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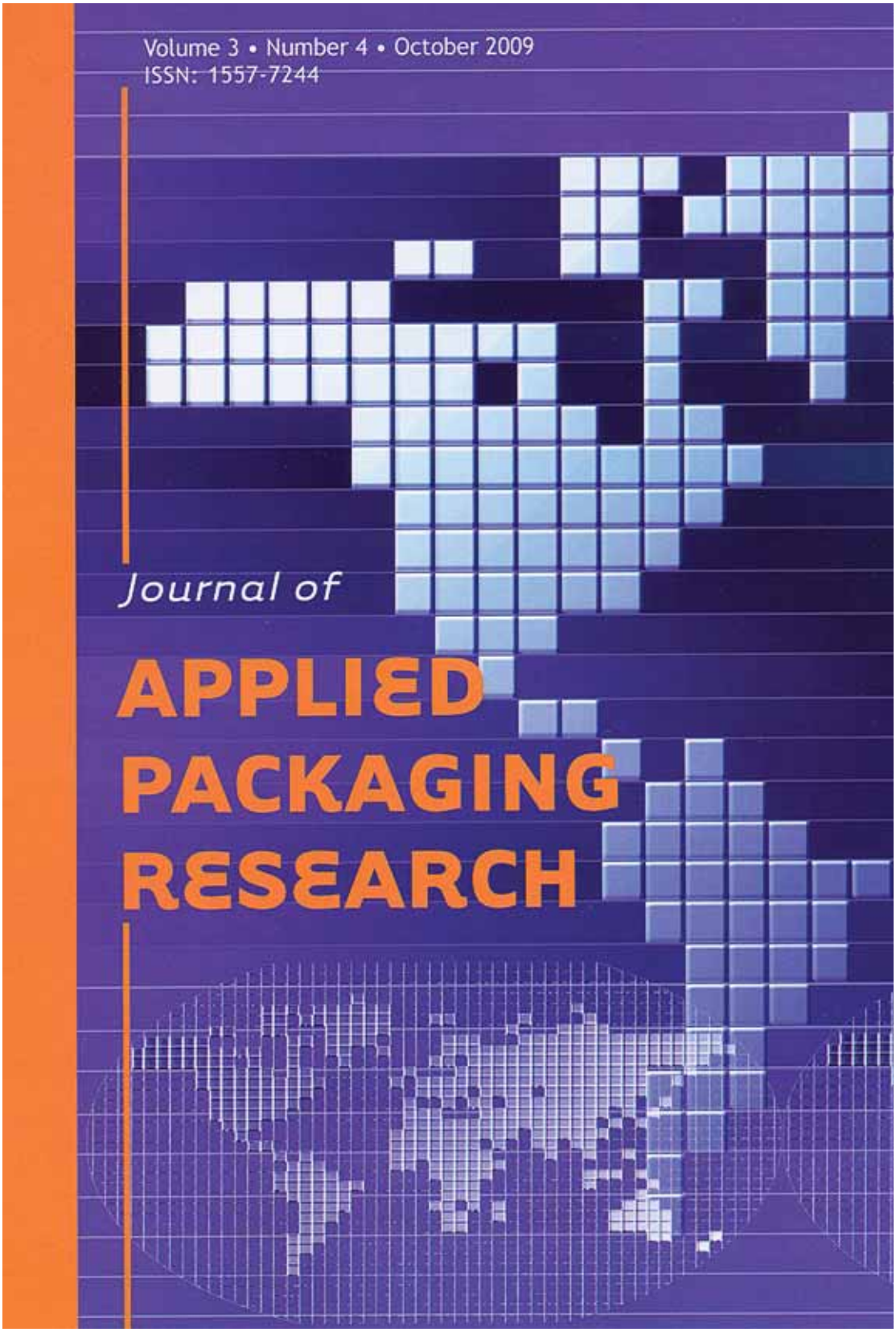

Journal of

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Aim and Scope

The *Journal of Applied Packaging Research* is an international forum for the dissemination of research papers, review articles, tutorials and news about innovative or emerging technologies for the packaging industry. The journal is targeted towards the broad packaging community including packaging scientists and engineers in industry or academic research and development, food scientists and technologists, materials scientists, mechanical engineers, industrial and systems engineers, toxicologists, analytical chemists, environmental scientists, regulatory officers, and other professionals who are concerned with advances in the development and applications of packaging.

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Research

RESEARCH

Quantitative Analysis of the Compressive Stress Distributions across Pallet Decks Supporting Packaging in Simulated Warehouse Storage

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ABSTRACT: This paper summarizes quantitatively analyzed compressive stress distributions across pallet deck surfaces supporting flexible and rigid packaging in simulated warehouse storage. Three different densities of polyolefin foams (2, 4, and 6 lb/ft^3) were used to simulate a variety of flexible and rigid packaging with a range of stiffness properties. A layer of single wall C-flute corrugated fiberboard acted as a sensing medium and also simulated the bottom of a corrugated box. Pressure sensitive films were used to detect compressive stresses at the interface between the polyolefin foams and the pallet deck-board. Image analysis software program was used to quantitatively characterize stress distributions left on the pressure sensitive film. In the final models, the three foams' resultant stress distributions across pallet deck surfaces in both rack and floor stack storage simulations were non-uniform. The measure of stress concentrations was the stress intensity factor, which was the ratio of initial maximum resultant compressive stress to the applied stress. In simulated block stack storage, the foam stiffness (package and product stiffness) had a more significant effect on the stress distributions and concentrations along the deck-boards than did the pallet deck stiffness. As a result, the stiffer foam presented a greater change in stress levels along the deck-board and lesser pallet deck deflections under the compression load. Applying the final models of resultant non-uniform stress distributions enabled the development of finite element analysis (FEA) models of pallet deck-board deflections. The predicted FEA models of the deck-board deflections were validated through comparison with experimentally measured deflections in the simulated warehouse storage systems.

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1.0 INTRODUCTION

A pallet is a flat, rigid, and portable structure on which goods are assembled, stored, stacked and transported as a single unit load. Since the 1940s, the pallet has been a fundamental device used with fork-trucks or hand-jacks in modern material handling systems throughout the world. As pallet performance has a significant influence in the efficiency of material handling and entire unit load system, understanding pallet performance is a critical step to improving the performance of the unit load and supply chain system.

The unit load system is developed to enable easy and efficient storage and distribution of products through the supply chain. Consequently, most consumer and industrial products are shipped in the unit load form throughout the U.S. It is estimated that two billion or more unit loads are in use on a daily basis [1]. The success or failure of the supply chain distribution system can be determined according to how well the unit load is designed based on the product, packaging, and materials handling equipment. The components within the unit load portion of the supply chain consist of packaging, pallets, and material handling equipment, all three of which physically and mechanically interact during handling, storage, and transportation [2].

Studies evaluating structural interactions between shapes and forms of packaging and pallets in a unit load system are complicated and not well understood, and transportation, storage and distribution systems have been changing rapidly over time [2]. Static stresses, especially static compressive stresses caused by the mechanical behavior of the interface between pallets and packaging during long-term warehouse storage, has not been well-documented by experimental research. Non-uniformly distributed compressive stresses imposed by packaging at the interface of pallets and packaging can cause significant economic losses and unsafe work places in a unit load system. Understanding the interactions between the primary components in a unit load design will have a significant impact on reducing economic losses caused by inefficiencies in the use of pallets and packaging. Moreover, it will also help improve workplace safety.

Figure 1 shows non-uniform compressive stress distributions during floor stacking storage. It demonstrates that stress concentrations occur at the interface of the packaging and pallet stringers; these concentrations are caused by the pallet deck-board bending under the weight of the

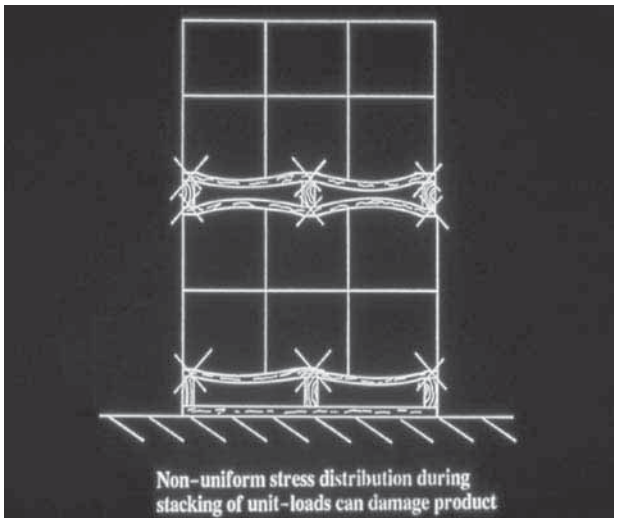


Figure 1. *Schematic of the Simple Unit Load Form.*

load. Stress concentrations may damage products assembled in unit loads during storage. Figure 2 shows a unit load of plastic bottles packaged inside a corrugated box and stacked on a pallet. In this example, the packaging designers did not anticipate the stress concentrations that have occurred in this unit load. As a result, some of the bottles have been damaged at the area of high stress concentrations.

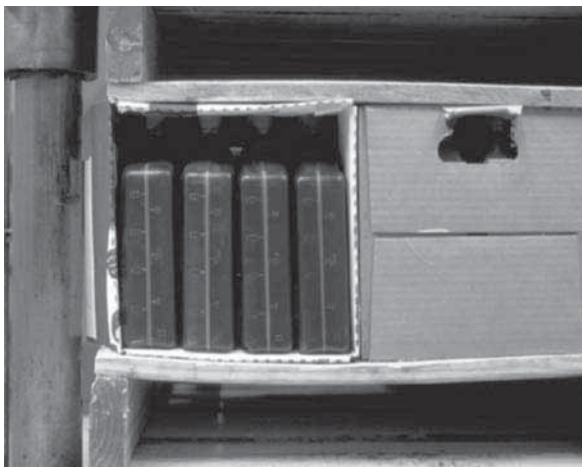


Figure 2. *Non-Uniformly Distributed Loads on Packaging and Pallet.*

A previous research quantitatively analyzed static stress distributions across pallet deck-board surfaces [3]. In this study, a predictive mathematical model was developed using finite element analysis (FEA). To simplify the analysis, this model predicted the deflections of pallet decks by compressive stresses utilizing a rigid load. However, almost all packaged products that are stacked and shipped on pallets have non-rigid loads.

The purpose of this research was to evaluate and quantify stress concentrations in unit loads at the interface between pallet deck surfaces and flexible and rigid product packaging during warehouse storage. The analyzed stress distributions and predicted finite element models of pallet deck deflections will allow pallet, packaging, and unit load designers to better optimize whole unit loads. This research also has great potential to increase supply chain efficiency for consumer and industrial goods when stack storage compressive stresses are present in pallet storage racks and block stack storage systems.

2.0 EXPERIMENTAL DESIGN

The packaging was simulated using a variety of materials with a range of stiffness properties. Also, this study simulated pallet storage rack and block stack storage systems, both of which are commonly used in warehouses. To understand the effect of the stiffness of pallet decks on compressive stress distributions and deflections in floor stack storage, this study used two different thicknesses of deck-board.

To characterize compressive stress distributions across pallet deck-boards, the deck-boards were covered with pressure sensitive films. Images on the pressure sensitive film were analyzed using an image analysis computer software program. The quantitatively characterized static stress distributions were used to develop mathematical finite element models to predict pallet deck deflections. The predicted deflection models were compared to experimentally obtained deflections to validate the prediction.

3.0 MATERIALS AND METHODS

All pallet section samples used in this research were assembled with one bottom and top deck-board, 40 in long and 3.5 in wide, as well as and three stringer segments, 3.5 in long and 3.5 in deep, and 1.5 in wide. The

test used three different pallet section samples, in which each deck-board component was constructed from 1/2 in thick cold roll steel, 1/2 in, and 3/4 in thick Plexiglas®, an acrylic base plastic material (Spartech Polycast Co., Clayton, Missouri, USA). It was selected for a deck-board material instead of wood, as its surface is more even and its physical properties are less variable. This study used Pressurex®, a pressure sensitive film (Sensor Products, Inc., East Hanova, New Jersey, USA), to identify compressive static stress distributions across the pallet deck and packaging interface. The study used single wall C-flute corrugated fiberboard with grades of 35-26C-35 as a testing material. Three different densities of CelluPlank® polyolefin fabrication foam (Sealed Air®, Grand Prairie, Texas, USA) were applied to simulate the various stiffnesses of packaging. The three foams, identified as 220, 400 and 600, had densities ranging between 2.0 to 2.4, 3.8 to 4.4 and 5.8 to 6.4 lb/ft^3 (pound per cubic foot, pcf), respectively. These were applied over corrugated fiberboard pads, pressure sensitive films, and pallet decks.

For the simulation of the pallet storage rack conditions, compression loads were applied to the samples on two-end supports using the 826.75 MTS servo-hydraulic compression tester (Eden Prairie, Minnesota, USA) with a 5,000 lb interface load cell model #661.20E-01 (Figures 3 and 4). A simplified schematic of the testing setup is illustrated in Figure 5. A strip of a pressure sensitive film was applied over the top deck of

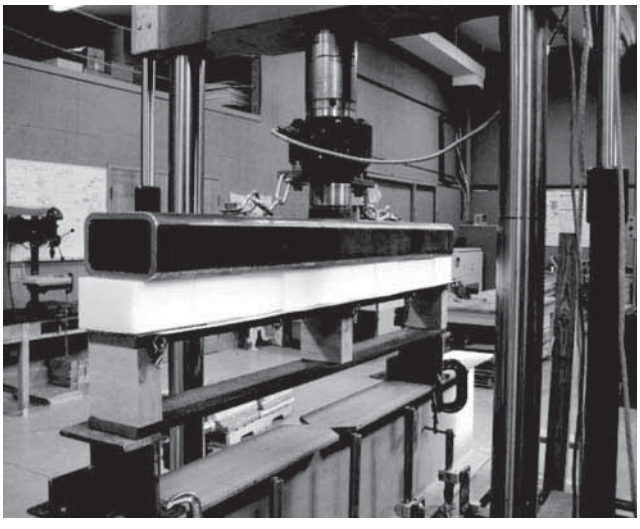


Figure 3. *Testing Setup for Simulation of Pallet Storage Rack.*

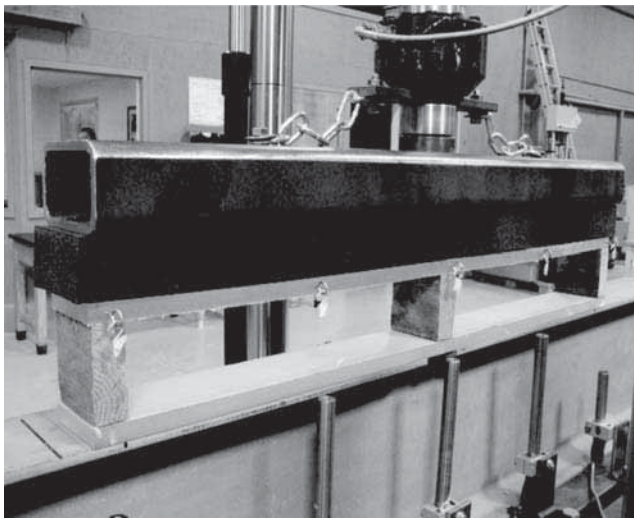


Figure 4. *Testing Setup for Simulation of Block Stack Storage System.*

each pallet section so that the film covered the entire top deck surface area. Then, a layer of single wall C-flute corrugated fiberboard, 40 in long by 3.5 in wide was applied. Its length was placed in a direction parallel to corrugation over the pressure film. Ten blocks of polyolefin foam with varying densities (4 × 4 in with a thickness of 2 in for each

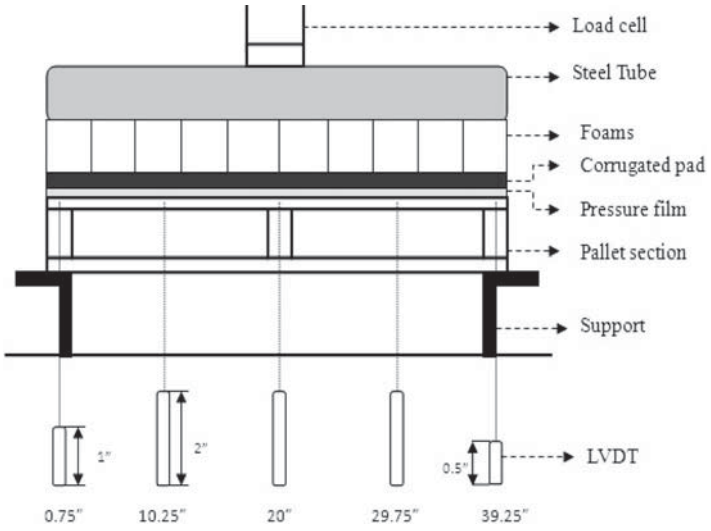


Figure 5. *Schematic of Testing Setup For Simulated Pallet Storage Rack.*

block) were applied over the corrugated fiberboard pad to simulate the various packaging stiffness. For a compression load applicator, a rigid steel tube spanning the length and width of the pallet section was then applied to the samples.

Since the Plexiglas® pallet section was not stiff enough over the two-end supports to generate measurable contrast within the range of the pressure film on high compression loads, a steel pallet section sample was used with these loads. Loading with the 5000 lb load cell was halted after reaching a load consistent with 1,500 lbs (approximately 11 psi) for the steel pallet section sample. To predict the actual stresses distributed over the deck during the simulated pallet racking, a 280 lb (approximately 2 psi) compression load was applied to the Plexiglas® pallet section with the deck thickness of 3/4 in. The Plexiglas® pallet section with the deck thickness of 1/2 in was not used since the deck was not stiff and too thin to predict the actual stresses distributed over the two-end supports.

To simulate floor stack storage in a warehouse, the two-end supports that were used for the simulation of the pallet storage rack were removed from the test setup (Figure 4). 4 pcf and 6 pcf foams over the steel pallet section were compressed using a 1,500 lb load. A maximum loading of 5 psi (approximately 700 lbs) was applied to the Plexiglas® samples. The deflection of the Plexiglas® top pallet deck-board was measured during compression testing. An LVDT (Linear Variable Differential Transformer) was used to measure the deflections of the pallet deck-boards at five locations along the top deck-board component.

For modeling the pallet, the study used a commercial finite element method software, ANSYS® 9.0 ED Version (ANSYS Inc., Canonsburg, Pennsylvania, USA). Two 2-D solid rectangles, 40 in long by 0.75 in wide and 40 in long by 0.5 in wide, were generated on the x and y-plane to be modeled so that the vertically deformed shape of the top deck-board could be predicted in the front view of the pallet section sample. PLANE 42, generally used for 2-D modeling solid structures, was selected to define the element type. The element type was applied as a plane stress and defined by four nodes, each of which had two degrees of freedom. The plane stress usually occurs in situations where one dimension is so small in relation to the other two, as in the case of a flat or thin element [4].

In this study, the plane stress with deck thickness of 0.05 in and 0.75 in was assumed for modeling since the thicknesses of Plexiglas®

Figure 6. *Boundary Conditions for Simulated Pallet Storage Rack.*

deck-boards are thin in the y-coordinates. The Plexiglas® used for the pallet deck-board material was assumed as a linear isotropic material with modulus of elasticity (MOE) of 4.4×10^5 psi and Poisson's ratio of 0.30 applied to define material properties. Meshes were generated by 0.25 in by 0.25 in square elements on the 40 in by 0.75 in and 40 in by 0.25 in simple solid 2-D rectangular structures.

The determination of boundary conditions depended on the support conditions of the simulated pallet storage rack and the block stack storage conditions. For modeling the semi-rigid joint of the pallet sample there should be zero displacement for all degrees of freedom at the outer and inner edges of the stringers. Figure 6 illustrates the applied boundary conditions in the pallet storage rack simulation, two outer stringers, 1.5 inches in depth, of a pallet section sample were supported by two-end supports. In the left half of the section, the outer edge (zero point in x and y-coordinates) and the inner edge (6th node from the end at zero in y-coordinates) of the outer stringer were fixed with zero displacement for all degrees of freedom. Boundary conditions in the right half of the section were symmetrically applied. There are three supports (three stringers), consisting of two outer and one inner supports in the applied boundary conditions in the simulated block stack storage condition (Figure 7). All outer and inner edges of the three stringers were modeled with zero displacement for all degrees of freedom. Boundary conditions applied in terms of the displacement constraints of the outer stringers were the same as in the pallet storage rack simulation. The inner stringer of the pallet section has zero displacement at the 3rd node at zero in the y-direction from the center of a FEA model for both ways.

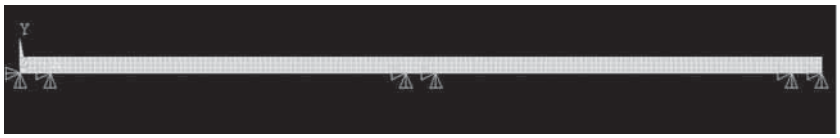


Figure 7. *Boundary Conditions for Simulated Block Stack Storage.*

4.0 RESULTS AND DISCUSSION

A typical image after compression is presented in Figure 8. The strips obtained from the impression of a corrugated fiberboard medium are presented in a direction parallel to the cross-machine direction. The thickness (or width) of each strip at each location along the pallet deck-board was measured and averaged using an image analysis computer software program. It was designed to count the number of pixels in black strips on the film image so that the average thickness of ten block strips at each given location was measured within designate standards.

Figure 10 shows the resulting calibration equation. The generated linear calibration equation was used to interpret all experiment results except for the 6 pcf foams tested in the stack storage condition. The calibration curve could predict compressive static stress values "y" as a function of the average width values "x" at each location along the pallet deck-board.

A calibration curve for the 6 pcf foams tested in the block stack storage simulation was separately regenerated since the corrugated fiberboard was reordered from another manufacturer and used for the 6 pcf foam compression tests in the stacking simulation. Figure 9 shows three replications of the test results. As indicated in Figure 9, stresses were non-uniformly distributed along the steel pallet deck; i.e., higher stresses were more concentrated around two outer stringers than around the inner stringer as shown in the image left on pressure sensitive film in Figure 8. Figure 11 shows the final models of resultant three foams' stress distributions in pallet storage rack simulation. As indicated in the final models, resultant compressive static stress distributions of the three foams were similar in their general tendencies, in which stresses around outer stringers were higher than the inner stringer.

However, the three foams had some differences in the degree of change in stress concentrations, calculated by the ratio of maximum stress level to applied stress. As indicated in Figure 11, the bold black

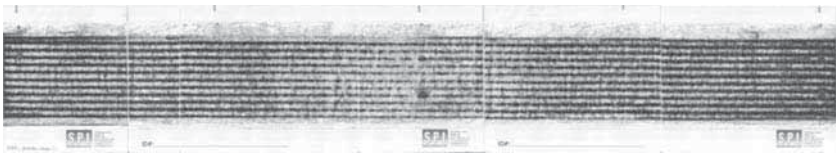


Figure 8. *Typical Image After Compression.*

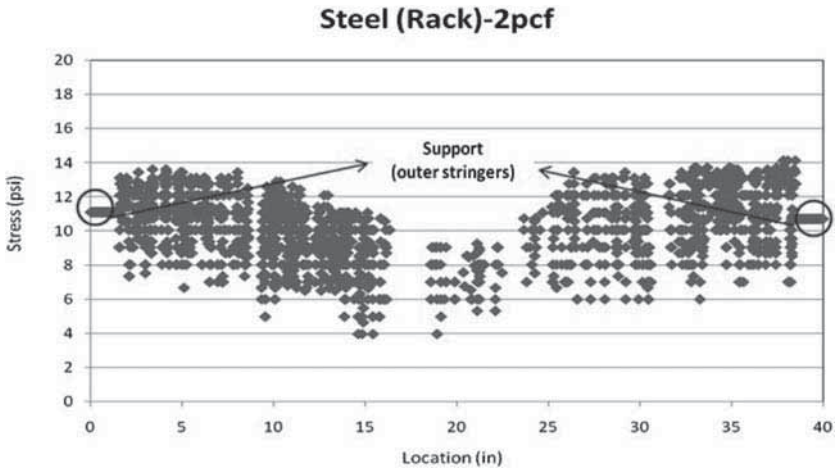


Figure 9. *2 pcf Foam Stress Distribution Across Steel Pallet Deck-Board in Simulated Pallet Rack Storage.*

line shows the applied compressive stress of 2 psi in a simulated pallet storage rack. The final model of resultant 2 pcf foam stress distribution showed approximately 89% increased stress around the outer stringer compared to the applied stress level. Approximately 73% of the higher stresses were concentrated around the edge of deck-board than in the applied stress in the 4 pcf foam final model of resultant stress distribution. In the final model of 6 pcf foam stress distribution, the stress level was about 200% higher around the outer stringer than in the case of the ap-

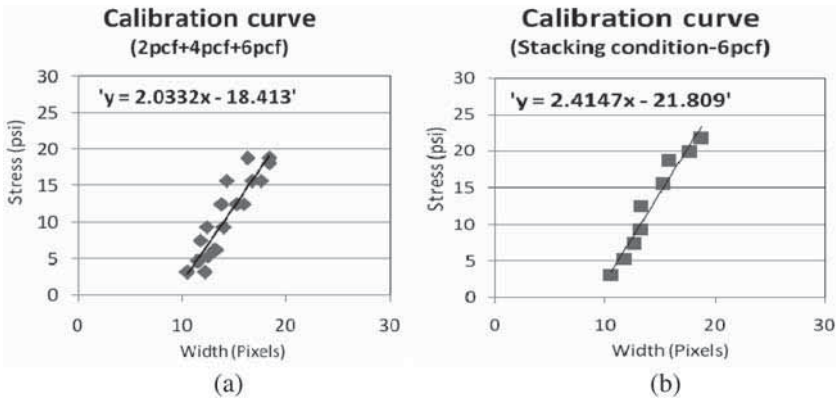


Figure 10. *Calibration Curve Indicated by a Linear Equation.*

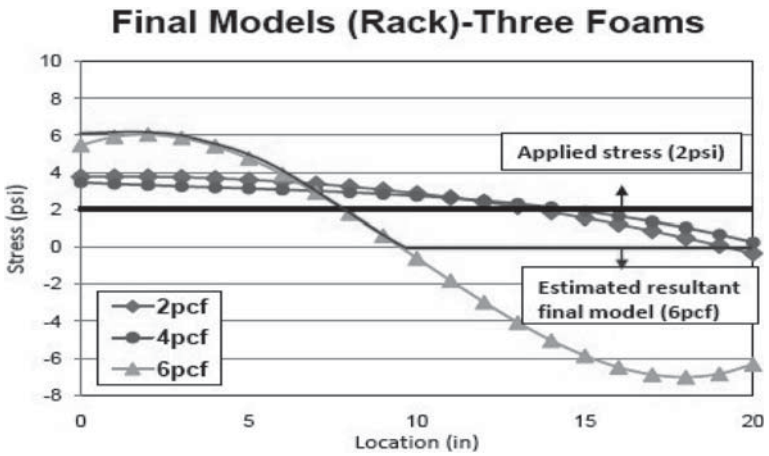


Figure 11. *Final Models of Three Foams' Resultant Stress Distributions from the Edge to the Center of 3/4″ Plexiglas® Deck in Simulated Pallet Storage Rack.*

plied stress of 2 psi. Greater stress concentrations occurred around the edge of the deck-board and edge to the center of 3/4″ of Plexiglas deck in simulated pallet storage rack. More dramatic decreases in the stress levels along the deck were shown in the resultant 6pcf foam's stress distribution than two other foams.

Figure 12 shows the final models of three foams' resultant stress distributions from the edge to the center of 1/2″ and 3/4″ Plexiglas® deck-boards in simulated block stack storage. The stress levels obtained from the 2 pcf and 4 pcf foams' compression tests showed 15% to 27% increases over the 3/4″ deck relative to the 1/2″ deck. This result explained why more measurable test data was generated over the 3/4″ deck-board than the 1/2″ deck. The results of 6 pcf foam stress distributions showed similar resultant final models between 1/2″ and 3/4″ deck-boards. From this, it is known that distributed stress levels across the deck-board shown in the 6 pcf foam final model were not dependent on the deck-board thickness. The degree and location of stress concentrations along the pallet deck showed differences among the three foams.

The final model of resultant 2 pcf foam stress distribution over the 1/2″ deck showed that the maximum stress concentrated around the inner stringer was a 31% increased stress relative to the applied stress of 5 psi in the simulated block stack storage. The resultant 2 pcf foam final model of the 3/4″ deck showed that the maximum stress was 51% higher than that for 5 psi. In the final model of resultant 4 pcf foam stress distri-

butions over the 1/2″ and the 3/4″, respectively, 41% and 59% higher stresses than the applied stress occurred and concentrated around the inner stringer. The 6 pcf foam final models of stress distribution showed the greatest change in stress levels along the deck-board, which means the stresses around the outer stringers were 218% to 248% higher than those in the center of the deck. The maximum stresses that occurred around the edge over the 1/2″ and the 3/4″ were 32% and 37% higher, respectively, than the applied stress of 5 psi, as shown in the final model of resultant 6 pcf foam stress distribution.

Consequently, the stiffer foam caused greater change in stress levels along the pallet deck-board. In a block stack storage situation, the stiffness of foams had more significant effect on the change in stress distributions and concentrations along the deck than does the stiffness of deck-board. There were a few limitations found in this study. It was expected that the shapes of final models could vary depending on the pallet deck stiffness. However, the same functional form was fitted to 1/2″ and 3/4″ Plexiglas® deck-boards for each of the 4 pcf and 6 pcf foams' test data. The same functional form resulted in parallel final models of resultant stress distributions over 1/2″ and 3/4″ deck-boards for each of 4 pcf and 6 pcf foam as shown in Figure 12.

As illustrated in Figure 13, because of the difference in the stiffness of

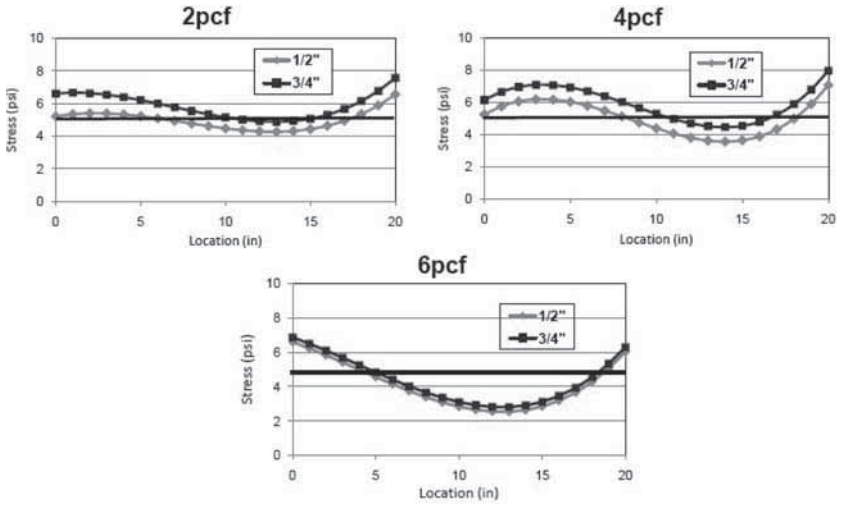


Figure 12. *Final Models of Resultant Stress Distributions from the Edge to the Center of 1/2″ and 3/4″ Plexiglas Deck in Simulated Block Stack Storage.* Note: *Bold black lines represent applied stress of 5 psi for compression testing.*

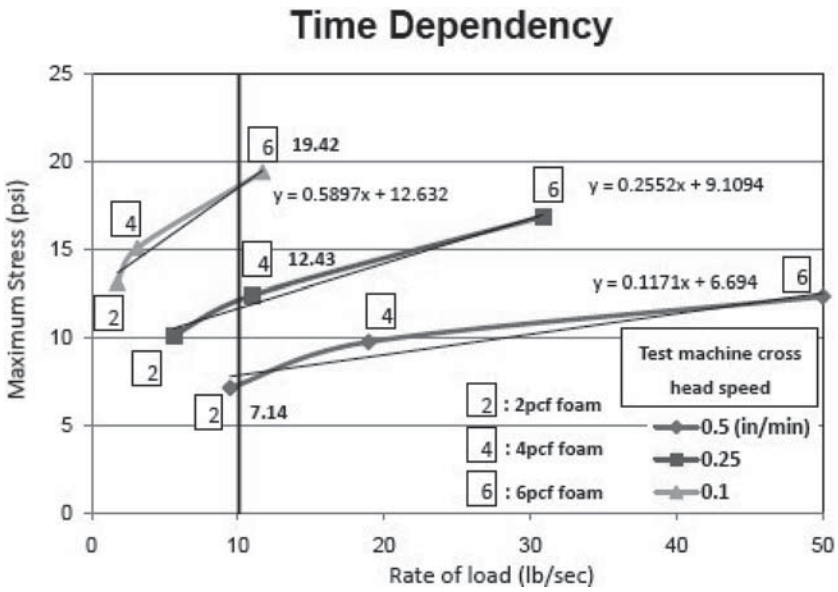


Figure 13. *Time Dependency of Maximum Stress for Three Foams.*

the foams, the rate of loading varied significantly, during testing using the same test machine rate of cross head movement 0.5 in/min. The estimated rate of loading was 9.5, 18.9, and 50.0 lbs/sec for the tests using 2, 4, and 6 pcf foams, respectively. The response of the corrugated medium and the pressure sensitive film may be influenced by the varied rate of test load application. The results shown in Figure 13 of the test conducted at different test machine cross head displacement rates indicates that increasing displacement rate reduces sensitivity to rate of loading. At the same load rate, for instance of 10 lb/sec, the maximum stress was approximately 74% higher in 4 pcf foams (12.43 psi) than in 2 pcf foams (7.14 psi) and 172% higher in 6 pcf foams (19.42 psi).

This means the maximum stresses will be higher than those shown in Figure 12 for 4 pcf and 6 pcf foams; however, this study did not control the rate of load during the testing.

Although the maximum stress levels could be predicted from the results shown in Figure 13, changes in the shapes of the final models would still be unknown. To study the effect of the load rate on the changes of final model shapes, functional forms must be generated from the testing of each foam at the same load rate.

Table 1 shows the adjusted initial maximum resultant compressive

Table 1. *Adjusted* Initial Maximum Resultant Compressive Stress Intensity Factors.*

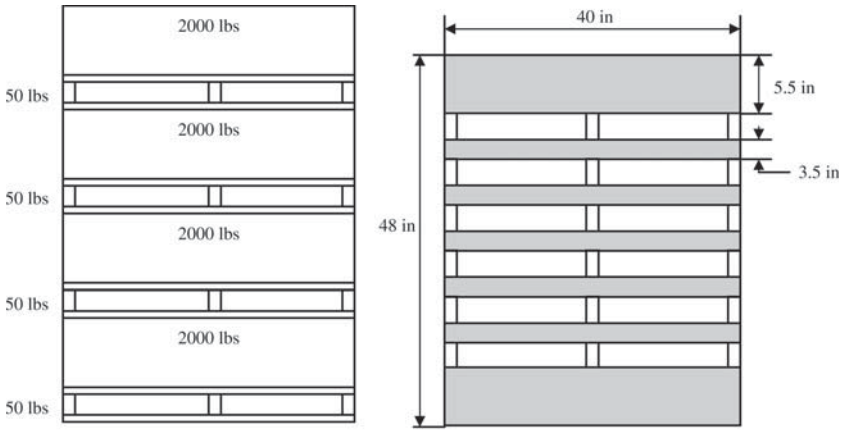
Foams		2 pcf**		4 pcf**		6 pcf†	
Stiffness of Decks		1/2″ (EI=16042)	3/4″ (EI=54141)	1/2″	3/4″	1/2″	3/4″
Support Conditions	Racking	Not Tested	1.9	Not Tested	3.3	Not Tested	5.1
	Stacking	1.3	1.5	2.3	2.6	3.6	4.1

*Adjusted maxiumum resultant compressive stresses to rate load.
**Similar to non-rigid packaging (e.g. flour sacks).
†Similar to rigid packaging (e.g. steel drums).

stress intensity factors after adjustment to the same 10 lbs/sec rate of load. The factors were calculated as the ratio of maximum resultant compressive stresses to the applied stresses. As seen in the table, the maximum compressive stress intensity factors were more significantly affected by the stiffness of foams than the stiffness of deck-boards. The stiffness of deck-boards for two different thickness of decks was indicated by measuring EI (Modulus of Elasticity × Moment of Inertia, lb in^2). These factors are useful to package designers who need to calculate the maximum compressive stresses which occur during warehouse storage. Clearly, the design of the pallet can influence the level of compressive stress concentrations. An example how the stress intensity factors can be used in a real warehouse distribution environment for designing packaging is described below Figure 14.

Figure 15 presents a comparison of maximum deflections obtained from a 280 lbs compression load placed on 2 pcf, 4 pcf, and 6 pcf foams compression load along a 3/4″ Plexiglas® deck-board in a simulated pallet storage rack condition. When comparing the degree of deflection among the three foams, the 2 pcf foam compression resulted in the highest deflection and the 6 pcf foam had the least. The deck-board deflection showed an approximately 41% decrease in the 4 pcf and an 82% decrease in the 6 pcf relative to the 2 pcf foam at the center of the deck where the maximum deflection occurred. Therefore, the stiffness of the foam had a significant effect on the deflection of a pallet deck in a pallet storage rack condition.

If stresses were uniformly distributed, the compression strength of the product or package must be at least 7.84 psi. However, because the pallet deck-boards deflect, one must design a rigid package to resist the compressive stresses of $3.6 \times 7.84 = 28.22$ psi or $4.1 \times 7.84 = 32.14$ psi plus a



Weight of each sku (2000 lbs) × the number of skus (4) = Total weight of skus = 8000 lbs

Weight of each pallet (50 lbs) × the number of pallets on bottom pallet (3) = Total weight of pallet = 150 lbs

Total load on the top deck of bottom pallet = 8000 + 150 = 8150 lbs

Top deck bearing area = $(5.5 \times 40 \times 2) + (3.5 \times 40 \times 5) = 1040$ in^2

Applied stress = 8150 lbs/1040 in^2 = 7.84 psi

Figure 14. *Sample Calculation of the Maximum Compressive Stress of the Pallet/Package Interface Using Maximum Resultant Compressive Stress Intensity Factor.*

safety factor depending pallet deck stiffness.

Figure 16 presents a comparison of maximum deflections obtained from three foam compression tests over 1/2″ and 3/4″ Plexiglas® deck-boards in simulated floor stack storage. For both 1/2″ and 3/4″ deck-board, maximum defections were calculated by taking the mean of the deflections at 10.25 and 29.75 in. In the case of the 1/2″ deck-board deflections, the maximum deflection difference between 2 pcf and 4 pcf foams was less than 10%. The maximum deflection occurring in the 6

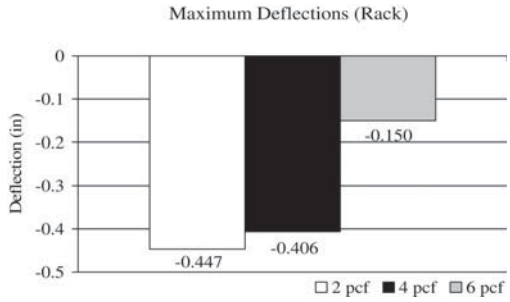


Figure 15. *Comparison of 3/4″ Plexiglas® deck-board maximum deflections by three foams compression testing in Plexiglas® simulated pallet storage rack.*

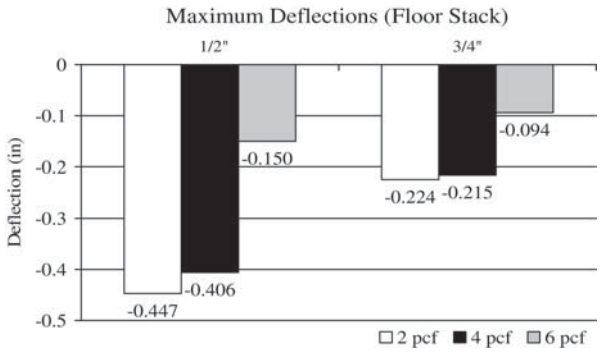


Figure 16. *Comparison of maximum deflections obtained from three foam compression tests over 1/2″ and 3/4″ deck-board in simulated floor stack storage.*

pcf foam was decreased by about 66% over that of the 2 pcf foam. The result obtained from the 3/4″ deck-board presents nearly the same deflection trend as the 1/2″ deck-board results. The differences in maximum deflections between 2 pcf and 4 pcf foams were less than 4%, while the 6 pcf foams shows about a 60% decrease relative to the 2 pcf foam. When comparing the deflection of the 1/2″ deck to the 3/4″ deck to the compressed 2 pcf foam, the results show that deflection decreased by approximately 50% in the 3/4″ deck-board. Similar to the 2 pcf foam result, the compression load applied to the 4 pcf and 6 pcf foams over the 3/4″ deck decreased the deflections by 47% and 37%, respectively.

The results of the deflection tests in both pallet storage rack and block stack storage system simulations demonstrated that the stiffness of the foams, which simulated the stiffness of packaging, had a considerable influence on the pallet deck deflections. In the simulated pallet storage rack condition, maximum deflection occurred at the 20 in point. Greater differences in the deck-board deflections were observed in the simulated pallet storage rack than in the block stack storage condition. Therefore, the interaction between packaging with stiffness in the range of 2 pcf and 4 pcf foams and the pallet should be taken into greater consideration in the pallet storage rack than block stack storage system.

In this study, the different thicknesses of pallet decks represented different stiffnesses of the pallet deck. The differences in the deck-board deflections, caused by various stiffness of packaging, were dependant on the deck-board stiffness. Stiffer deck-board resulted in the greatest decrease in deflections with the 2 pcf foam. The 2 pcf foam simulated the most flexible and softest packaging. Using more stringers as well as a

thicker deck will increase pallet stiffness. Another way to decrease deflection is to place more stringers between the deck-board components. These experimental deflection results are compared to predicted results from FEA modeling in the next section.

Figure 17 shows an FEA model of the predicted deflection of a top pallet deck-board in a pallet storage rack simulation. A final model of resultant 2 pcf stress distribution was applied to the modeling. The final model of resultant stress distribution is valid from the edge to the center for the left half. This half of the final model was mirrored so that the stress distribution could be defined for the other half of the top deck-board. FEA simulations for 4 pcf and 6 pcf foams were performed in the same way as the 2 pcf. Figure 18 shows an FEA model of a predicted 1/2″ top deck-board deflection by the 2 pcf foam compression in the block stack storage condition. As expected, the model shows minimum deflections around the three stringer areas due to the boundary conditions of zero displacements enforced at the edge of the stringers. Maximum deflections occur around the midpoint between two stringers (left outer and inner stringer; right outer and inner stringer).

Table 2 presents a summary of the comparisons between the predicted deflections using FEA modeling and experimental deflections; in both the pallet storage rack and floor stack conditions for the three foams. The differences of the maximum deflections for the 2 pcf, 4 pcf, and 6 pcf foams in the rack simulation between the predicted and the experimental results were –10.8%, –4.7%, and –1.9%, respectively. The differences between the experimentally measured and the predicted maximum deflections for the three foams in the floor stack simulation were evaluated by taking the difference of means of the deflections measured and pre-

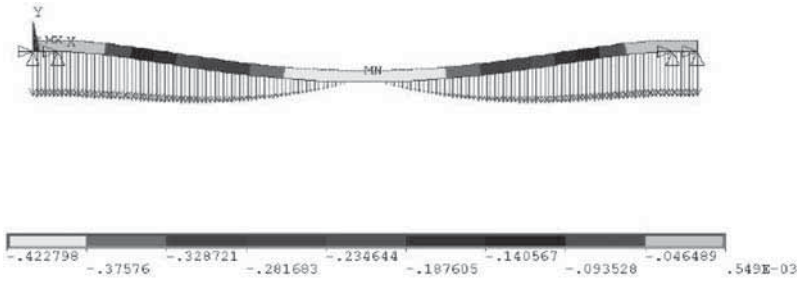


Figure 17. *The Predicted Deflection (in) for Top Deck by Compressed 2 pcf Foams in Pallet Storage Rack Condition Using FEA Modeling.*

Table 2. *Summary of Comparison of Predicted and Measured Deflections of Pallet Deck.*

Warehouse Storage		Foams	Predicted (in)	Measured (in)	Difference (%)
Rack		2pcf	–0.423	–0.468	–10.8
		4pcf	–0.265	–0.277	–4.70
		6pcf	–0.081	–0.083	–1.90
Floor Stack	1/2″	2pcf	–0.422	–0.447	–6.00
		4pcf	–0.418	–0.407	–2.90
		6pcf	–0.210	–0.150	–28.6
	3/4″	2pcf	–0.194	–0.224	–15.4
		4pcf	–0.199	–0.215	–8.30
		6pcf	–0.129	–0.094	–26.7

dicted at 10.25 and 29.75 in along the deck-board. The mean differences between the experimental and the predicted maximum deflections of 1/2″ deck-board for the 2 pcf, 4 pcf, and 6 pcf foams are –6%, 2.9%, and 28.6%. In comparisons between the predicted and the test maximum deflections of 3/4″ deck-board, the results from the 2 pcf, 4 pcf, and 6 pcf showed differences of –15.4%, –8.3%, and –26.7%.

Although there were some differences between the simulation and the experiment results, the FEA models that predicted top deck deflections showed similar tendencies in the deflection results. These similarities were found in the location of maximum and minimum deflections, which occurred along the deck-board. The differences between the results are due to several possible reasons. During FEA modeling, only the top deck-board was modeled to simplify the simulation. However, the connection stiffness between stringers and decks may have significant effect on the deck-board deflections during the testing. Loose nails may

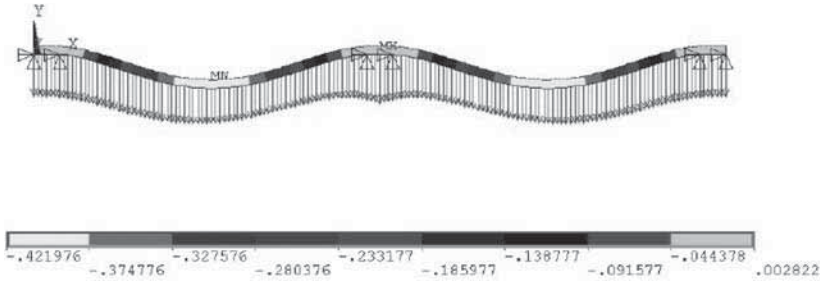


Figure 18. *The Predicted Deflection (in) for 1/2″ Top Deck by Compressed 2 pcf Foams in Block Stack Storage Condition Using FEA Modeling.*

allow the free movement and greater deflections of deck-board during the testing. Inaccurately defined properties of Plexiglas® used for a pallet deck-board material or element types may also create the errors or differences.

5.0 CONCLUSIONS

With the increased utilization of unit loads in long-term warehouse storage, any increase in storage efficiency can have a significant effect upon the profitability of this undertaking. Understanding the physical and mechanical interactions between unit load components can help maximize this efficiency. The compressive stress distributions between the simulated packaging and pallet deck were non-uniform in both simulated warehouse racking and floor stacking condition.

The difference in the stiffness of the foams resulted in a significantly varied rate of loading during testing. The response of the corrugated medium and the pressure sensitive film were influenced by the varied rate of test load application. The stress intensity factors were adjusted to the same rate of loading. The stress intensity factors were affected more by the stiffness of the foam than the stiffness of the pallet deck. The warehouse rack storage simulation resulted in greater stress concentrations (stress intensity factors) than the floor stack storage simulation. Resultant adjusted initial maximum compressive stresses were 89% to 414% higher than the applied stress around the outer stringers during simulated rack storage and 31% to 311% higher than the applied stress around all three stringers in simulated floor stack storage. However, the compressive stresses are greater over the center stringer.

Preliminary tests indicated the 2 pcf and 4 pcf foams represented flexible packaging and sacked products and the 6pcf foam represented rigid packaging. There is little difference between the 2 pcf and 4 pcf foams in the levels of compressive stresses distributed along the pallet deck during both the simulated pallet storage rack and block stack storage conditions. The adjusted maximum compressive stresses between the pallet deck and the 6 pcf foam was greater than 2 pcf and 4 pcf foams during both the warehouse storage simulations.

The differences in deflection among the three foams were relatively large when compared with differences in maximum compressive stress. The deck deflections were less when compressing the stiffer foam. The maximum deck deflections occurred at the center of the deck-board in

simulated warehouse rack storage, and at the deck location of 10.25 and 29.75 inches in the floor stacking condition. The stiffness of the pallet deck-board had an effect on the stress distributions and the pallet deck deflections in the block stack storage condition (the stiffness of the deck was not controlled in the pallet storage rack simulation). It was observed that 15% to 27% higher stresses are distributed over a 3/4″ (EI = 54140) deck-board than a 1/2″ (EI = 16041) deck-board when the compression load was applied in the floor stack storage condition. The stiffer deck-board reduced deflection by approximately 37% to 50% during the floor stack storage.

Predicted deck-board deflections developed by applying the resultant stress distributions to a 2-D FEA model of the pallet deck were validated by the comparison with experimental deflections. The agreement between predicted and measured deflections of a 3/4″ Plexiglas® deck-board in pallet storage rack simulation is good, with a difference of less than 10%. In the block stacking condition of 1/2″ and 3/4″ deck-boards, the differences between measured and predicted deflection was 3% to 28.6%.

In this study, the locations where the highest stresses were concentrated on pallet deck-board surfaces were identified by analyzing and quantifying stress distributions for both storage system simulations. These findings will be useful in understanding the interactions between a pallet and packaging in a warehouse storage system. Consequently, economic losses resulting from product damage and unsafe working environments will be reduced in warehouses. The final models obtained from the FEA simulation as well as these analyzed stress distributions will allow the industry to better optimize pallets, packaging, and unit load designs.

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Antimicrobial Packaging: Potential vs. Reality—A Review

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ABSTRACT: The market need for natural and safe food products and the stringent regulations to prevent food borne infectious diseases and food recalls have motivated researchers into finding novel technologies for antimicrobials delivery which should result in improved safety and quality of the food products over the storage period. Antimicrobial packaging (a subset of "active packaging" and "controlled release packaging") is one such technology that effectively incorporates the antimicrobial into the packaging material and delivers it over the required period of time, thus causing no reduction of the antimicrobial's concentration in the product. This technology has come a long way in the development of different materials and methods to incorporate the antimicrobials and release them based on the application. Numerous natural antimicrobials have been tested using this technology both in medicine and food and are proved to be effective. Although the potential of antimicrobial packaging system is noticeable in laboratory conditions this is not effectively extrapolated into real life situations. This paper aims at discussing the potential of antimicrobial packaging systems, evaluating the reasons for the gap between laboratory conditions and real life situations, and providing possible solutions to overcome this situation.

INTRODUCTION

THE safety and quality of the food supply has gained significant attention in recent years, yet increasing concerns over recalls and ingredient sourcing trouble many consumers [12]. These concerns lead to a need for more effective safety regulations as well as better systems for maintaining food quality. However, there is also an increase in consumer desire for natural, local and organic products which creates new challenges in providing efficient food preservation, especially in the

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area of microbial safety [12,22,80]. Many current methods for maintaining and enhancing food quality do not satisfy consumers' demand for products from natural sources. Therefore, food industry has begun exploring alternatives to presently used chemicals. Numerous natural substances have been tested, from grapefruit extract to bacterially-synthesized antimicrobial peptides known as bacteriocins and mustard oil [13,14,38,45]. Several natural-source substances, including antimicrobials and antioxidants, had proven effective in laboratory settings. However, their effectiveness in real life applications is still challenged by the specific characteristics of the foods and conditions of application.

In addition to the desire for natural compounds that enhance quality, there is also a need for an efficient method for their delivery into foods. Addition of compounds directly into food (so-called "formulation") is an established practice with some disadvantages. FDA regulations specify safe levels of the substances that could be added into food. Instant addition of antimicrobials in formulation often results in instant inhibition of non-desired microorganisms. However, the survivors will continue to grow, especially when antimicrobials added by formulation will get depleted. This may happened due to complex interactions with the food matrix or by natural degradation over time causing short shelf-life [15,44,64]. In addition, gradual decrease in antimicrobials' concentration may lead to development of the antimicrobial-resistant mutants [15]. To overcome these disadvantages, new technologies, namely "Active Packaging" and "Controlled Release Packaging (CRP)" emerged that use packaging as a delivery system to release the antimicrobial into food in an effective manner, thereby extending the product's quality, safety and shelf life.

The potential of these antimicrobial packaging technologies is quickly creating interest in the scientific world leading to extensive research and is being reviewed in this paper. In contrast, previous reviews have dealt either with the packaging polymers themselves, the compatibility of specific active substance with a specific polymer, or the regulations made and needed to deal with emerging active and intelligent packaging [13,22,38,65]. Little has been made of the comparative benefits and drawbacks of these systems, their concepts and applications. While this review is mainly geared towards the use of active packaging and controlled release as it relates to microbial food safety and quality, important advances in medicinal and personal care uses will also be ad-

dressed. Most importantly, the relative advantages and disadvantages of different approaches, their effectiveness in complex real "life systems" and the gaps that need to be filled will be discussed.

ANTIMICROBIAL PACKAGING: POTENTIAL

Antimicrobial packaging integrates all useful technologies or delivery systems for incorporating antimicrobial compounds into the packaging material and their release over a period of time to maintain the product's quality and safety. This will ultimately lead to the extended shelf life.

Antimicrobial Packaging Technologies

Active Packaging

Active packaging is an innovative concept developed to actively modify the internal environment by continuously interacting with the food over the stipulated shelf-life. It is defined as an intelligent system that modifies the environment inside the package thus altering the state of the packaged food system or headspace to improve food quality through extension of shelf-life, maintenance of microbial safety or enhancement of sensory qualities [22,38,67,80]. Active packaging has gained much popularity due to the increased desire for high-quality, natural, safe and fresh products by consumers [13,38,65].

Active packaging is a broad area where the packaging material(s) actively interacting with the food. Active packaging systems include O_2/CO_2 scavengers, CO_2/ethanol emitting systems, ethylene and moisture absorption systems, and antimicrobial/antioxidant releasing/containing systems [13,22,38,65]. Scavenging systems absorbs harmful compounds from the surface of the food or from the headspace, while emitting systems release compounds acting at the surface of the food or within the headspace [38,67]. Materials such as ascorbic acid, iron powder, photo-sensitive dyes are packed in sachets and used to scavenge oxygen to prevent growth of aerobic bacterias and molds [28].

Ethanol emitters are encapsulated and sold commercially by Mitsubishi Gas Chemical Co. (Japan) as antimicrobial preservatives for some bakery products. Many examples of active packaging materials have come to the market in Japan and in the U.S. Some of these systems are attractive to the consumer as they are composed of substances con-

sidered 'natural'. Moreover the slow release nature of the packages prevents large amounts of the antimicrobials from being present in the food at the time of consumption, while still maintaining the desired activity [82]. The concentration of antimicrobial in the packaging must be calculated based upon the amount needed in or regulated for the final product [62].

Controlled Release Packaging

Controlled release packaging, which is a relatively new technology, is a sophisticated form of active packaging that focuses on the releasing systems. It is an active system that uses packaging as a delivery vehicle to efficiently bring the actives in specific controlled rates over prolonged periods into the food to enhance food quality and safety [46]. The key term being "control" helps to regulate the concentration of the antimicrobials in the food at a targeted level that is effective in slowing down microbial growth kinetics and rendering it safe for human consumption. Controlled release applies the principle of active packaging but what sets it apart is the ability to manipulate the release of the antimicrobials as desired by regulating the package containing these substances.

Controlled release (also known as time-release and slow-release) of active substances has been in existence for many years now both as a concept and as a marketable method of utilizing drugs, antimicrobials and many other compounds in various applications. It can be employed to release prescription medications, vitamins, antioxidants and many other compounds into a variety of environment. Simply taking medicine in small doses over a period of time can be considered a method of controlling the delivery of the medicine and its effects. Of course, technology has allowed for significant advancement to the concept. Not only can drugs be taken over a period of time, they can also release the compounds over time or provide with the triggered-release when certain conditions are reached; for instance, pH-based release can be initiated by exposure to stomach acid or intestinal pH levels [69].

Controlled Release Packaging in Medicine and Personal Care

A variety of approaches are currently used in the medical area to enable continuous release over a prolonged period, including microparticles, gels, osmotic minipumps and adhesive patches [57]. Often, the fine-tuning of the details is where controlled release systems can

differ the most. Various polymer compositions can affect the release rate of the antimicrobials; in addition, incorporation of active substances into the polymer can change polymer chemistry, which in turn can affect its characteristics such as oxygen permeability, tensile strength, release rates and brittleness [2,46,66,72,73,80,89].

The control of release rates has large implications for the medical and personal care industries. Many diseases or conditions result from persistent infections or hormonal imbalances [14,19,57]. The controlled release of drugs as treatments for those conditions can more effectively address the cause of the disease. In particular, implants are a major concern for the medical industry due to their susceptibility to contamination, leading to infection in the host and ultimate rejection or replacement of the implant [10,19,20,27]. To prevent biomaterial-related infections, the current strategy is to treat patients systemically with antibiotics at high concentrations. Sometimes, this approach alleviates the infection, but often it leads to rejection of the implant and a subsequent second surgery to remove and replace it in the patient. The controlled release of antimicrobials and antiseptics from the implant itself can greatly decrease the rejection rates of implants like heart stents and knee replacements [8,9,10,19,20,39]. In addition, many skin conditions and external wounds could benefit from dressings or patches that release treatment compounds in a controlled manner, eliminating the need for constant reapplication of creams and bandages [5,41]. Another facet of medical treatment that can be aided by controlled-release applications is protein therapeutics. Proteins have low oral bioavailability and are particularly susceptible to degradation by metabolic activities or temperature, which can be solved by encapsulation or incorporation into a polymer. Release rates can be adjusted by modifying polymer composition and up to fourfold less drug may be required when using sustained release as opposed to immediate delivery [66].

Controlled Release Packaging in Food

Though the concept of controlled release has existed for some time now in the field of medicine and personal care it is still being explored and developed in food. Controlled release of flavors, enzymes, sweeteners and other food preservatives has been accomplished through encapsulation [42]. Lysozyme, a natural antimicrobial known to inhibit lactic acid bacteria causing wine malolactic fermentation is incorporated in PVOH films. The varied degree of crosslinking of the films helps to con-

trol or vary release rates of the antimicrobial to provide an effective inhibition [11]. Similarly antibacterial and antimycotic effect of potassium sorbate added to HDPE and LDPE films on American cheeses has been studied. Sorbate released from HDPE films were found to be effective and were able to store the cheese for 5 months at room temperature [82]. In the case of food products, the standardized films/coatings designed with consideration for the efficient control of the targeted organisms and, ultimately, for the extended product's shelf life have far more potential than the simple addition of antimicrobials.

Controlled release application of bacteriocins may offer a way to treat resistant bacterial strains [9,15]. Studies have shown that while instantaneous release of nisin can inhibit cell growth, the survivors will undergo mutations to develop resistance to nisin. On the other hand, merely releasing nisin from packaging without any nisin added directly into the formulation did not reduce cell counts. A combination of the two resulted both in reduced cell counts and lack of mutation; instead, the cells adapted and regained their sensitivity to nisin following one passage through nisin-free medium [15]. Since the main target of antimicrobial peptides is the bacterial membrane, resistance to them would require a restructuring of the membrane structure. In addition, preventing the initial attachment of bacteria to prevent biofilm formation greatly reduces the inherent resistance to stresses within the cell.

Antimicrobial as Polymer Building Blocks

Another novel approach for antimicrobial packaging other than emitting, absorbing or releasing systems is the use of the antimicrobial itself as the polymer matrix. As the polymer degrades, it releases one or more substances into the environment. This approach to active packaging is easily expanded into multi-purpose packaging systems to enhance food quality. Polyanhydrides are a class of biodegradable polymers gaining popularity in biomedical application, including drug delivery, implant coatings and tissue scaffolds. They frequently contain hydrophobic compounds bound by hydrolytically labile anhydride bonds, and the degradation rate can be controlled by changing the composition of the polymer [73]. Anhydrides added to films made of other polymers have proven antimicrobial activity [80], and films made of these active anhydrides can act as prodrugs, breaking down to release the compound in a controlled manner in the desired area. Poly(anhydride-ester) or PAE polymers can controllably release salicylic acid as they undergoes

hydrolytic degradation [25,26]. Salicylates and other non-steroidal anti-inflammatory drugs (NSAIDs) are known to prevent bacterial adhesion onto medical devices [4]. PAEs have been shown to prevent biofilm formation, and could be used in combination with other active substances for food packaging to enhance food safety [10,70]. Polyanhydride films are easily manipulated into many functional forms and are currently among the few biodegradable systems approved by the FDA for use in humans, though use in foods has yet to be determined [3]. These films, which have great potential for the food safety industry, will be discussed in more detail in later sections.

Systems for Delivering Antimicrobials

Spheres

Microencapsulation of flavors, enzymes, probiotics, antioxidants, preservatives, colorants etc for application in foods has been commercially utilized for a long time [35]. Lactic acid bacteria such as *Lactococcus lactis* subsp. *cremoris* were immobilized by encapsulation within alginate bead for continuous lactic acid production. To enhance the efficiency of encapsulation and prevent leaking, the beads were coated with Poly-L-lysine, nylon and polyethyleneimine [48]. Microencapsulation of antimicrobials such as nisin and lyzozyme in phospholipid liposomes, to enhance their stability in foods, showed greater than 2 log cfu/ml activity against two strains of *Listeria monocytogenes* with entrapped nisin (3.3 mg/ml) compared to free nisin [88].

Microspheres and nanospheres are among the most common applications of controlled release, especially in medical and personal care applications [41]. The surface area of the sphere has an effect on the release rate and can change as the active substance is release from or through the surface of the sphere. In addition, larger particles have the potential to absorb more water from the surrounding environment [53].

Due to their hypothesized usefulness in the human body, many micro- or nanosphere applications have been researched [41,43,57,59]. Solid lipid nanoparticles, for example, are capable of controlled release of drugs, vitamins and other lipid or emulsified active substances. They can be used as a drug, an additive or suspended in semi-solid hydrogels or emulsified creams for topical applications [41]. Other substances have been investigated for *in vitro* drug release, including novel microspheres

made from hyaluronic acid and chitosan, with the intent on enhancing drug absorption through mucoadhesion. The spheres display a characteristic burst release, and though the majority of the microphores dissolved within 1 hour, release of the antimicrobial was not complete after 5 hours. The remaining compound retained activity, lengthening the effectiveness of these microspheres for drug release [53].

Another novel application of controlled release is the encapsulation of living cells in microspheres for testosterone-replacement therapy. Cell encapsulation by a biocompatible, semipermeable polymeric barrier helps protect the cells from attack by the host immune system and prevents the metabolic inactivation of the hormone which occurs during oral administration [57]. Other microspheres, made from fast-degrading hydrophobic polymers, are good bioadhesives and enhance the uptake of drugs that are inefficiently absorbed by the body [59]. The same principle can be applied to DNA microencapsulation. Microencapsulation in poly(DL-lactide-co-plycolide) polymers (PLGA) resulted in increased stability and release rates characterized by an initial burst followed by slow release due to polymer degradation. DNA released during the burst phase had much higher activity than that released during the second phase [86].

Films

Films and coatings are considered as promising systems for the controlled release of substances into an environment. They are especially effective in foods, where changes often take place on the surface or in the headspace of the package interior [38,44,45,67]. The amount of antimicrobial can be changed by percentage incorporated into the polymer matrix as well as the thickness of the coating. Films on the inside of bottles can prevent the loss of important vitamins and nutrients, like ascorbic acid, during storage [6]. Another application of films and coatings is for release of antimicrobials into food systems to prevent outgrowth of non-desired microorganisms and to prolong shelf-life [15,24,32,38].

As mentioned above, antimicrobials can either be released onto the surface or within the headspace between the food and the packaging. Compounds released into the gaseous environment within the package can change the atmosphere to prevent ethylene production, lipid oxidation or growth of microorganisms [55]. Incorporating volatiles into packages requires the optimization of analysis techniques for determin-

ing release rates and effectiveness of volatile antimicrobials in the vapor phase [7,38]. The increasing interest in the use of essential oils with antimicrobial activity makes antimicrobial packaging using volatile antimicrobials crucial [7,12]. Essential oils (EOs) are lipid fractions obtained from plant materials through a variety of methods, including extraction and steam distillation. They are mostly used in flavors and fragrances, but recent scientific studies are supporting their possible health and safety benefits for the food and medical industries [47]. Some benefits of EOs include antimicrobial, antiviral, antimycotic, antioxidant and other functional effects [12]. Frequently, the EOs with the highest antimicrobial properties contains high concentrations of phenolic compounds [75]. An alternative aspect of active packaging or CRP would be the use of enzyme immobilized onto the packaging material. This technology is currently used in production lines to catalyze enzymatic reactions without losing the enzyme itself along the way. However, in order for this packaging concept to work, the packaging needs to be in contact with the food surface. Unlike volatile or diffusible compounds that can migrate through headspace, enzymes can only work when the substrate is in close proximity. It is also possible to immobilize antimicrobial compounds, like silver ions or covalently-linked peptides and organic acids. Some polymers, like chitosan, are inherently antimicrobial, but it is also possibly to make plastic surfaces themselves antimicrobial using UV radiation. A UV excimer laser can convert nylon amides to antimicrobial amine groups [55].

Antimicrobial Polymers

As mentioned above, polyanhydrides shows promise for use in medical, food and personal care controlled release systems. The polymers degrade at different rates depending on the antimicrobials and linkers that are incorporated into the backbone and other functional materials like antibiotics or antioxidants can be physically admixed into the polymer and manipulated into many forms, including films [3,89]. Recent studies investigated the effects of polyanhydride polymers on biofilm formation and discovered that the release of salicylic acid from polymer films can prevent the formation of *Salmonella typhimurium* biofilms. These results are rather promising, especially considering biofilms are highly resistant to antimicrobials as compared to free (planktonic) microorganisms [7,70]. Eradicating persistent biofilms is difficult because they require action of antimicrobials and physical removal. Therefore, preventing biofilm for-

mation in the first place is crucial to food safety. The potential for producing polymers capable of releasing antimicrobials of natural origins that can prevent biofilm formation and enhance food quality is very attractive to industry as well as to consumers, and the results of this research have generated interest in the media and scientific publications. The mechanism of action is currently under investigation, as is the utilization of other natural antimicrobials in these polymer films for future use as food packaging technology. This especially has implications for use as multiple hurdle technology, which will be discussed in more detail later in this review, due to the ability to formulate polymers with multiple active components, whether they are integrated into the backbone itself or physically admixed and co-extruded into packaging materials.

Other Delivery Systems

Devices or materials pre-treated with in an appropriate for purpose solution of an antimicrobial(s) are required for certain applications. Standardizing the time of the contact and the concentration of antimicrobial in the solution replaces coating known quantities of film containing specific concentrations of the antimicrobial [9,20]. For example, collagen patches impregnated with antimicrobials are in use as biomaterials. Antimicrobial efficiency and adhesive strength as a biomaterial have been evaluated, but release rates or profiles were unavailable [5]. Another application using a less controlled method of application is the soaking of plaster of Paris implants in antibiotic solution. Antibiotic effect was retained both in vitro and in vivo; slow release on the antibiotic did not even approach 50% of the initial concentration within 3 weeks [8].

Such results have potential for clinical uses, where extended time of antibiotic's presence in the environment may be required for treatment of persistent infections [9,19,20]. Dental caries and periodontal diseases are the most common bacterial diseases in the world, and systemic antimicrobials are recommended for treatment [21]. Controlled-release antimicrobial systems are very attractive both to consumers and to the industry since they have the potential to treat chronic dental problems as well as satisfying the consumer's desire for naturally-derived products.

Materials Used for Delivering Antimicrobials

The release of antimicrobials from polymers depends on the polymer type, composition and processing methods and conditions. Varying the

above variables helps manipulate or control the release from packaging systems. Thus selecting the right kind of polymer is essential to get the desired microbial inhibition.

Synthetic Polymers

Plastics have been the polymer of choice for packaging in recent years, due to low cost and high performance [54]. The cost of plastics has been reduced due to innovations in the packaging field as well as the inherent properties of the barrier material [13]. Biodegradable polymers, defined as polymers created from raw materials of agricultural or marine sources and broken down through biological or chemical reactions, have been manufactured for biomedical purposes for over 30 years and are gaining in popularity over plastics [2,13,40]. Although most commercial active packaging systems currently available are made from plastics, tests of those made from biodegradable polymers show comparable efficacy [13].

The limitations of specific plastics and biodegradable polymers lead to the combination of different polymers to accomplish a particular packaging or coating goal [2,13,46,55]. The rationale for using combination of polymers is in different diffusion coefficients attributed to the variations in the polymers' chemical and mechanical properties. These variations in diffusion coefficients can be translated into release properties and thus by combining polymers into single films varies their structures and morphology results in unique features appropriate for the particular application. Therefore, the active substance's release can be tailored as required by combining the right for the purpose types of polymers [46]. For example, it was reported that release rate of natural antioxidant, tocopherol, from polypropylene (PP) into 95% aqueous ethanol was the slowest followed by its release from high density polyethylene (HDPE) and low density polyethylene (LDPE) respectively [71]. This variability in release rates of active ingredients can be exploited by combining LDPE and PP in different ratios to help tailor the package suitable for a wide range of food systems. Many studies have been conducted to determine release rates of compounds from these polymers in addition to assays to determine activity of the compounds following the release [36,45]. However, the increased use of plastics in packaging materials can lead to larger amounts of waste and concerns about unintended migration of polymer components into food items, especially those given to children [2,13,55,67]. Biodegradable films address some of these is-

sues. Edible films and coatings made from natural sources are also an attractive alternative to plastics that addresses those consumer concerns. These films often have the added benefit of being made from otherwise unused byproducts of industrial processes, further increasing their attractiveness to concerned consumers [13,64].

Biopolymers

Due to increase in environmental concerns and need for natural materials biopolymers are widely explored as antimicrobial packaging for food. Biopolymer films including both edible films and coatings and can be classified into several categories: carbohydrate-based (also known as hydrocolloids), protein-based, lipid-based and composites [13]. Some hydrocolloid polymers being researched include cross-linked starch films, cellulose-based films, agar and carrageenan which are both galactose polymers, and chitosan films [13,36,39,75]. Cross-linked starches have been used in food applications for years, and have properties that extend well into controlled-release applications. The shelf life of strawberries coated with starch based coatings containing potassium sorbate was effectively increased from 14 days to 28 days [33]. Release rate of drugs increases with increased cross-linking of the amylose, while it slows down with low crosslinking as the conformation of starch changes from V-type, single helices to B-type double helices and the resulting release profiles are not greatly affected by manufacturing conditions [51]. Cellulose-based films are receiving the deserved attention due to their high water-solubility, which makes it easier for additives to be released into foods with high water content [36]. Chitosan is especially of interest for the antimicrobial packaging and biomaterials industries because it is cationic and naturally antimicrobial. The antimicrobial property is mainly due to its protonated amino group which interferes with negatively charged membrane components [13,18,24]. Proteins that are being investigated for use in packaging films and coatings include zein, soy protein, gluten, collagen and whey protein as well as other milk proteins [13,75]. Whey protein films especially have gained attention in recent years, due to their mechanical strength and excellent barrier properties [39,75]. Lipid-based films are mostly used as moisture barriers, especially for fresh fruits and vegetables [13]. Protein and lipid based polymers has good potential as antimicrobial packaging due to their mechanical and barrier properties.

The major limitation in using the renewable biopolymer films is the

inability to achieve high mechanical properties and water resistance, due to their hydrophilicity. Composite polymers may present a solution to this limitation. Using a blend of protein and polysaccharide can provide gas barrier [43], while a composite of lipid/ polysaccharide [23,37] or lipid/protein [16,76] can provide moisture barrier. Addition of polymer-clay nanocomposities into polymers is gaining wide approval to improve the mechanical strength of polymers [1,34,77].

ANTIMICROBIAL PACKAGING: REALITY

Gap between "Test Tube" and Reality

The main concern with antimicrobial packaging is the effective extrapolation of lab results into the complexity of the real world. Often, lab tests are done with food simulants that are far less complex than actual food systems [45]. Real foods will have more nutrients, lower water activity, higher salt contents and fats or proteins which may interact with the antimicrobials [6,12,36,60,85]. In addition, the conditions in which the foods are transported and stored have a great effect on its characteristics [12,13,32,45,49]. Temperature and moisture content have a great effect on release rates of compounds and their effectiveness [64,81]. Release rate is an important parameter, since it determines how much of the compound will emerge from the packaging and how long it will take to saturate the area. When simple diffusion is employed, antimicrobials diffuse across a gradient, but as the food surface or headspace becomes saturated, the release may slow to a stop [38]. In addition, many substances undergo an initial burst effect, releasing a large quantity all at once and ceasing release until it is all consumed [39]. Often, the release of the active substance is not governed solely by diffusion, but also due to swelling and water uptake of the film [64]. Polymer matrices which are not influenced by the food system, especially water in food, diffuse by Fickian diffusion where the diffusion depends only on temperature variation while the diffusion coefficient varies with time in polymers that swell or change their matrix.

Microbiological, chemical and analytical tests can determine where the antimicrobial goes, in what quantities and the method of action of antimicrobials in experiments that simulate food systems [7,15,81]. However, achieving the same results in real foods is far more challenging. When tests using real foods are reported, they often reveal that the

developed antimicrobial packaging system is less effective than it was in previous lab experiments [24,45]. Tests with essential oils have revealed that much higher levels of EOs than are used for *in vitro* tests are needed to achieve an effect in foods, including milk and cheese applications [12]. Some of the suggested explanations for this phenomenon are greater availability of nutrients for cellular repair, higher organic acid and trace metal content, and interactions with compounds in the food that may interact with or inactivate the active substance [12,49].

With medical applications, clinical trials reveal whether the developed controlled release system is effective. For example, catheter tubes containing a bacterially-synthesized antimicrobial protein active against closely related species (also known as a bacteriocin) called nisin were proven effective at reducing bacterial infection for 24 h (at which time the nisin activity drops significantly) without any adverse effects to the animals used in the testing for up to a week. The authors of this study suggest further experiments using replacement of the nisin over time to enhance its effects, as well as further tests to retain nisin activity for longer periods of time and ascertain nisin's effects on tissues and bacterial cells over longer periods of time [9]. Another study used chitosan for wound dressings loaded with antibiotics to inhibit wound infection, especially of wounds from armed conflict where extensive medical care is often not immediately available. The incorporation of silver sulfadiazine, an antimicrobial commonly used in burn wounds, reduced cell counts by 7-logs in 7 days, a rather impressive result. Sulfadiazone release showed a burst effect followed by slower release, while the silver ions were released very slowly over the time period [61]. This dual-action film proved very effective in lab tests, and demonstrated suitability for real situations where a slow, sustained delivery of antimicrobials can mean the difference between life and death.

Often, conclusions that are reached by the results of a study may not be applicable for the desired field. For example, packaging containing triclosan was investigated with regard to food applications. No triclosan was released in pure water, but even in 10% ethanol solution less than 2% was released. Approximately 2-log reduction of *Enterococcus faecalis* was achieved at this amount [17]. While the reduction is impressive for such a small amount of antimicrobial, due to the high minimum inhibitory concentration (MIC) of triclosan, it might not be sufficient to prevent illness in humans. In addition, the majority of foods do not contain a high enough proportion of hydrophobic substances on their sur-

face for the triclosan to be released in an effective concentration from the packaging material. Another study using triclosan-containing films showed some inhibition in laboratory conditions but none when applied to chicken breasts vacuum-packed and stored at 7°C [85]. Due to suspected correlation between resistance to triclosan and resistance to other antimicrobials and antibiotics, the widespread use of triclosan should not be encouraged, especially not in food systems [74,79]. Perhaps a more efficient conclusion from these results would be the use of triclosan in low amounts can be effective in combination with natural antimicrobials or other stresses to the bacterial system to provide a preservation system with multiple modes of action. This would prevent resistance from becoming more widespread, as will be discussed in more detail later in this review.

Lack of Good Experimental Design

A frequent deficiency on the part of some experiments is the lack of proper study design, which should include measurements of essential parameters including pH, released substance vs. amount retained in the packaging, kinetics of growth and effects of the active substances on resistance. For example, conclusions in a study focusing on nisin release from cellulose-based films attributed the failure of nisin to inhibit *Listeria monocytogenes* to neutralization of the bacteriocin by the pH of the peptone water used as a food stimulant. Yet pH was not measured over time, and no pH data was given. In addition, no zones of inhibition were seen between the first 30 minutes and 4 days but at day 8 the inhibition reappeared. This was attributed to the possibility that the nisin released in the first 30 minutes was neutralized by 24 h, but it took until the time between 4 days and 8 days for the remaining amount of nisin to be released to act against the microorganism and overcome the pH neutralization [36]. Again, there were no data to confirm this assumption besides the fact that at 8 days there was inhibition while at 4 days there was none. This lag in release can allow bacteria not only to overcome the stress of the antimicrobial but also for survivors of the first wave of release to develop resistance.

Discrepancies and Error in Judgment

Sometimes, the results using liquid media or lab simulants are not

very impressive to begin with, and the application of these systems to real life applications also results in further unimpressive results. In one study, researchers tested a nisin-containing film against *Micrococcus luteus,* a common reference organism, in TSB media and milk. At 4°C, less than 1-log reduction was seen over 50 hours as an effect of nisin; at 25°C, the nisin-treated cells reached, over 30 hours, the same concentration as untreated cells took approximately 5 hours to reach. While the slowed growth is promising, the cells still reached the same concentration in a relatively short period of time. When the coating was tested in raw milk, pasteurized milk and UHT milk, the largest decrease in cell numbers was 2-logs, in pasteurized milk. Only in raw milk was a pH decrease seen, which seems to be an effect of the native lactic acid bacteria present in raw milk rather than an effect of the action of nisin on the *M. luteus*. In the release rate studies, it was shown that a back-absorption mechanism, in which the released nisin is reabsorbed by the film, resulting in an alternation between high inhibition and low inhibition [60]. While the results of this study alone do not lead to a fully developed packaging concept, the data obtained from these experiments can aid in the development of a combination system, with a second antimicrobial to supplement nisin.

However, the attempt to validate antimicrobial packaging systems in real food products leads to increased knowledge as to the potentials and limitations of the systems—as long as the results are accurately reported and not inflated in significance. Chitosan films have been tested for antimicrobial activity for a variety of foods, sometimes in combination with other substances and sometimes as the sole antimicrobial. When tested as a coating on *Pseudomonas*-challenged Emmental cheese samples, chitosan films reduced cell counts by more than 2 logs [18]. Though not an impressive reduction, the results could lead to further development of the films using additional antimicrobials to further stress the cells. Indeed, chitosan films containing lysozyme, a lytic enzyme used in cheese manufacturing to prevent growth of *Clostridia* ssp., were also tested against cheese following preliminary laboratory tests, this time of the Mozzarella variety. The films reduced cell counts of *P. fluorescens* by slightly more than 2 logs and all other microorganisms tested by less than 2 logs, yet the significance is marred by the fact that the control cell counts dropped approximately one log over the two week test period. This drop is attributed to lactic acid produced by the native bacteria in cheese, which makes the actual effect of the chitosan and

lysozyme difficult to determine. In addition, only one strain of yeast was evaluated, *Candida inconspicua*, and the results showed almost no inhibition by the coatings. The films when tested against molds showed less than 2-log reduction and were yet concluded as 'complete inhibition' [24]. Considering yeast and molds are the most common colonizers of cheese products, testing more species would have been prudent and a more realistic view of the results is necessary so as not to over-inflate the effects of systems that still require more research and fine-tuning.

Another example of a system tested in various real-life applications is that of the ethanol-emitter. Ethanol, when emitted from a sachet or packaging material, lowers the water activity of the system and acts as an antimicrobial [22,32]. As bakery products are particularly susceptible to yeast and mold contamination, since they do not contain the preservatives present in commercial baked goods, the absorption of ethanol from the headspace could extend the shelf-life significantly. At the two highest doses of ethanol tested, the buns remained yeast- and mold-free for almost 20 days as opposed to the 4 days seen in untreated control buns. However, bacterial counts were too high, due mainly to the growth of *Bacillus cereus* in the center of the buns [32]. Further research should be dedicated to reducing the bacterial count through other methods in combination with the ethanol.

Many active packaging concepts utilizing nisin as an antimicrobial have been evaluated, especially in combination with other stresses or antimicrobials to provide a multiple hurdle approach. This approach utilizes multiple stresses on the cells with different modes of action in the pursuit of maintaining food safety without causing resistance to any one stress factor. Many of these combinatorial studies utilize nisin, an antibacterial peptide produced by *Lactococcus lactis* that has GRAS status as a food preservative for the inhibition of *Clostridium botulinum* and other bacteria for certain food applications [83]. One such study, assessing antimicrobial packaging materials made from acrylic and vinyl acetate-ethylene polymers, was aimed specifically at highly liquid foods and beverages. The polymer caused a 6-log reduction of total aerobic counts from the control samples. The authors speculated that the targeted cells were sensitized to nisin by additional stress factors, specifically sublethal injury to the cells from pasteurization, so further research was required to check the effects of pasteurization levels and possible post-process contamination on initial cell counts as well as nisin activity [44]. Another study along the same lines examined low-density polyeth-

ylene films containing nisin and lactocin for fresh oyster and ground beef packaging. The goal was to extend the shelf life of real food systems beyond their current limits. Unfortunately, the promising laboratory results did not translate into an extension of the shelf-life in this case, with less than 2-log reduction in total aerobic and coliform counts at 10°C for both oysters and ground beef [45]. The authors deemed this reduction significant, but in foods that are so often involved with recalls and pathogen outbreaks like ground beef [29,30,31], more research needs to be done into further preventing cell growth through higher concentrations or combinations of antimicrobials.

Errors in judgment, like the above-mentioned, are occasionally seen when assessing results, but sometimes erroneous assumptions plague a paper from start to finish. One such paper involves evaluation of composite films formed from poly (lactic acid), also called PLA, and pectin for use in antimicrobial packaging [54]. First, assumptions were made regarding the antimicrobial activity of PLA polymer based on prior results from PLA oligomers in solution or PLA monomers used in conjunction with antimicrobials. Polymers are not the same as solutions and do not behave the same at all, and certainly antimicrobial activity cannot be assumed for one component in a mixture when other components in the solution possess their own antimicrobial activities. Then, when the polymers were formed, they were loaded with nisin before being evaluated for inherent antimicrobial activity. If the polymer is expected to have its own antimicrobial activity then it should be tested, before loading nisin, to ascertain its activity and get a baseline activity. The choice of bacterial strain was not justified, and the application for which this polymer was being researched was also not clearly outlined from the beginning. The chemical and physical evaluations of the polymer were detailed and well-outlined, but the antimicrobial data were given very little attention or thought. An image of the control and nisin-loaded polymer samples tested for antimicrobial activity claims that samples without nisin have no zones of inhibition. However, even a cursory examination of the image shows that the pectin/PLA polymer without nisin has a zone of inhibition. There is no diffusion of antimicrobial, since it is a result of the polymer itself and not a diffusible compound, but the zone was apparent. They failed to measure the zones or compare it to nisin solution or diluent as additional controls. The zone size was simply described as 'significant inhibition'. The authors failed to establish the criteria for mentioning significance. A line chart comparing cell growth in the pres-

ence of polymer samples fails to elaborate on the control sample and since the PLA/pectin control images contained its own antimicrobial effects, the distinction of which polymer was used as the control becomes of utmost importance to prevent skewing of the results. The time marks on the chart are not equidistant, leading to an altered and inaccurate view of the results. Overall, the paper started with a good idea but as a result of all the misjudgments that occurred, the results can't be considered reliable or accurate.

Lack of Studies on Resistance Development of Organisms

Another such study involved cellulose casings for frankfurters coated with nisin [56]. The concept of nisin resistance developing in cells from prolonged exposure to the antimicrobial is not a novel one, though introduced at the beginning it was never pursued in the rest of the research. The difference in *L. monocytogenes* growth between control casings and casings coated with nisin was about 0.2-logs, a very insignificant number but was referred in a rather unscientific term as 'decreased somewhat'. In addition, tests in which lactic acid bacteria were used showed higher levels of cells in nisin-coated casings than in the controls. After 90 days (a typical shelf-life for refrigerated frankfurters), *L. monocytogenes* reached the same cell density in control and nisin-coated samples. The effect of nisin in this case was not clarified. The cell growth in nisin-coated frankfurters decreased until 15 days, then rose to the same levels as the control. There is no indication that testing was done to determine if the survivors had nisin resistance following the treatment, as was alluded to in the beginning of the paper. If the cells had become resistant, than using the antimicrobial packaging could theoretically be worse for food safety than not using antimicrobials. The authors maintain in the discussion that resistance is unlikely because three strains of *L. monocytogenes* were used. It would have been clear if tests were done to evaluate the resistance development than just making that assumption, as it is not unreasonable to consider that under the same conditions, three closely related strains of the same microorganism might react in the same manner. The possibility of comparing the coatings on frankfurters with different ingredients and processing techniques is mentioned, yet it would have been fairly simple to have done it together with the currently-published data, and the results would have been far more ro-

bust as a result. Towards the end, further research is mentioned, aiming to use higher levels of nisin (to overcome the diminishing effect) and 'variants of nisin' either alone or in combination with other substances. A better explanation of such statements is required, and assays to determine if resistance occurs should have been the first thing planned for future research.

While many papers regarding controlled release applications for the medical field discuss the possibility of resistant strains developing [27,39], almost no studies involving food systems investigate the development of resistance as a result of the antimicrobials involved in the research. The current research is often brief and without experimental data from an investigation of whether resistance occurs or how it could be avoided. The researchers emphasize extended lag phases of growth, with the resulting cells growing to lower cell counts [50]. However, tests for mutations or adaptations to the antimicrobial are not done or discussed, and neither are the implications of such a recovery on shelf-life.

Lack of Multi-disciplinary Approach

Lack of multi-disciplinary approach is one of the major problems for the poor analysis of the obtained data in the aforementioned and many other published papers. Changes should be made in the materials used, the functional compounds, the engineering of the application and combinations of compounds with complementary activities [24,38]. We can see that there is an evident need to relate the release rate of antimicrobials from polymers to microbial growth kinetics and shelf life and this can be accomplished by multi-disciplinary teams comprised of food microbiologists, chemists and engineers. Each field contains nuances which may not be fully explored by many current studies, such as cases where the packaging structure and chemistry are fully realized but microbiological tests are underdeveloped. Only through the combined efforts of all aspects of food science can successful active packaging concepts be developed.

IMPLICATIONS FOR THE FUTURE

Comparing the potential and reality it is pretty obvious that though these deliver systems have a huge potential as antimicrobial packaging to inhibit microbial growth and extend the shelf life of foods, we still need to do extensive research to make it a reality. The research should

move from just showing the potential of the delivery systems in food simulants to actually proving their efficacy in real food.

Selecting Right Package, Antimicrobial and Environment

It is essential to select the right package for a particular antimicrobial and environmental condition. Selecting a polymer that releases the antimicrobial very slowly over a period of few months will not be effective when the microbes have a very short lag period. Also it is important to choose the right antimicrobial for a food and package. The antimicrobial should not be too compatible with a package that it does not get released or incompatible that it gets released within minutes. We need to select a volatile or a non-volatile antimicrobial based on food contact with the package. If there is no contact between food and package then the antimicrobial has to be volatile to be effective and vice-versa. Proper care should be taken when dealing with the internal and external environment of the package. The diffusion rate of antimicrobials from packages depends highly on temperature, also the microbial growth kinetics depends on the pH and water activity of the food. Thus it is imperative that we establish the relation between environment, package and food before doing the study.

Integrating Packaging Research and Food Research

Development of models needs to integrate packaging research and food research, in this case microbial growth kinetics, is essential to expand and use active packaging and controlled release packaging effectively, which is similar to the development of any other technology. For example microbial growth has an inherent short lag period and the amount of antimicrobial added during that period is critical. Very slow release rate may not be sufficient to inhibit growth while high quantity or faster release rate may develop resistance and mutation. Thus it is critical to know the extent of release i,e., how fast or how slow the antimicrobial should be released into the system. To understand this we may need to study and evaluate the microbial growth kinetics with respect to their stress due to food composition; environmental factors; antimicrobial release rates from active and controlled release systems. This will help us determine the optimum range of release rates for antimicrobial release from polymers to limit or inhibit microbial growth by extending the lag

period to slow down growth rate or by reducing the viable count of microorganisms over the desired shelf life.

Using Hurdle Technology

Hurdle technology, the use of multiple preservation techniques in the same product, is another effective approach, especially desirable today with the current trend towards shelf-stable convenience foods [68,85]. The use of multiple types of stresses can extend the shelf-life of many food products without exceeding the legal limit for many antimicrobial compounds or changing the sensory qualities of the food. Research geared towards the use of antimicrobials that work synergistically with other stresses (including temperature, osmotic, pH and antimicrobial compounds) has the potential to greatly enhance the area of food safety.

A further extension of the antimicrobial packaging trend would be multi-purpose films or other examples of hurdle technology. Films containing nisin and α-tocopherol have been studied in milk cream applications in order to deliver antimicrobial and antioxidant functionality within the same packaging concept [49]. Films containing multiple antimicrobials with different mechanisms of action, like bacteriocins together with chitosan or essential oils, are another method of maintaining food safety and quality while still upholding a natural viewpoint. One such film used chitosan as the base material and irradiating it to increase its antioxidant capabilities. When applied to fresh meat products, fungal and bacterial growth was inhibited for up to 28 days of storage at ambient temperatures [68]. Another novel hurdle technology concept is the combination of modified atmosphere packaging (MAP) with active packaging. The application, aimed mostly at preventing mold and yeast growth on bread, utilized volatile mustard EO together with different levels of CO_2 and O_2 gases in the atmosphere of the package [78]. The inhibitory effect could be overcome with time and/or high inoculum levels, but the validity of the concept holds true and the potential for future use is high. MAP alone can lead to elevated levels of psychrotrophic and anaerobic pathogens, which can lead to food safety issues [81]. Engineering active packaging that specifically counters this tendency has many possibilities.

Hurdle technology is an extremely important tactic in the battle against current food safety and human health issues. Biofilms have the most defensive mechanisms against hostile environments and stresses

found in prokaryotic life, including low pH [52,58] and limited oxygen diffusion [87]. These biofilms consist of bacterial cells networked in an extracellular matrix that communicate through releasing and responding to signaling molecules [19]. In order to eradicate bacteria, which preferentially grow in a biofilm, the concentration of antimicrobial or antibiotic must be many times higher than the minimum inhibitory concentration, or MIC [8]. It has been discovered that not only do sublethal concentrations of antimicrobials fail to eliminate pathogenic or spoilage organisms, they can cause resistance to other antimicrobials and even promote biofilm formation [63].

Utilizing a combination approach, similar to the way other organisms combat bacterial infection, would result in more effective treatments that prevent the development of resistant strains as best as possible [27]. Chitosan films containing other antimicrobials are one example of hurdle technology as applied to active packaging. The GRAS status of certain bacteriocins, like nisin and pediocin, in certain foods and proven safety in clinical trials [9,50] allow them to be used either as an alternative to or in conjunction with other antimicrobials for a hurdle effect [36]. Specifically, nisin works extremely well against Gram-positive organisms while chitosan inhibits growth of a wide range of microorganisms, including yeasts and molds [50]. Essential oils have been investigated for the same purposes due to mechanisms of action different from common antimicrobials and the GRAS status some of them possess [7].

Safety Evaluations for Antimicrobial Packaging Systems

Active packaging has the potential to enhance food safety and help prevent the formation of resistant strains of bacteria, but in addition to testing for the occurrence of resistance in survivors of the treatments, safety evaluations for the antimicrobials and packaging materials are also required. Although many materials used in active packaging systems are safe for use in foods on their own, the mere act of incorporating them into a new packaging system changes the regulatory rules. Some essential oil components are considered flavorings in the EU and have GRAS status in the US, while others are specifically prohibited for toxicological reasons. Some compounds can cause irritation due to cytotoxic effects, while others can cause allergic or spasmodic reactions. In addition, organoleptic changes may occur due to the release of some antimicrobials, like EOs or their main components [12]. In the EU, no

specific regulations exist for active packaging systems. Compounds released into the food would fall under the category of food additives and be subject to those particular laws, but antimicrobials that remain in the packaging materials would be considered food-contact material constituents. Regulations for food-contact materials are very strict to prevent migration of undesirable components into the food [22]. As of 2003, a limit of 10 mg/dm^2 has been set for migration of active materials from packaging polymers [84]. Assurance that the compounds utilized are safe for use in humans, especially through research evaluating their safety specifically from the standpoint of an active packaging system, will greatly influence the ongoing legal debate. As active packaging research addresses the mentioned issues, including the possibility of resistance, the safety of the packaging and functional materials, and the synergistic effects of different types of compounds, the number of commercial systems should expand even more in the consumer consciousness and the market.

CONCLUSIONS

A comprehensive review of the available information on antimicrobial packaging systems, namely, controlled release and active packaging presents an interesting and as-yet-incomplete picture. The majority of antimicrobial packaging systems are aimed at improving food quality and safety through the reduction of bacterial growth and the extension of product shelf-life. While some experimental results of the research are promising, they are quite limited in scope. Careful examination of the actual efficacies of the main components is required to expand the formulations into a complete antimicrobial packaging system. Synergy between functional substances with different modes of action will assuredly develop the systems into safe, efficient packaging concepts that serve to extend shelf-life, maintain food quality and prevent adverse conditions like biofilm formation and resistance promotion in bacteria.

Use of a multidisciplinary approach by bringing together experts from microbiology, engineering and material science to evaluate the situation would be more promising. This system approach would help to answer questions as to whether, the release rate of the compounds from the polymers designed is indeed sufficient to bring the microbial load to a safe level; how fast or how slow the designed polymer should release, with

respect to microbial growth kinetics, to get an effective inhibition and prevent resistance development; how close is the effectiveness of the designed system to real-life scenarios.

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Analysis of Peelable Film in Food Packaging

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ABSTRACT: This paper is an analysis of peelable lidding films used in cup and tray style food packaging applications, focusing on what should be considered when developing a new package or adapting an existing package application to a peelable film. Three types of peelable films will be discussed and how they influence the various parts of a packaging line and also any advantages and disadvantages at each point in the packaging line. This paper will also focus on the machinery aspect including both hot fill and retort applications. However, to do so, requires an understanding of the film and what affects a packaging machinery change may have on transportation and food quality, therefore several post production areas will also be mentioned. Medical bags or pouches such as those from vertical form fill seal machines are not under the same production conditions as cups or trays so they will only be mentioned when and if applicable.

INTRODUCTION

THE key focus on any peelable film is to increase the ease of use for the consumer without compromising any of the other properties of the package. Traditionally, film covered trays or bowls are welded together either by heat or ultrasonic methods. These extremely robust seals provide superior tamper evidence, but it can be difficult to remove without a cutting utensil. "[Consumers] don't want it to be really difficult to break the seal because you end up tipping the contents all over yourself" [1].

Peelable films were first used to package medial equipment so that the packages were easy to use in operating rooms and emergency situations. As plastic technology has developed, new applications for peelable films have been applied to the food industry. While the idea of a peelable film is the same, the food industry exposes packaging to different stresses than those found in medical packaging. Subsequently new ma-

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terials and combinations of polymers have been adapted to meet these requirements.

THREE TYPES OF PEELABLE FILMS

There are three basic ways a film can be designed to peel which is also referred to as the type of failure. These types of failure are adhesive, cohesive, and the less used delamination. All three types are easier to interpret with these diagrams from Rollprint Packaging Products Inc [2].

Adhesive Failure Films

Adhesive failure is a type of film failure in which the adhesive pulls away from the container just like a piece of tape (Figure 1).

The first advantage of adhesive film is that it leaves no residue behind after being peeled. This leaves the container aesthetically pleasing. The disadvantage is that there is no indication of peel quality. This makes them less appealing for medical products or perishable foods where an indication of contamination is helpful. The residue as a quality indicator will be discussed further in the cohesive film section.

Because of their simplicity adhesive films can be less expensive than other types of film. However, this simplicity can also result in a film that does not perform all functions well. The adhesive layer performs hot tack, seal and peal functions all within the contact area of the film and the container. Hot tack is the strength of the bond between the film and its package immediately after being sealed [3]. This multitasking often re-

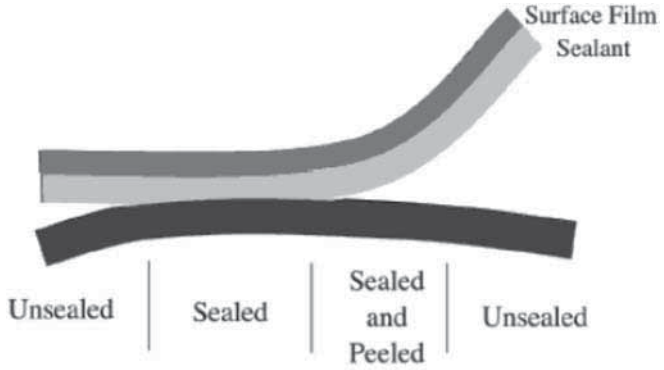

Figure 1. *Adhesive Peel [2].*

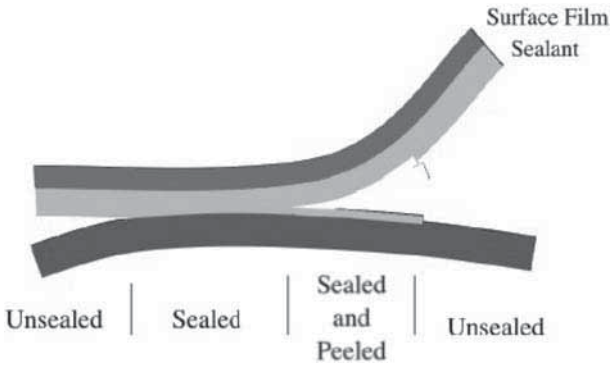

Figure 2. *Cohesive Peel [2].*

sults in a film that requires more force to peel, or not have enough hot tack strength for hot fill applications.

Lastly, adhesive failure films are more susceptible to welding. Welding occurs when the adhesive layer has been extruded typically as a result of too much time, temp or pressure from the sealing heads.

Cohesive Failure Films

The second failure type is Cohesive, where the adhesive layer is designed to fail inside itself as shown in the "sealed and peeled" section of the diagram from Rollprint Packaging Products (Figure 2) [2].

The cohesive failure film is more complex in the design of its adhesive and thus is more expensive to produce. Unlike adhesive failure, it does not perform the seal and peel function at the same point in its structure. This ability to peel "inside itself" means that the film can have higher seal strength than the peel force necessary to remove it. This means a stronger seal and a more functional package for the consumer.

Cohesive films have the disadvantage of being thicker than adhesive failure films. This is because the adhesive layer must be thick enough to seal and to have room to fail within themselves. An increase in thickness may result in lid fitment issues or sealing issues on the production line.

The main characteristic of a cohesive failure is that it leaves behind a residue of adhesive or "seal transfer" that is noticeable on the container from which it is removed. Customers may find this opaque band around the rim of the container unappealing. There is also a matching ring on the removed film that corresponds to the area where the adhesive was re-

moved. "Seal transfer provides a visual method of evaluating seal integrity" [4]. If there are lines in the film or missing sections of residue on the container, it may indicate an improper seal. This ability to observe seal quality is helpful to ensure a sterile and uncontaminated product.

The largest disadvantage compared to adhesive failure films is that if there are irregularities in the film or sealing parameter (time, temp, pressure), the film may "string" or produce "angel hair" as it is removed. Angel hairs are thin pieces of film that remain attached to the container and may fall into food products. Angel hair is the most obvious visual cue of poor performance of a film to consumers and is therefore important to prevent.

Delamination Failure Films

A delamination film is designed to fail between the substrate and the adhesive layer (Figure 3).

This film is the most likely of the three to produce angel hair and an inconsistent peel quality [2]. Delamination is also the least common of the three failure types.

MACHINERY PRODUCTION CONSIDERATIONS

In comparison to welded films, peelable films seal best at lower temperatures and lower pressures but require longer dwell times. While it is difficult to eliminate this problem, the goal is to operate as close to the original line speed without the packaging quality getting affected. Since food applications of this type are either hot filled or retorted, the film

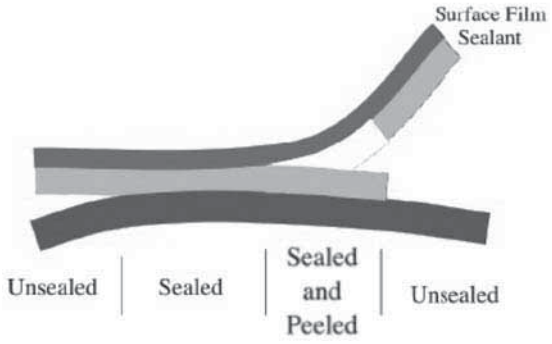

Figure 3. *Delamination Peel [2].*

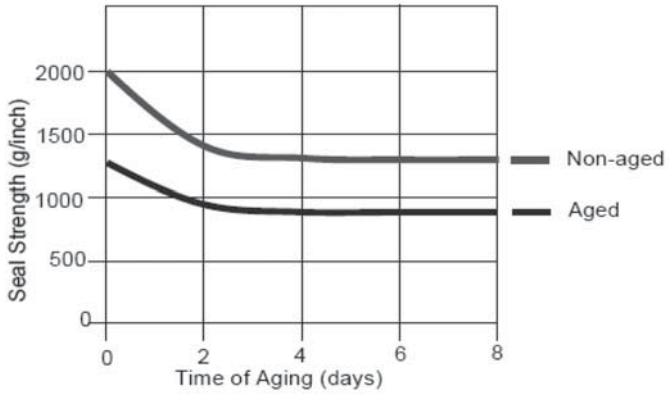

Figure 4. *Effect of Aging on the Seal Strength of Polybutene Sealants.*

needs both a sufficient hot tack and a strong seal. In production, there are many adjustments that can be taken into consideration to help achieve a sufficient seal.

To compensate for peelable films, four things must be considered: sealing parameters, container, film, and the machinery itself. Each can be adjusted in some areas but are restricted in versatility elsewhere. The following discussion will cover each of the four and how they may affect the manufacturing and machinery of a peelable film food package.

Sealing Parameters

Before making a change to peelable film, it is important that a machine be able to easily adjust its time, temperature and pressure. Even if all three are adjustable they may not have the range necessary to compensate for the new film. This is especially true with the pressure adjustments on older machinery.

As shown in Figure 4 above from Rollprint Packaging [2], not only is there a difference between an aged film and a non-aged film, but there is also a reduction in seal strength over time. The figure illustrates that the production timeline is also be a determining factor in the success of a film, and machinery may need to be adjusted accordingly. If a roll of film is stored for an extended amount of time it might not perform to its original standards even if all other parameters are constant. As a result what once may have been considered an outside variable becomes relevant when adjusting a machine to run a peelable film.

Containers

In tray or cup style food packaging, the container has an affect on the machinery and the film performance. One of the best ways to ensure the success of a peelable film is to use a container with a wide rim or lip. The larger sealing surface provides superior contact area for the seal, and the larger surface helps alleviate several other potential issues. First, the larger sealed area exponentially increases hot tack and seal strength without greatly increasing the force necessary to peel the film. The larger area reduces the chance of channels or defects in the seal area as well as helping compensate for any discrepancies in older sealing heads. Finally, the larger area can withstand more pressure from the sealing head without the adhesive layer being extruded out the sealing area. If any adjustments are made to a container, it may not sit in platens as well or jam up a lidding machine, so appropriate adjustments to other line components should be made.

A larger flange or lip does have one drawback: the large flat surface increases the chance of food contamination. Under fast filling conditions or intermittent production lines, food is often sloshed and can end up resting on the container lip. Most food contaminates that are small or liquid are pushed away and have no ill effects. However, food such as green beans or bits of garnish are harder to remove and can remain in the seal. Careful monitoring of production is necessary because even with particulate in the seal, a container may still hold a vacuum for days, but will not be shelf stable.

Films

The film is one of the easiest aspects of production to change besides the sealing parameters. If the machinery cannot provide sufficient sealing, another option is the addition of a heat seal coating. “Heat seal coated materials can be formulated to have excellent hot-tack properties, and can therefore form seals under a wide array of sealing conditions” [4]. These coatings can also allow a variety of polymers not normally considered for heat seal applications to be used [4]. More polymer choices may save cost or provide much needed advantages in other areas of the production process.

A film that is too thick, for example, may cause the lid not to seal properly and jam the lidding machine. In this case, it may be advantageous to

reduce the thickness of the film and use a stronger polymer for the substrate. A thinner film will take less dwell time to reach the heat sealing temperature at the heat sealing interface [5].

Choosing to use a peelable film is inherently more expensive than a welded film. That cost can increase further if a proprietary film needs to be developed or modified. With new peelable technologies in constant development, specific polymers and additives are becoming cheaper. When a company chooses to develop a new package or modify an existing one, a film converter or manufacturer will be able to assist in deciding which film is best for that application. In depth discussion of different polymers is outside the scope of this paper. However it is important to choose the best film to make the total package development as smooth a process as possible.

Machinery

When sealing trays and cups for food applications, the most important factor is line speed. Line speed directly affects dwell time and is the hardest to adjust as compared to temperature and pressure [4]. Traditionally with a heat sealer designed for welding, the temperature and pressure are high, but the dwell time is very short. This is especially apparent in rotary sealing machines. However, with modern computer controlled sealing machines the dwell time can be increased by fractions of a second without slowing the line. Another option of more modern sealers is to have a seal head that can also heat from the underside. This provides a more consistent temperature in a shorter dwell time, which increases the hot tack, in thicker peelable films.

Other issues may result if a machine was not originally designed for peelable films. These include seal heads that were not machined to high tolerances or variations in pressure across a multi-head sealer. The multi-head sealer can be especially frustrating if one bank of sealing heads is not producing a seal but the other seals normally. While these variations were insignificant with welded films, the adhesive layer of a peelable film is much less forgiving.

If a seal head contains both the heat sealer and cutter, the proper pressure for the film may not be substantial enough to provide a clean cut. As a result, the winding roll will peel the container. In extreme cases, the entire package may be pulled from the platen, throwing product and stopping production.

The filler and sealer are not the only production elements that may need to be taken into consideration in applications of peelable films. One example would be steam or vaporized hydrogen peroxide sterilization in aseptic food packaging. These processes would need to be tested to determine the effects on seal strength for each application.

Down line from the filler, any rough transitions or handling may cause a peelable film to fail. In the case of hot fill products, after they are removed from the chiller the film will have recessed into the container. This is due to the change in the internal pressure. If the film is not recessed into the package, then the seal has not held its vacuum and should be deemed contaminated. The drastic change in temperature and the often slippery and wet conditions of a chiller can cause leaks that are not easily recognized. A post chiller check of seal integrity is important, because water from the chillers can be drawn into small seal leaks. If a retort is used, excessive condensation in the package may be a sign of seal failure and contamination.

As previously mentioned, rough transitions may damage a container down the line. Bumping of containers as they slide into an accumulator could pose a potential issue. Short drops onto an accumulator during hand case packing, could not only break a seal but stop the run for clean up.

When sealing peelable film, there are many machinery issues to consider as well as a matrix of other factors. With the many variations of film, machinery, and production considerations, all issues addressed here by no means should be considered all the ones possible. Test runs with helpful capable suppliers and staff will efficiently address all problems that may arise when starting a new peelable film line.

TESTING

Testing of peelable films throughout the development process is essential. Proper testing will provide quantitative data on film and packaging machinery performance. And can also provide qualitative data that may foreshadow consumer opinions. Testing can be separated into categories where each group addresses related issues. For the purpose of this paper the tests are separated into three main categories: performance, quality assurance, and end use. These categories have been assigned to demonstrate how each group will help pinpoint any issues on the manufacturing line. All of these tests should follow the basic ASTM (Ameri-

can Society for Testing and Materials) or ISTA (International Safe Transit Association) guidelines where applicable, to give a consistent picture of the packages performance.

Performance Group

Performance tests provide quantitative data. This data is used to ensure consistent manufacturing and to resistance to damage from handling or distribution, so that a product safely reaches the point of sale. Basic tests would include, seal strength/integrity (ASTM F88, F1886, F1929, F2228), hot tack (ASTM F1921), drop testing (ASTM D5276), burst strength (ASTM F1140, F2096, F2338) and compression (ASTM D642) or stacking strength (ASTM D4577). Each test may or may not be necessary for a particular packaging application. For example, vacuum testing will demonstrate if a seal is too weak to survive transportation in low pressure conditions such as air freight.

Quality Assurance

Quality assurance (QA) testing for food applications is very important for the safety of the consumer. These would include test such as permeability of the film (ASTM F1307, F1927, F372-73, D1434, F1769), migration (ASTM D4754), resistance to flex cracking (ASTM F392), or microwave testing (ASTM F1308, F1500, F1519). The use of a product determines the necessity of a particular test. For example, a package not intended to be put in the microwave by the consumer would not require a test for microwave volatiles. Any issues in QA testing may indicate previously unnoticed issues in the performance testing and should be addressed accordingly.

End Use Group

End use/qualitative testing is used to show that the peelable film is performing as intended. Peel strength testing will show if the force required to open the package is too great. For example, an elderly consumer may not have the hand strength to open the package. A second more ambiguous test (peel quality test) is used to find the percentage of seals producing angel hair or are welded to the container. This is accomplished by peeling large numbers of containers, and recording the number of unsat-

isfactory peels. End use tests, while ambiguous, help a company judge whether a peelable film is truly performing and functioning as was originally intended for the customer.

CONCLUSION

The current use of peelable films in the packaging industry makes packages much more consumer-friendly. There are many factors to be taken into consideration when designing, implementing, and testing a new package. The machinery used in all steps of manufacturing a peelable package have an influence on the finished product. All of these obstacles are more difficult if an existing package is being modified to fit peelable technology. All the issues addressed here are not always present, but a company that is prepared will be able to address any issues in a fast and cost efficient manner.

Packaging science has always, and will always be, the joining of many scientific disciplines. With the development of new machinery to handle these technologies, the production of peelable films will become faster and cheaper. Peelable film technology has progressed in recent years, and its applications in the future are endless.

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Effect of Manufacturer's Joint Fastening Techniques on Compression Strength of Corrugated Fiberboard Boxes

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ABSTRACT: A flat piece of corrugated fiberboard, which has been cut, slotted and scored, is often referred to as a box blank. For several box styles, in order to convert the box blank into a box, its two ends must be fastened together with tape, staples or adhesives such as water soluble glues. The location at which the two ends meet is known as the manufacturer's joint. There are several variations within the three fastening techniques mentioned with most corrugated box manufacturers following their own protocols for fastening the manufacturer's joints. This study explored the compression and tensile strengths of RSC style corrugated boxes based on adhesive (glue) coverage, three different types of tapes (acrylic, paper and reinforced paper) and application angle of staples. The fabricated boxes were also tested for compression strength and deflection. Test data ($N = 10$) was collected for each dependent variable of peak force, deflection at peak force and tensile strength using the analysis of variance procedure with a Turkey probability distribution at a 0.05 critical limit. The results suggest an overall higher tensile strength for glue than the other fastening techniques evaluated ($P < 0.05$) with no significant difference ($P > 0.05$) for peak force or deflection at peak force for all glued, stapled or taped treatments.

1.0 INTRODUCTION

DUE to its high strength to low weight ratio corrugated packaging is poised as the leading choice for transport packaging in the United States. By some estimates corrugated packaging is used to package ap-

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proximately 90% of all products for retail distribution in the United States [1]. The popularity of corrugated packaging also stems from the fact that it is practical, useful, economical, renewable and recyclable [1]. It is also a substrate that can be custom designed and provides excellent merchandising appeal through printing on box panels. Twede [2] accounted that 80% of the $46 billion worth of paper based packaging used is corrugated fiberboard shipping containers.

Corrugated fiberboard is a paper-based material consisting of a fluted containerboard sheet and at least one flat linerboard. It is widely used in the manufacture of corrugated boxes and shipping containers. Throughout the journey of a containerboard from the paper mills to box plants, which include the corrugated box plants and sheet plants, close quality control is provided to material properties such as basis weight, caliper, burst strength, water absorption, porosity to air and smoothness. Variations in material properties can affect the strength and performance of corrugated boxes.

Boxes from the corrugated fiberboard sheets can be formed in the same plant as the corrugator or alternatively, sheets of corrugated fiberboard can be shipped to a sheet plant for conversion into boxes. At both these facilities the corrugated board is creased or scored to provide controlled bending of the board. Slots are typically cut to provide flaps for boxes. The Regular Slotted Container (RSC, FEFCO 0201) is the most common style of corrugated box used in the industry [1]. All flaps for this style of construction are the same length and the outer (major) flaps meet at the center of the box. Figure 1 illustrates a box blank for a RSC style box as well as an assembled box.

At the conversion plants, the two ends of the box blank are fastened together with tape, staples or adhesives (glue) for conversion to a box. The location at which these two ends meet is known as the manufacturer's joint. It may be noted that not all corrugated containers, such as bliss

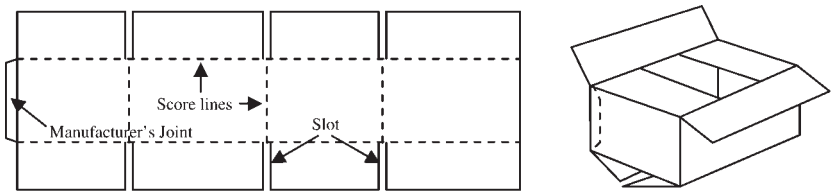

Figure 1. *Box Blank Showing Score Lines, Slots & Manufacturer's Joint and Assembled RSC.*

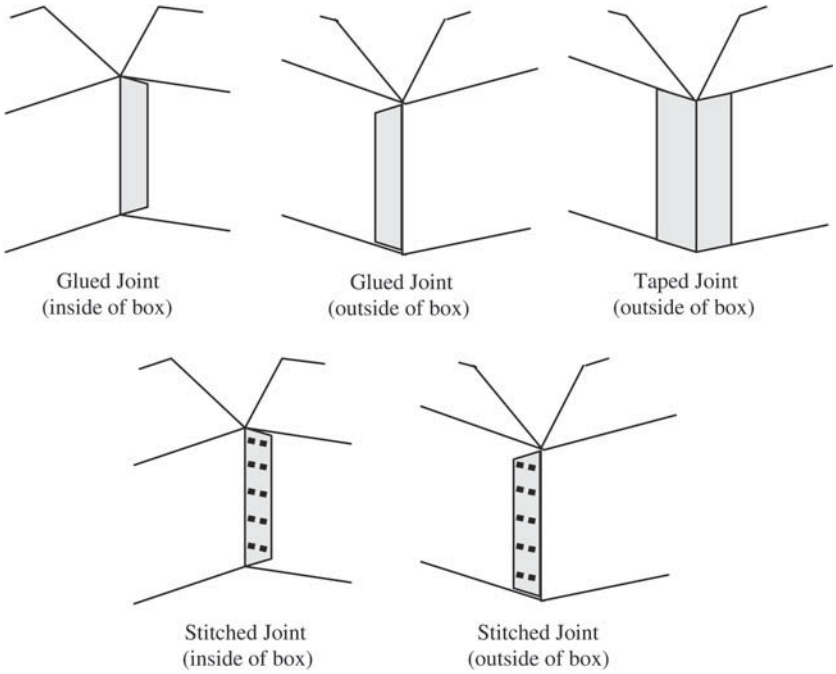

Figure 2. *Common Styles of Manufacturer's Joints.*

boxes, have manufacturer's joints. Figure 2 illustrates the common types of manufacturer's joints used by the industry.

The side panel thickness and paper basis weight commonly determine the kind of fastening technique used for manufacturer's joints. Adhesive joints are also referred to as "glue" joints in this paper. Glue and tape joints are most commonly used for most single wall constructions whereas, staples are frequently used for double and triple wall constructions. All three techniques have their own advantages and disadvantages as discussed below:

- *Glued Joints:* Provide higher strength and rate of productivity, are better for rough handling, typically provide higher tensile strengths, do not interfere with printing when placed on the inside and offer lesser likelihood of scratching the product and personal injuries. They are the most economical method but can be messy in the manufacturing environment. They are also sensitive to temperature and humidity.
- *Stitched/stapled Joints:* Preferable for containers subjected to moisture such as waxed board, required on weather resistant boxes for U.S.

government, objectionable when used with food products, may interfere with printing layouts, may scratch a finely finished product's surface and may cause wrinkles and permit the corner of the box to fold on the line of stitches.

- *Taped Joints:* They do not require a tab and hence use lesser material and by providing more efficient layouts decrease scrap, knocked down boxes lie flatter in tied bundles, the inside of the box is smoother, provides convenient means of easily opening the box, interferes with some print layouts and is more expensive than glue. A simple shift from glue to taped boxes reduces corrugated material use, but can result in additional costs.

1.1 Manufacturer's Joint Related Regulations

There are several regulations related to corrugated products such as those set by carriers (rail and truck), U.S. government (DOT, FDA, USDA, and EPA) and the Council of State Governments which provide guidelines regarding corrugated container construction [1,2]. More clearly defined specifications which can be considered as industry standards for corrugated materials are provided by the Fiber Box Association (FBA) or the Association of Independent Corrugators (AICC), and machinery and fabrication equipment guidelines and standards can be obtained from the Packaging Machinery Manufacturers Institute (PMMI) [3,4,5]. Although the tolerances provided by FBA and PMMI are voluntary, most corrugated manufacturing companies and many corrugated users consider these as specifications to be used when manufacturing or specifying most corrugated packaging.

The carrier rules provide the following guidelines for manufacturer's joints [1]:

Single and Double Wall Fiberboard Constructions

Boxes must have manufacturers' joints formed by lapping the sides of the box forming the joint not less than 3.18 cm, where the 3.18 cm is the actual overlapping or mating area (Figure 3). As regards to fastening techniques, the following guidelines are provided:

- *Metal staples or stitches:* generally spaced not more than 6.35 cm apart except when weight of box and contents is 63.5 kg or more—spaced not more than 2.54 cm apart.

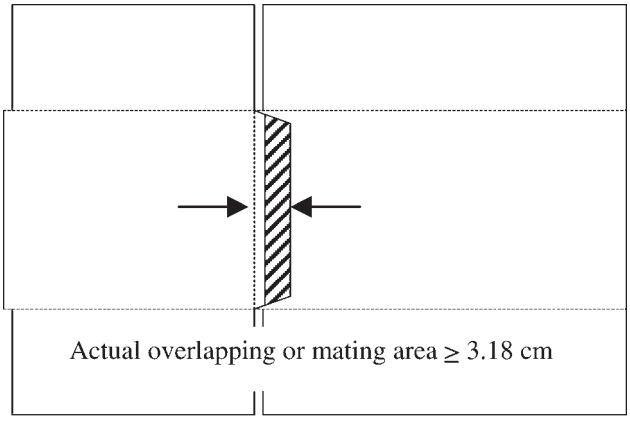

Figure 3. *Carrier Rule for Manufacturer's Edge Overlap.*

- *Glue:* gluing the entire area of contact with a water-resistant adhesive.
- *Taping (butted joints)*: sealing strips firmly glued to the box and extending the entire length of the joint. Sealing strips must be of sufficient strength that rupture of the joint occurs with fiber failure of one or more of the facings.

Triple Wall Fiberboard Construction

Boxes must have the manufacturer's joint formed by one of the following methods:

1. By lapping the sides of the box forming the joint not less than 5.08 cm and fastening the joint with *metal staples or stitches* spaced not more than 2.54 cm apart. Both sides of the joint must be crush-rolled in the area of contact before stapling or stitching.
2. By lapping the sides of the box forming the joint not less than 7.62 cm. The joint must be firmly *glued* with 100% glue coverage in the area of contact with glue, or adhesive which cannot be dissolved in water after the film application has been dried under pressure.

Corrugated shippers are designed to overcome the distribution environment hazards so that the products they carry reach the consumers, intact and ready for use. The transportation and warehousing hazards faced commonly by corrugated shippers include compression, shock, vibration, temperature, creep and humidity among others. Most material (containerboard) and corrugated package testing procedures are provided by the Technical Association of the Pulp and Paper Industry

(TAPPI) and American Society for Testing and Materials (ASTM) [6,7,8,9].

When a shipping container is dropped during handling or compressed during stacking, its manufacturer's joint is subjected to stresses along with all other edges. The TAPPI Test Method T 813 om-04 (Tensile Test for the Manufacturer's Joint of Fiberboard Shipping Containers, Test Method) helps determine the strength of the manufacturer's joint of commercially made corrugated and solid fiberboard shipping containers and is applicable to taped, stitched, or glued joints which may also be used to evaluate laboratory fabricated joints similar to commercially made joints [6]. ASTM D 642 (Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads) is commonly used for measuring the ability of the container to resist external compressive loads applied to its faces, to diagonally opposite edges, or to corners [7].

At present there is no data available to demonstrate the effect of variations in the prescribed methods of joining the manufacturer's edge as related to the compression or the tensile strengths of corrugated boxes.

The two objectives of this study were to:

1. Compare the strength of various methods used to fasten the manufacturing joint in RSC style boxes.
2. Evaluate the affect of manufacturer's joint fastening methods with respect to box compression strength and deflection.

2.0 SURVEY OF INDUSTRY PRACTICES

Before initiating the experimental study a survey was conducted targeting the manufacturers of corrugated boxes with regards to the common practices used to form the manufacturer's joint. Responses were received from ten leading corrugated packaging manufacturers. It was found that most manufacturers did not agree on the same technique. Based on their operational capabilities and customer orders most follow their own protocols for fastening the manufacturer's edge. The following were some key findings from this survey:

- 90% used glue and 10% used staples.
- 80% made internal manufacturer's joints for 75% or above of their production.

- 80% made external manufacturer's joints for 25% or below of their production.
- 90% had at least 3.5 cm overlapping/mating between the manufacturer's joint and the panel.
- Of the manufacturers using staples, only 33.3% used 2.54 cm spacing between staples. Others used 3.81 cm to 5.08 cm as the spacing; with one manufacturer using a double stitch start and then a spacing of 2.54 cm between adjacent staples.
- 55.6% of all users that stapled the manufacturer joint used a 45° angle of application, followed by 22.2% of users who applied horizontal staples along the depth of the box.
- 70% of the manufacturers that used glue, had at least 75% glue coverage between the manufacturer's joint and the panel. 30% used 50% or less glue coverage.
- Of the manufacturers using glue, 70% applied the glue using one or more vertical lines along the depth of the box.
- 89% of the manufacturers that used tape, preferred reinforced paper tape along 100% of the depth of the box.

3.0 MATERIALS AND METHODS

3.1 Manufacturer Joint Tensile Testing

The TAPPI test standard T 813 om-04 (Tensile Test for the Manufacturer's Joint of Fiberboard Shipping Containers, Test Method) was used to compare the performance of various fastening methods for manufacturer's joints. This test gives an indication of the ability of the joint to withstand rough handling without failure, to the extent that failure is related to the tensile strength of the joint itself [6]. The initial jaw span for the tensile tester was set at 180 ± 5 mm and the rate of separation used was 25 ± 5 mm/min. A Testometric tensile tester Model M350-5kN (Testometric Materials Testing Machines Company, Lancashire, United Kingdom) was used for all tests. C-flute corrugated fiberboard was used with a basis weight of 20/15/20 kg/ 92.9 sq. m. (44/34/44 lb/ 1000 sq. ft.), a bursting strength of 125 N/cm², and an edge crush test (ECT) of 79 N/cm.

Figure 4 indicates the location of the test samples obtained as related to the corrugated container.

Tensile test strips were prepared in accordance to TAPPI T 813 om-04

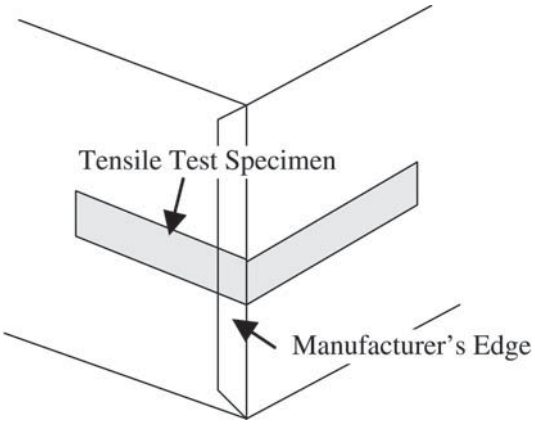

Figure 4. *Tensile Test Specimen Location.*

(Figure 5). The length of all samples was 200 mm. Glued and taped manufacturer's joints used a width was 25 ± 0.5 mm, with stapled joints having a 38 ± 0.5 mm in accordance with the standard. The distance between the outer edge of the staples and the corresponding outer edge of the joint was 6.35 mm and only one staple was included per sample.

Table 1 provides details of materials used to fasten the manufacturer's joint. All materials were procured from Uline Shipping Supplies (Waukegan, IL, USA)

For the glue joint, 25, 50 and 75 percent of the area on the manufacturer's joint tab was covered with hot melt glue. For the stapled joints, the angles of staple applications were varied between 0, 15, 30 and 45 degrees along the depth direction. Ten samples for each variable were

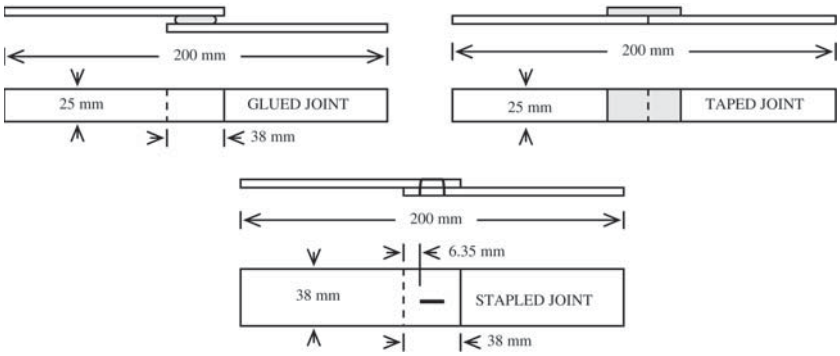

Figure 5. *Tensile Test Samples for Glued, Taped and Stapled Joints.*

Table 1. *Materials used for Fastening the Manufacturer's Joints.*

	Material	Supplier	Model No.	Description
1	Reinforced paper tape	Uline	S-2350	7.6 cm wide, Kraft paper reinforced with fiberglass yarn, water activated
2	Paper tape	Uline	S-9682	5.1 cm wide, pressure sensitive
3	Acrylic tape	Uline	S-472	5.1 cm wide, solvent acrylic adhesive
4	Glue	Uline	S-509	1.3 cm diameter, hot melt glue
5	Staples	Uline	S-1396	3.2 cm crown width, 1.9 cm leg length

tested after conditioning for 24 hours at 23°C and 50% relative humidity in accordance with ambient conditions as described in ASTM D4332 [8].

3.2 Box Compression Strength Testing

The ASTM D 642 (Standard Test Method for Determining Compressive Resistance of Shipping Containers, Components, and Unit Loads) was used to test the compression strength [7]. The procedure is commonly used for measuring the ability of the container to resist external compressive loads applied to its faces, to diagonally opposite edges, or to corners. This test method is also used to compare the characteristics of a given design of container with a standard, or to compare the characteristics of containers differing in construction. This test method is related to TAPPI T 804 om-02 [9]. The tests were conducted using a fixed platen arrangement on a Lansmont compression tester Model 152-30K (Lansmont Corporation, Monterey, CA, USA), with a platen speed of 1.3 cm/minute and a pre-load of 22.68 kg for zero-deflection in accordance with the standard.

The same materials and joining methods as described in 3.1 were used for box compression testing. The spacing between the staples for all angles was maintained at 5.08 cm. All boxes used for this study were regular slotted containers (RSC) style with dimensions of 50.8 cm × 40.6 cm × 25.4 cm and having a 3.8 cm wide manufacturer's joint. All corrugated box samples used for this study were created using ArtiosCAD software and the Premium Line 1930 model of the Kongsberg table (Esko Graphics, Ludlow, Massachusetts, USA). Five box samples for each variable were tested after pre-conditioning for 24 hours at 50% relative humidity and 23°C.

4.0 DATA AND RESULTS

Test data was collected for each dependent variable: peak force, deflection at peak force, and tensile strength on ten samples of each joining method. A total of 300 observations were used for this study. The test data were compared for the three dependent variables using one way analysis of variance (ANOVA) with a Tukey post-hoc test. A family-wise error rate of $p = 0.05$ was use to determine significance. Table 2 provides a summary of the test data.

4.1 Peak Force

The data showed little difference among the fastener technologies with respect to peak force capability. None of the general categories of glue, staple, or tape were consistently higher or lower than another. The overall ANOVA was significant at a 0.05 level. Variability was observed within the fastener technologies with a 45 degree stapling having particularly low values and reinforced tape having particularly high values (Table 3). Overall glue coverage did not affect the peak force performance significantly ($P > 0.05$) indicating that 25 percent glue coverage was as effective as 75 percent. Similarly, no significant difference was found between tape systems ($P > 0.05$). Table 3 indicates the 95 percent confidence intervals for each fastening system.

4.2 Deflection at Peak Force

All tape systems used in this study allowed significantly more deflection than the other general categories of fasteners ($P < 0.05$). Tape systems deflected an average of 0.42 cm while the other fasteners deflected and average of only 0.28 cm. Tape systems also exhibit significantly higher coefficients of variation than either of the other general joining methods (Table 2). No significant differences were found between glued or stapled units with respect to means or coefficients of variation. Table 4 shows the 95 percent confidence intervals for each technology.

4.3 Tensile Strength

All glue coverages had significantly higher tensile strengths than any

Table 2. *Tensile Test Data Summary.*

Joining Method	Specimen Width (mm)	Peak Force (N)		Deflection at Peak Force (cm)		Tensile Strength (kN/m)	
		Mean	C. of V.*	Mean	C. of V.*	Mean	C. of V.*
Glued Joints							
Glue 25%	25	1857	3.1%	0.292	7.4%	15.42	9.2%
Glue 50%		1794	3.3%	0.287	7.%3	18.80	4.7%
Glue 75%		1820	2.7%	0.277	2.9%	21.16	4.4%
Stapled Joints							
Staple 0°	38	1814	5.3%	0.277	8.0%	1.98	14.2%
Staple 15°		1783	5.9%	0.277	5.2%	2.04	11.0%
Staple 30°		1882	3.4%	0.272	6.3%	2.13	7.3%
Staple 45°		1705	5.4%	0.287	6.0%	2.58	6.2%
Taped Joints							
Acrylic	25	1826	6.1%	0.432	31.1%	4.68	11.4%
Paper		1923	6.5%	0.427	34.1%	7.17	5.7%
Reinforced Paper		1810	11.4%	0.401	38.0%	6.68	7.3%

*Coefficient of Variation

Table 3. *Peak Force (N) 95% Confidence Intervals by Joining Method.*

Level	Mean	Std. Dev.
glue 25	1857	58
glue 50	1794	59
glue 75	1820	49
staple 0	1814	97
staple 15	1783	105
staple 30	1882	64
staple 45	1705	92
tape acrylic	1826	112
tape reinforced	1923	125
tape unreinforced	1810	206

Pooled Std. Dev. = 106

of the other fasteners with each increase in glue coverage having significantly better performance ($P > 0.05$). The average glue performance was 18.5 kN/m. The stapled samples had the lowest performance with an average tensile strength of 2.2 kN/m and no significant affect from staple angle. The tape systems were stronger than the stapled samples with an average of 5.3 kN/m. Acrylic tape was significantly weaker than the other tape systems. Using reinforced tape did not significantly improve tensile strength. Table 5 shows the 95 percent confidence intervals for each technology.

Table 4. *Deflection at Peak Force (cm) 95% Confidence Intervals by Joining Method.*

Level	Mean	Std. Dev.
glue 25	0.292	0.022
glue 50	0.287	0.021
glue 75	0.277	0.008
staple 0	0.277	0.022
staple 15	0.277	0.014
staple 30	0.272	0.017
staple 45	0.287	0.017
tape acrylic	0.432	0.134
tape reinforced	0.427	0.146
tape unreinforced	0.401	0.152

Pooled Std. Dev. = 0.080

Table 5. *Tensile Strength (kN/m) 95% Confidence Intervals by Joining Method.*

Level	Mean	Std. Dev.
glue 25	15.42	1.42
glue 50	18.80	0.89
glue 75	21.16	0.93
staple 0	1.98	0.28
staple 15	2.04	0.22
staple 30	2.13	0.16
staple 45	2.58	0.16
tape acrylic	4.68	0.53
tape reinforced	7.17	0.41
tape unreinforced	6.68	0.49

Pooled Std. Dev. = 0.675

5.0 CONCLUSION

The results of this study showed:

1. Superior strength for tensile load to failure and breaking load for glued joints followed by stapled and taped joints.
2. Reinforced taped joints showed the highest box compression strength followed by glued joints covering 25% of the overlap or mating area,

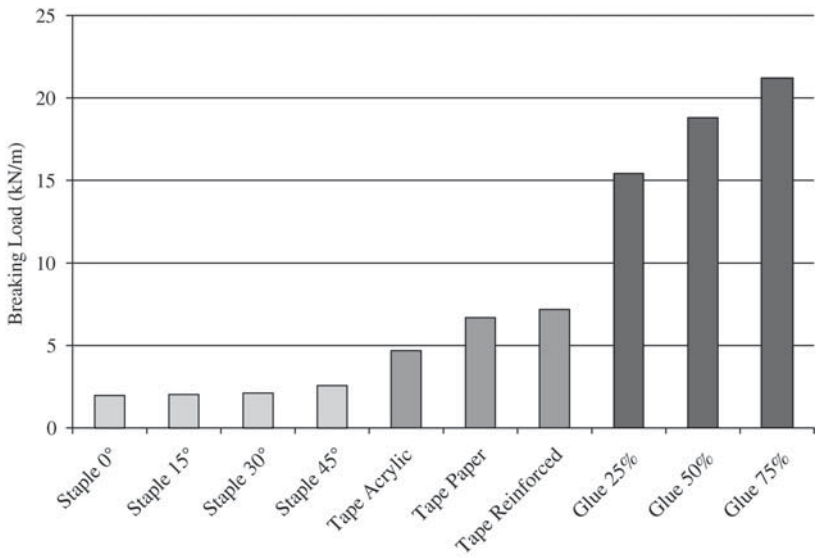

Figure 6. *Breaking Load (kN/m) Comparison for all Sample Types.*

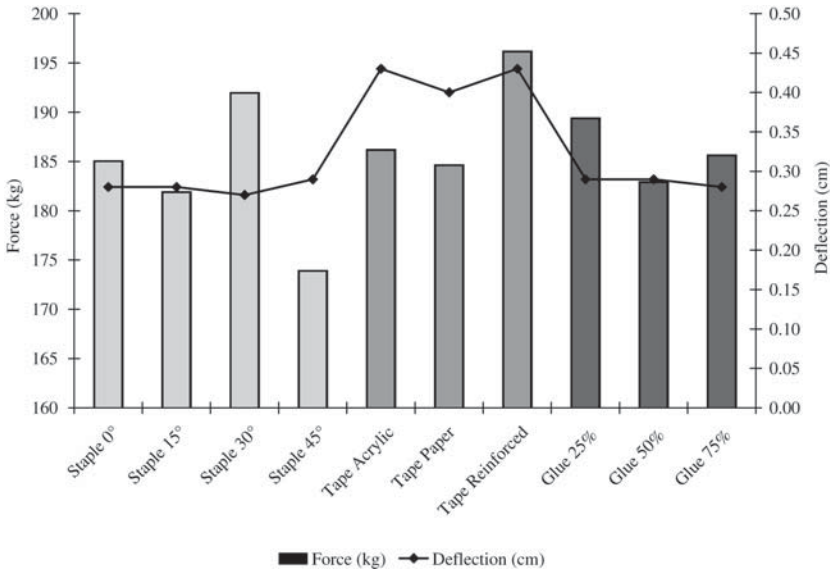

Figure 7. *Compression Strength of Boxes with Different Types of Manufacturer Joints.*

and stapled joints applied at 30 degrees offset from the direction of depth of the box.

3. This study suggests that boxes with glued manufacturer's joints can offer better containment during shipping and handling.
4. Caution should be exercised when relying on taped joints for deflection performance.

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Table 5. Comparison of state-of-the-art matrix resins with VPSP/BMI copolymers.

Resin System	Core Temp. (DSC peak)	Char Yield, %
Epoxy (MY720)	235	30
C379: H795 = 1.4	285	53

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