A Simplified Elastic Model for Predicting the Stretch Film Forces on Unit Loads

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Abstract

The most common method of stabilizing unit loads of products moving through supply chains is the application of stretch film. The metric most common for characterizing the level of stabilization is the "Containment Force" as described in ASTM D8314. Vector analysis and the elastic properties of the film were used to predict the horizontal forces being applied to the vertical edges of a test unit load. The model was sensitive to both film properties and wrapping patterns. An instrument was designed and built to measure these forces on the edge of the unit load. Three levels of layering, film overlap, and three levels of film pre-stretch were tested. The difference between predicted and measured edge forces varied from 0.7 to 2.3 %. The same instrument was used to compare the force on the edge of the to the containment force using the "pull plate" method in ASTM D8314. The correlation between the edge forces and the film force on the side was an R^2 of 0.6712. The average ratio of film force/edge force was 0.094 with a standard deviation of 0.0069. Using this factor to adjust the edge force resulted in the model over predicting containment force by 2 to 13%. An adjustment of .090 would result in better predictions. These results indicate the potential for a commercial tool that can help packaging and logistic professionals select the most efficient and safe film applications for stabilizing unit loads, moving consumer and industrial products through unitized supply chains.

Key Words: Unit Loads, stability, supply chains, film force, stretch film

Introduction

Stretch film is used to stabilize unit loads moving through supply chains of industrial and consumer products. The level of stability depends on both the film selection and the method of application to the unit load. The films are generally cast extruded LLDPE in thicknesses of 12 to 30 microns or 50 to 120 gage. The width of film varies from 30 to 50 cm.

The application variables are; level of pre-stretch, an additional stretch to load (tension to load), effective number and location of layers applied to the unit load. The number of layers depends on the amount of film overlap of each rotation and the number of rotations or cycles covering the unit load.

The primary metric of the stretch wrap contribution to unit load stability is the "containment force". This measurement is described in ASTM D8314 "Performance testing of Applied Stretch Films and Stretch Wrapping"(1) and ASTM 4649 "Standard Guide for Selection and use Selection and Use of Stretch Wrap Films(2). Vendors of stretch film and wrapping equipment have published recommended levels of containment force to stabilize unit loads, as a function unit load mass and geometry (High Light Industries(3) and LanTech Industries(4)). There is no corresponding ISO test methodology describing containment force. ISO 10531, "Stability Testing of Unit Loads"(5) and EUMOS 40509, "Rigidity and Stability of Unit Loads" (6) describe stability testing of the unit load after stretch film application. Tests described in ASTM D5414(7) and ASTM D5415(8) are evaluations of stability of stretch wrapped unit loads subjected to horizontal impact and vibrations, respectively. ASTM 4169(9) and ISTA 3E(10) describe test sequences that simulate various supply chains. Many of the sequences can be used to evaluate unit load stability. Singh et. al.(11) proposed a simple platform tilt test that may help evaluate unit load stability subjected to long term events such as breaking, acceleration, and the centripetal forces of trucks rounding curves in the road.

Literature review

There is a body of research, based on these and other standard test methods, that attempts to correlate stretch wrapping with various performance of unit loads. Park et. al.(12) correlated containment force and the stiffness of palletized unit loads. He showed that the horizontal compression created by the film, reduced the bending deformation of the unit load. He described this effect, as the load on the pallet "bridging" across the pallet deck when unit loads are stored in free span warehouse storage racks. Singh et. al. (13) described the effect of the level of pre-stretching of the film on unit load containment using the ISTA 3e test protocol. They concluded that the level of pre-stretch and load stability were weakly correlated. Dunno et. al (14) noted a significant level of containment force measurement across several grades of stretch film and suggested that containment force can be used as part of ongoing quality assurance programs and less so a predicter of success during transportation. Dunno and Symanski (15) Studied the effect of storage time and conditions on containment force. They showed that most loss of containment force occurs during the first two hours after application.

Dunno et.al.(16) showed that stretch wrapping unit loads does impact the level of transmissibility of tertiary and secondary packaging subjected to random vibration inputs. Finnemore (17) Matyja(18) both created dynamic layer models of a unit load responding to external stimuli during supply chain movement. Finnemore examine the effects of film layering and found agreement between predicted and measured stability. Matyja assigned horizontal forces to represent the containment force imposed by stretch film on the unit load to understand how the force would affect the displacements of the layers. For small displacements there was good agreement between predicted and measured correlation with containment force. Perhaps the most comprehensive investigations of stretch film selection and application on unit load stability was by Bisha(19). He described the influence of the film forces on the edge of the unit load and this relationship with the containment force on the sides of the unit load as traditionally measured. Cernokus(20) Showed there is no effect of film pre-stretch level (100% to 300%) on film force. Pre-stretching film, does impact the economy of the process, as increasing pre-stretch, reduces the amount of film used.

While this body of research shows the effect of containment force on unit load stability, what is lacking is a simplified method of predicting the containment force as a function of stretch film properties and the method of application. Such a tool would streamline the design of stretch film solutions to stabilize a range of unit load configurations. This would lead to more sustainable and safer domestic and international supply chains for a range of products. It would replace the current "trial and error" approach of selecting a stretch wrap solution.

Elastic model development

The general approach was to predict the direction and magnitude of the forces created by the stretch film, at the edge of a unit load. These predictions are then adjusted, empirically, to reflect the ASTM D8314, pull plate, containment force on the side of the unit load. As such, creep of the film is ignored and the predictions are based on the specified, pull plate measurement at 5 minutes after application.. The applied film force (F_f) at the edge of the unit load is assumed to be parallel to the face of the unit load and equal in both directions of the adjacent faces of the unit load. The film force is a stretch film machine setting, and adjustable. The resultant force (F_r) compressing the edge of the unit load, is derived as shown in Figure 1.

Model inputs include the width of film, film gage (determined from the roll mass and the length of film on the roll) film force setting on the stretch wrap machine, percent pre-stretch, number of rotations of the unit load at the bottom, number of rotations at the top load, The amount of film over the top and the amount of film over the pallet at the bottom, the percent of film overlap between top and bottom, as well as number of rotations between the top and bottom. The applied film force at an edge of the unit load is adjusted based on how much of the pre-stretch film contacts the edge. If a 50 cm wide film is pre-stretch to 200% the film width is 46 cm. If this film is wrapped 7 cm above or below the unit load then the film force is adjusted by this ratio of 39/46 and the number of times the film crosses the edge during wrapping. At the top and bottom of the unit- load, the film force is horizontal. However, wrap patterns include a vertical movement of the carriage on the stretch wrapper. The resultant angle "α" of the film application, results in a vertical component F_v of the film force between the top and bottom of the unit load. This angle is a function of the vertical movement and number of rotations between the top and bottom of the unit load. These forces are shown in blue in Figure 1 and can be resolved to the horizontal film force F_f on the face of the unit load and the resultant force F_r, is derived. A single wrap cycle is assumed to be the machine carriage wrapping up and wrapping down and can represent multiple crossing of the edge of the unit load. The total film force and resultant force at each edge is then a function of the number of times the film crosses the edge and thus additive from top to bottom.

$$F_r = F_f/\cos\beta$$

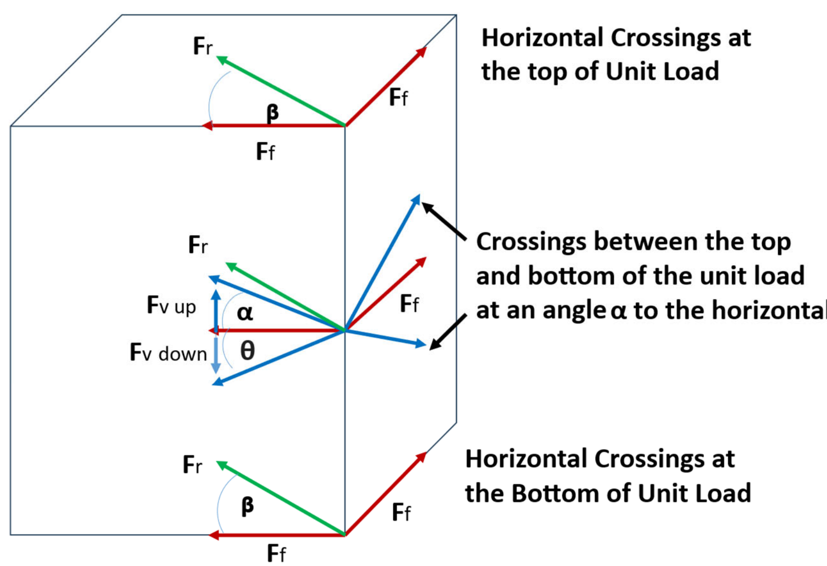

Figure 1 Schematic diagram of a unit load and the film force (F_f) created by the stretch wrapping process and the resultant compressive force (F_r) on the edge of the unit load.

$$Total\ edge\ force = \sum_{n=1}^{n} \text{Fr}$$

Where "n" is the number of times the film crosses an edge of the unit load. The first rotation will result in one less crossing on one edge where the film is first attached to the unit load.

Model validation.

To compare model predictions with actual forces at the edges of the unit load, a test "cube" was constructed. The cube was 1.22 meters by 1.22 meters by 1.27 meters high. This is shown in Figure 3. Two 45 Kg capacity load cells were used measure the total force at the edge of the simulated unit load. The load cells were mounted in one edge of the cube, as shown in the Figure. The ASTM 8314 containment force was measured on the side of the cube using the pull plate method. This method was chosen because it is the common measurement referenced in guidelines for force levels, recommended to stabilize various unit loads moving through various supply chains. This method is shown in Figure 4. The plate is 152 mm in diameter and inserted between the film and the surface of the cube 254 mm from the top and 457 mm from the vertical edge. The plate is pulled to 100 mm from the surface of the cube and the resisting containment force is measured. A High Light Synergy 4 High Profile stretch wrap machine was used for all testing. This machine is shown in Figure 5. The stretch film used for all tests was 50 cm wide, 55 gage (14µm), cast, LLDPE with tack on both sides. The film force setting on the machine was set to 89N. This is a very typical force level and works well for many films and pre-stretch levels. The design of experiments is in Table 1.

Test series	Overlap	Pre-stretch	Overall stretch	No. of Layers
Effect of layers	50%	200%	200%	1
				2
				3
Effect of Overlap	25%	200%	200%	2
	50%			
	75%			
Effect of Pre-stretch	50%	100%	200%	2
		200%		
		300%		

Three replicate tests at each treatment level were conducted. The percent overlap was controlled by varying the number of unit load rotations from bottom to top and from top to bottom of the unit load, during wrapping. The level of pre-stretch was confirmed using the marking wheel method in ASTM D8314.

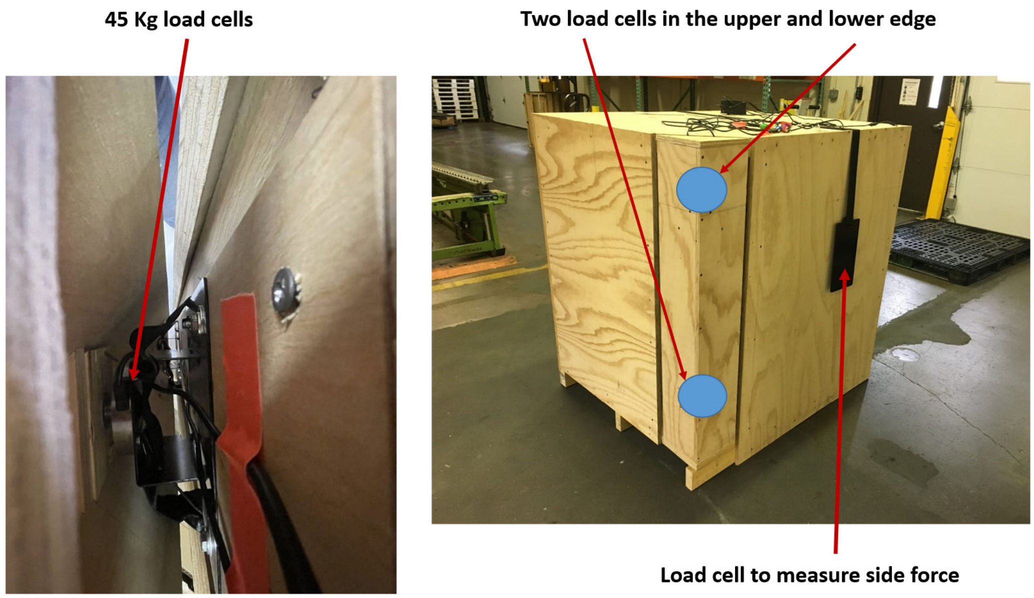

Figure 3 The test cube showing the location of two 45 Kg load cells to measure the film force at the edge of the cube.

Figure 4 Measurement of the containment force on the side of the simulated unit load.

Figure 5 The High Light Synergy 4 High Profile machine used for applying the stretch film to the test cube.

Results and Discussion

As expected, there was no significant effect of stretching of the film on the measured containment force. This is consistent with prior research (see Table 2). Though a trend of a reciprocal relationship between film stretch and force at the edge seems to exist, the difference is insignificant across the wide range of film stretch. Do to limitations of the stretch wrap machine it was not possible to change the level of overlap of the film without changing the effective number of film layers. The top and the bottom wraps will be layered and this is 2/3 of the edge. For the remaining middle 1/3 of the edge a single up and down cycle with film overlapped by 25 %, is roughly one layer. A single cycle with 50% overlap will result in a double layer and a 75% overlap in three layers over the middle 1/3 of the edge of the cube. Therefore, the film overlap data was merged into a single set of layering effects.

Table 2 The effect of film stretch level on the measured edge and containment force

Stretch Level (%)	Measured Edge Force (N) (Std.Dev.)	Measured Containment Force (N) (Std.Dev.)
100	591.0 (4.9)	53.8 (7.6)
200	573.2 (1.4)	51.3 (3.1)
300	570.5 (4.5)	63.6 (3.6)

Figure 7 is a regression analysis of the measured corner force and the measured ASTM, pull plate, containment force on the side of the simulated unit load. While the variation does compromise the level of correlation, the relationship is strong and the trend clear and predictable. The average ratio of containment force on the side/total force on the edge is .094. The range of this ratio is 0.081 to .111. The average ratio of .094 is used to adjust the predicted edge force to a predicted containment force.

Table 3 is a comparison of predicted edge and containment forces and measured edge and containment forces. The variation of the measured edge forces is low at 1 to 2%. The model seems to slightly under predict the measured forces at the edge of the test cube. However, the margin is small, from 0.7% to 2.3%. Within the scope of this research the vector analysis model developed, is a reliable tool for predicting these forces on unit loads resembling cube geometries. The empirical adjustment to predict containment force from the edge forces results in predicted containment forces greater than those measured, during testing by 2.4% to 13%. While the average ratio would seem a rational choice for this adjustment, additional testing may lead to a ratio that better adjusts the edge forces.

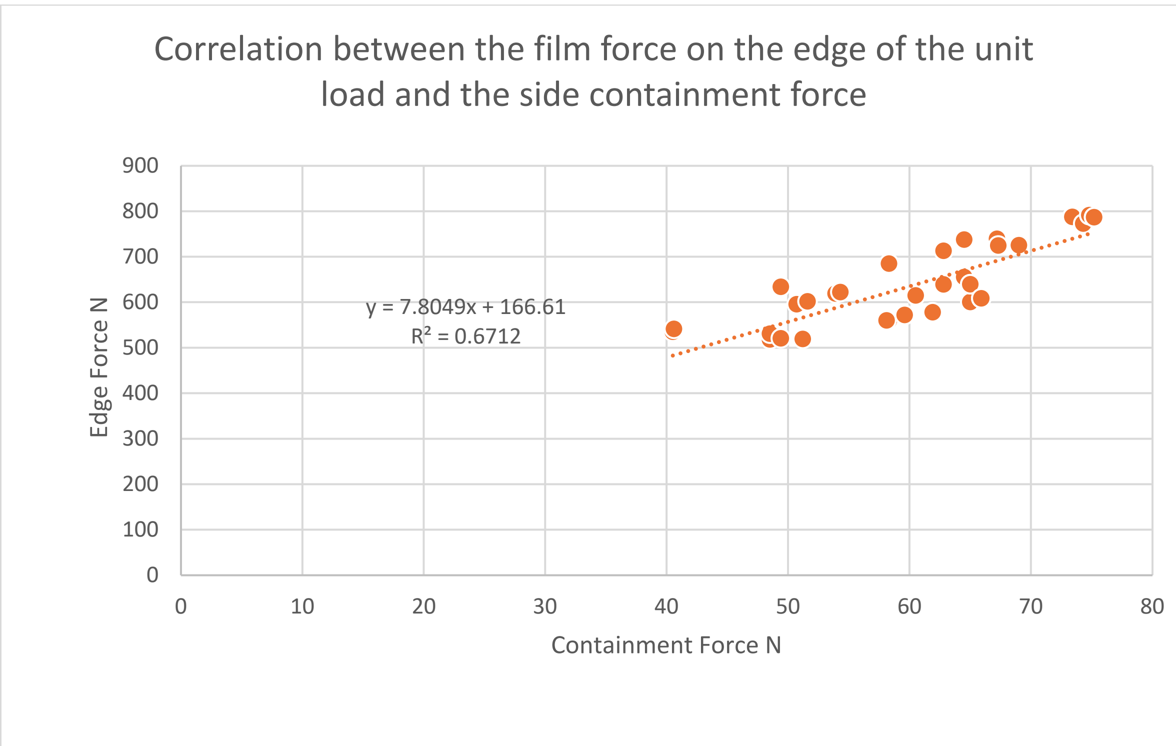

Figure 7 Regression analysis showing the correlation between the force on the edge of the test unit load and the ASTM D8314 containment force on the side of the unit load.

Table 3 Correlation between predicted and measured edge forces and containment forces.

Number of Film layers	Total edge force (N)	Total Edge force (N)	Deviation from measured (%)	Containment Force (N)	Containment Force (N)	Deviation from measured (%)
	Predicted	Avg. measured (Std.Dev.)		Predicted	Avg. measured (Std.Dev.)	
1	523.3	535.8 (5.3)	-2.3	49.2	43.2 (4.5)	+13.0
2	605.7	610.1 (12.5)	-0.7	56.5	55.2 (4.9)	+2.4
3	722.2	730.3 (14.7)	-1.1	67.6	65.0 (2.2)	+4.0

Conclusions

For a range of stretch film applications, the elastic vector analysis model developed, seems to predict the forces of the film on the edges of cubically shaped unit loads. The empirical adjustment of .094 results is over predicting the ASTM containment force. An adjustment of .090 would result in better prediction of the containment force. This is well within the range of ratios measured, during testing. This research clearly shows the potential for this modelling approach to be used commercially, to help design more stable unit loads moving through supply chains. Additional verification of the model reliability is warranted. The validation should be extended to additional films and film gages and film width, as well as different levels of film force. Also, the model should be verified for applications to unit loads of different geometries such as pail or tube unit loads with rounded edges.

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