film force, an analysis of variance was performed.

An ANOVA 1 Way test was used with the following inputs:

- Factor: Pre-Stretch Response: Pull Plate Film Force
- P-Value is < .05 reject null

H₀= Pull Plate Film Force has no association with pre-stretch

H_a= Pull Plate Film Force is associated with pre-stretch

The following P-Values were generated for the pull plate method:

Table 13: Pull Plate P-Values

ANOVA	PP Face 2	PP Face 4	PP Face 5	PP Face 6
P-Value	0.58	0.05	0.62	0.19
R or FTR Ho	FTR	FTR	FTR	FTR

The P-Values generated from the ANOVA test failed to reject the null hypothesis. There is no evidence suggesting that pull plate film force has an association with pre-stretch.

5.3 Relationship between Pre-Stretch on Load Dispersion

Load dispersion was quantified in two ways: load overhang and load perimeter.

In order to determine if there is a relationship between input percentage pre-stretch and load dispersion, an analysis of variance was performed.

- ANOVA 1 Way: Analysis of Variance
- Factor: Pre-Stretch Response: Load Dispersion
- P-Value is < .05 reject null

H₀= Load dispersion has no association with pre-stretch

H_a= Load dispersion is associated with pre-stretch

The following P-Values were generated for the load overhang quantification method:

Table 14: Overhang P-Values

ANOVA	2 OH	4 OH	5 OH	6 OH	Total OH
P-Value	0.833	0.115	0.368	0.598	0.832
R or FTR Ho	FTR	FTR	FTR	FTR	FTR

The following P-Values were generated for the load perimeter quantification method:

Table 15: Perimeter P-Values

ANOVA	Top Perimeter	Mid Perimeter	Bot Perimeter
P-Value	0.34	0.90	0.60
R or FTR Ho	FTR	FTR	FTR

All of the P-Values for the load overhang and load perimeter method failed to reject the null hypothesis. There is no evidence suggesting an association with load dispersion and percentage pre-stretch.

6.0 Conclusion

6.1 Summary of results

The findings from this study suggested that the marking wheel procedure is the most consistent method for measuring percentage pre-stretch, followed by the cut and weight procedure and the tapeless measure procedure. No evidence suggesting an association between the marking wheel procedure and input percentage pre-stretch was found. The results from the experiment did suggest that there is an association between the cut and weigh procedure and the tapeless measure procedure with input percentage pre-stretch. The tapeless measure and cut and weigh methods deviate in the negative direction as percentage pre-stretch increases. The marking wheel procedure deviation is not affected by percentage pre-stretch.

The findings also showed that film force is generally higher at the top and bottom of the load than the middle of the load. No evidence suggesting an association between initial film force and percentage pre-stretch was found.

No evidence suggesting that there is an association between the change in film force of the individual section values with the input pre-stretch levels was found from the distribution test. No evidence suggesting that there is an association between the change in film force of cumulative values with the input pre-stretch levels was found from the distribution testing.

No evidence suggesting that pull plate film force has an association with pre-stretch was found after distribution testing.

Finally, no evidence suggesting an association with load dispersion (load perimeter or overhang) and percentage pre-stretch was found.

6.2 Significance of results

The findings from the study suggest that percentage pre-stretch does not have an effect on film force or load dispersion. This means that a load can be wrapped with the highest possible pre-stretch level without sacrificing film force, load dispersion, and possibly load containment. Using high pre-stretch levels decreases the total amount of film used per load, decreasing film costs.

6.3 Suggested further research

As mentioned earlier, load containment is dependent on three factors: unitized load type, wrapping configuration, and distribution environment. This study focused on one main variable, film pre-stretch. The goal was to determine if there is a correlation between percentage pre-stretch to change in film force and film force/ load containment during simulated distribution. It was found that there is no correlation between pre-stretch and film force/ load containment.

Further research could be conducted to observe the relationships between the following:

- Input film force and output film force / containment force / load containment
- Warp pattern and Δ film force / containment force / load containment
- Stacking orientation and Δ film force / containment force / load containment
- Distribution cycle and Δ film force / containment force / load containment
- Container size and Δ film force / containment force / load containment
- Film force / containment force and load containment

An alternative method of quantifying load dispersion can also be investigated such as a 3D scanning system. In this method, a coating of opaque aerosol is applied to the exterior of the load. The load is scanned using a 3D system such as ScanWorks or Perceptron. Software is used to scan, import and view a point cloud. This allows the load to be viewed in sections. Innovmetric produces software capable of this process. With this method, load dispersion can be quantified about the entire pallet in a consistent and repeatable fashion.

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Appendices

Appendix A: Initial and Final Film Force Values

Initial Film Force

Pre-stretch	Wrap-Top	Wrap-Mid	Wrap-Bot
100-1	11.71	7.65	10.92
100-2	11.58	7.46	11.36
100-3	11.30	8.32	11.91
AVG	11.53	7.81	11.40
150-1	9.98	6.40	10.03
150-2	10.24	7.06	10.62
150-3	11.43	8.60	12.36
AVG	10.55	7.35	11.00
200-1	11.29	7.21	10.81
200-2	10.48	7.91	13.44
200-3	11.00	7.05	10.74
AVG	10.92	7.39	11.66
250-1	11.87	7.83	12.57
250-2	10.04	7.15	10.96
250-3	10.53	7.18	11.44
AVG	10.81	7.39	11.66
300-1	9.79	7.02	9.12
300-2	10.85	7.09	11.13
300-3	12.83	7.71	10.57

Final Film Force

Pre-stretch	Final-Top	Final-Mid	Final-Bot
100-1	3.80	7.02	7.68
100-2	5.66	6.07	8.36
100-3	5.35	6.72	8.66
AVG	4.94	6.60	8.23
150-1	4.18	7.32	7.30
150-2	x	x	x
150-3	8.44	4.35	7.60
AVG	6.31	5.84	7.45
200-1	5.10	4.27	8.60
200-2	3.40	6.77	9.80
200-3	4.82	5.75	8.04
AVG	4.44	5.60	8.81
250-1	3.67	4.56	8.90
250-2	7.70	4.01	8.45
250-3	5.31	6.58	7.68
AVG	5.56	5.05	8.34
300-1	3.84	7.18	5.81
300-2	3.21	5.39	7.85
300-3	9.65	5.68	9.20

AVG	11.16	7.27	10.27
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AVG	5.57	6.08	7.62
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Appendix B: Individual Film Force Values

Sequence 1: Incline Impact

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-7.52%	-3.01%	-1.28%
100-2	-8.12%	-0.94%	-5.00%
100-3	-8.67%	2.05%	-2.69%
150-1	-0.90%	-5.46%	-0.70%
150-2	-2.64%	-3.83%	-14.88%
150-3	-4.55%	-8.50%	-2.19%
200-1	-12.87%	-9.03%	-0.37%
200-2	-4.30%	-7.59%	-8.49%
200-3	-10.10%	-8.24%	-8.85%
250-1	-12.49%	-11.91%	-4.69%
250-2	-0.30%	-9.23%	-8.41%
250-3	-6.08%	-3.06%	-7.17%
300-1	-4.49%	-4.42%	0.55%
300-2	-6.63%	-6.49%	-7.28%
300-3	-9.44%	-8.04%	-2.18%
P-Value	0.317	0.036	0.768

Sequence 2: Rotational Edge Drop

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	2.13%	-8.50%	-4.18%
100-2	-1.03%	-12.58%	-11.36%
100-3	9.98%	-14.50%	-11.05%
150-1	2.83%	-11.72%	-2.62%
150-2	-4.21%	-1.62%	-1.44%
150-3	-2.47%	-14.12%	-18.13%
200-1	2.55%	2.90%	-13.29%
200-2	5.09%	-8.89%	-10.83%
200-3	1.42%	-8.82%	-8.49%
250-1	13.31%	-4.22%	-14.77%
250-2	-4.20%	-2.62%	-6.09%
250-3	4.76%	-7.04%	-3.11%
300-1	-0.85%	-9.24%	-9.06%
300-2	-3.94%	-19.46%	-13.47%
300-3	-4.65%	-9.03%	-14.02%
P-Value	0.323	0.275	0.807

Sequence 3: Compression

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-4.62%	0.29%	-0.19%
100-2	-2.38%	0.77%	0.73%
100-3	-6.08%	1.24%	1.17%
150-1	-3.15%	-1.12%	-2.17%
150-2	x	x	x
150-3	-3.38%	0.15%	-1.82%
200-1	-5.36%	-3.86%	-2.47%
200-2	-9.78%	-0.90%	-1.10%
200-3	-5.89%	-1.02%	-1.01%
250-1	-8.60%	0.46%	2.45%
250-2	-1.67%	0.00%	0.00%
250-3	-2.90%	-1.39%	-3.21%
300-1	-2.15%	-0.66%	-2.16%
300-2	0.10%	1.12%	-0.67%
300-3	-3.88%	-1.86%	-2.59%
P-Value	0.237	0.198	0.279

Sequence 4: Vibration

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-72.49%	5.29%	-18.85%
100-2	-59.10%	-2.76%	-6.72%
100-3	-57.79%	-11.04%	-19.29%
150-1	-63.65%	27.41%	-16.83%
150-2	x	x	x
150-3	-29.09%	-26.18%	-15.04%
200-1	-86.46%	-66.82%	-8.35%
200-2	-79.89%	-1.82%	-5.17%
200-3	-60.98%	-4.97%	-6.66%
250-1	-76.07%	-46.83%	-15.87%
250-2	-35.88%	-39.40%	-11.80%
250-3	-63.48%	-10.03%	-34.44%
300-1	-75.47%	0.99%	-28.83%
300-2	-84.00%	-24.44%	-14.66%
300-3	-21.43%	-20.54%	-7.04%
P-Value	0.679	0.52	0.414

Sequence 5: Rotational Edge Drop

Pre-stretch	TOP LC	MID LC	BOT LC

1 Hour Static

Pre-stretch	TOP LC	MID LC	BOT LC

100-1	33.10%	-0.98%	-7.07%
100-2	30.48%	-3.00%	-5.99%
100-3	14.22%	4.90%	2.85%
150-1	13.97%	12.17%	-8.27%
150-2	x	x	x
150-3	13.58%	-12.22%	-8.12%
200-1	279.07%	103.72%	5.40%
200-2	68.06%	6.94%	-2.43%
200-3	27.17%	4.69%	-4.11%
250-1	38.13%	37.22%	4.43%
250-2	26.49%	10.44%	4.70%
250-3	40.33%	18.99%	21.44%
300-1	60.54%	20.29%	-1.90%
300-2	96.15%	38.24%	7.66%
300-3	15.55%	17.30%	19.01%
P-Value	0.368	0.486	0.097

100-1	-1.55%	-0.99%	-1.03%
100-2	3.28%	-1.14%	-1.42%
100-3	4.09%	-1.90%	0.12%
150-1	2.45%	-3.17%	1.25%
150-2	x	x	x
150-3	1.93%	-0.68%	0.26%
200-1	4.29%	-2.51%	-2.16%
200-2	5.92%	-2.31%	-2.20%
200-3	2.99%	-0.86%	1.39%
250-1	3.38%	-5.59%	-3.16%
250-2	0.79%	-5.20%	-2.76%
250-3	3.11%	-3.66%	-3.15%
300-1	7.26%	-2.31%	2.11%
300-2	4.90%	-4.43%	-3.68%
300-3	-0.10%	-3.73%	-3.97%
P-Value	0.675	0.015	0.344

Appendix C: Cumulative Film Force Values

Sequence 1: Incline Impact

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-7.52%	-3.01%	-1.28%
100-2	-8.12%	-0.94%	-5.00%

Sequence 2: Rotational Edge Drop

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-5.56%	-11.26%	-5.41%
100-2	-9.08%	-13.40%	-15.79%

100-3	-8.67%	2.05%	-2.69%
150-1	-0.90%	-5.46%	-0.70%
150-2	-2.64%	-3.83%	-14.88%
150-3	-4.55%	-8.50%	-2.19%
200-1	-12.87%	-9.03%	-0.37%
200-2	-4.30%	-7.59%	-8.49%
200-3	-10.10%	-8.24%	-8.85%
250-1	-12.49%	-11.91%	-4.69%
250-2	-0.30%	-9.23%	-8.41%
250-3	-6.08%	-3.06%	-7.17%
300-1	-4.49%	-4.42%	0.55%
300-2	-6.63%	-6.49%	-7.28%
300-3	-9.44%	-8.04%	-2.18%
P-Value	0.317	0.036	0.768

100-3	0.44%	-12.76%	-13.45%
150-1	1.90%	-16.54%	-3.30%
150-2	-6.74%	-5.39%	-16.10%
150-3	-6.91%	-21.42%	-19.92%
200-1	-10.65%	-6.39%	-13.61%
200-2	0.57%	-15.80%	-18.41%
200-3	-8.83%	-16.34%	-16.59%
250-1	-0.84%	-15.62%	-18.77%
250-2	-4.49%	-11.61%	-13.99%
250-3	-1.62%	-9.89%	-10.05%
300-1	-5.30%	-13.25%	-8.56%
300-2	-10.31%	-24.68%	-19.77%
300-3	-13.65%	-16.34%	-15.89%
P-Value	0.397	0.667	0.883

Sequence 3: Compression

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-9.91%	-10.99%	-5.60%
100-2	-11.24%	-12.73%	-15.18%
100-3	-5.66%	-11.67%	-12.44%
150-1	-1.30%	-17.47%	-5.41%
150-2	x	x	x
150-3	-10.06%	-21.30%	-21.38%

Sequence 4: Vibration

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-75.21%	-6.28%	-23.39%
100-2	-63.70%	-15.15%	-20.88%
100-3	-60.18%	-21.42%	-29.33%
150-1	-64.13%	5.15%	-21.32%
150-2	x	x	x
150-3	-36.22%	-41.91%	-33.20%

200-1	-15.44%	-10.00%	-15.74%
200-2	-9.26%	-16.56%	-19.30%
200-3	-14.19%	-17.19%	-17.43%
250-1	-9.37%	-15.24%	-16.79%
250-2	-6.08%	-11.61%	-13.99%
250-3	-4.47%	-11.14%	-12.94%
300-1	-7.34%	-13.82%	-10.54%
300-2	-10.22%	-23.84%	-20.31%
300-3	-17.00%	-17.90%	-18.07%
P-Value	0.239	0.097	0.619

200-1	-88.55%	-70.14%	-22.78%
200-2	-81.76%	-18.08%	-23.47%
200-3	-66.52%	-21.31%	-22.93%
250-1	-78.31%	-54.93%	-29.99%
250-2	-39.78%	-46.43%	-24.13%
250-3	-65.11%	-20.06%	-42.92%
300-1	-77.27%	-12.96%	-36.33%
300-2	-85.64%	-42.45%	-31.99%
300-3	-34.79%	-34.76%	-23.84%
P-Value	0.555	0.555	0.403

Sequence 5: Rotational Edge Drop

1 Hour Static

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-67.01%	-7.20%	-28.81%
100-2	-52.64%	-17.69%	-25.61%
100-3	-54.51%	-17.57%	-27.31%
150-1	-59.12%	17.94%	-27.83%
150-2	x	x	x
150-3	-27.56%	-49.01%	-38.62%
200-1	-56.61%	-39.17%	-18.61%
200-2	-69.34%	-12.39%	-25.34%
200-3	-57.42%	-17.61%	-26.10%
250-1	-70.04%	-38.16%	-26.89%

Pre-stretch	TOP LC	MID LC	BOT LC
100-1	-67.52%	-8.12%	-29.54%
100-2	-51.08%	-18.63%	-26.67%
100-3	-52.65%	-19.13%	-27.23%
150-1	-58.12%	14.20%	-26.93%
150-2	x	x	x
150-3	-26.16%	-49.36%	-38.46%
200-1	-54.75%	-40.69%	-20.37%
200-2	-67.53%	-14.41%	-26.97%
200-3	-56.14%	-18.32%	-25.07%
250-1	-69.03%	-41.61%	-29.20%

250-2	-23.83%	-40.84%	-20.57%	250-2	-23.23%	-43.92%	-22.76%
250-3	-51.05%	-4.87%	-30.68%	250-3	-49.52%	-8.36%	-32.87%
300-1	-63.51%	4.70%	-37.54%	300-1	-60.86%	2.28%	-36.22%
300-2	-71.82%	-20.45%	-26.77%	300-2	-70.44%	-23.98%	-29.47%
300-3	-24.65%	-23.48%	-9.37%	300-3	-24.73%	-26.33%	-12.96%
P-Value	0.815	0.886	0.708	P-Value	0.817	0.854	0.742

Appendix D: Pull Plate Film Force Values

Input Stretch %	Pull Plate Face 2	Pull Plate Face 4	Pull Plate Face 5	Pull Plate Face 6
100.00%	22.38	39.06	21.56	35.56
100.00%	37.06	34.56	27.38	34.13
100.00%	17.81	43.25	23.69	38.38
150.00%	34.56	24.13	28.19	32.25
150.00%	26.00	28.50	26.06	31.13
150.00%	28.00	22.13	21.75	35.19
200.00%	29.44	31.00	29.13	36.25
200.00%	33.81	35.88	31.69	35.56
200.00%	34.31	28.56	23.31	37.63
250.00%	29.06	31.19	24.13	37.56
250.00%	31.31	28.31	28.63	41.13
250.00%	35.25	26.56	23.06	40.38
300.00%	28.13	26.38	27.31	36.19
300.00%	24.25	32.56	36.19	32.50
300.00%	32.13	42.25	23.38	44.19