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R E S E A R C H

Meeting Sustainability Initiatives by Reducing Primary and Secondary Packaging Using Stiffer Reusable Pallets to Reduce Transmitted Transport Vibration

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ABSTRACT: This study compared the performance of a new type of reusable wood pallet that uses special wood fasteners that eliminate the use of nails as in conventional wood pallets. This new fastener system allows the pallets to have a more rigid joint among deck-boards and blocks to form pallets that transmit less vibration. Vibration testing was done to measure levels of transmitted vibration to palletized loads of food products ranging from steel cans of juice and baked beans, and aluminum beverage cans in paperboard cartons. Results show that the new pallet system reduces transmitted vibration to the palletized product as compared to the conventional Grocery Manufacturers Association recommended wood pallets. This shows that the amount of primary and secondary packaging being used for palletized loads can be reduced for pallet merchandizing products that are sold in club stores. This helps in reducing use of packaging materials, thereby making these choices more sustainable. In addition the choice of making wooden pallets from a single material reduces separating the metal nails at end of use before they are converted to other uses such as wood chips.

INTRODUCTION

THE most extensively quoted international definition of *"sustainability"* according to the U.S. Environmental Protection Agency (EPA) is *"Meeting the needs of the present without compromising the ability of future generations to meet their own needs"*. According to EPA packaging constitutes as much as 1/3rd of non-industrial waste

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streams in most developed worlds. The EPA points out that the most practical strategy to reduce such waste and save natural resources is to adopt the method of reuse. This will reduce demands on extracting raw materials from earth, transporting and processing these into new materials and eventually discarding the material into waste streams.

Sustainability was first defined by The Report of the Brundtland Commission, *Our Common Future,* published by Oxford University Press in 1987. "The Brundtland Commission, formally the World Commission on Environment and Development (WCED), named after its founding chair Gro Harlem Brundtland, was convened by the United Nations in 1983. The commission was created to address a growing concern *"about the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development."* In establishing the commission, the UN General Assembly recognized that environmental problems were global in nature and determined that it was in the common interest of all nations to establish policies for sustainable development.

Wal-Mart Stores Inc. initiated one of the largest sustainability efforts in 2005 in the corporate world [1]. In this effort Wal-Mart has been transitioning to renewable sources of energy, improving efficiency of its transportation fleet and retail store buildings, reducing energy use and emissions, recycling waste, making more recycled commodities for development of new packaging and products. The lead author of this paper has been a member of Wal-Mart Stores Sustainable Value Network (SVN) since its inception and has demonstrated through previous projects that the use of reusable containers for fresh produce that were widely adopted by Wal-Mart produce an impressive reduction in damage to the environment based on energy use, waste generated and production of green house gases (GHG) [1].

Wal-Mart's efforts as part of the SVN, has reduced their impact on the environment along with customer satisfaction. Wal-Mart has shown its commitment in reducing energy use by achieving a 25% increase in fleet efficiency [2], opened a viable store prototype that is up to 25 to 30 percent more efficient and produces up to 30 percent fewer greenhouse gas emissions (2005 Baseline) [1]. They have retrofitted low- and medium-temperature refrigerated display cases at more than 500 U.S. stores with energy saving light emitting diode (LED) lighting (2005 Baseline). They have met goals to reduce waste extensively by eliminating 91% of jewelry pallets [1]. Wal-Mart has a goal to reduce total packaging use by 5% by 2013 [2]. They have taken the initiative to connect their product suppliers with packaging suppliers who can suggest sustainable packaging options for their currently packaged products [2]. They were successful in assisting a private label apple juice supplier to procure 50% of their corrugated boxes made from 35% renewable energy generated by hydroelectric plants [2].

REUSABLE PACKAGING

Reusable packaging is becoming a rapidly popular concept among environmentally conscious corporations. Reusable packaging comes in many forms such as reusable pallets, racks, bins, drums, intermediate bulk containers, containers, glass beverage bottles, etc. These are made from durable materials such as metal, glass, plastic and wood, and able to withstand rough transport and handling conditions. Therefore multiple use of such reusable packaging minimizes the need to manufacture new single use packaging thus reducing the impact on environment and natural resources. Pallets are widely reuse and are made of different materials. Various studies have been conducted to compare the performance of pallets based on potential trips they can survive and compare this to cost and weight [3]. In addition different types of test methods help compare and evaluate the performance of wood and plastic pallets [4]. Previous studies have also been done on a comparison of single versus multiple use containers [5].

For a transport package to be classified as 'Reusable' it must meet four criteria according to 'Reusable Packaging Association' which represents various manufacturers, service providers and users of this type of packaging and specifically defines this term, to mean [6]:

1. The selected reusable packaging is reused for the same or similar application
   - *Reusable Packaging:* A bulk bin used for transporting automotive parts is returned to the original supplier for reuse.
   - *Non-Reusable Packaging:* A consumer re-uses a shoe box to store old letters.
2. The packaging must be able to meet the original design requirements for three consecutive uses (i.e. two reuses).
   - *Reusable Packaging:* A plastic collapsible intermediate bulk container is designed to hold 3,300 lbs, stack five high and have an all smooth interior/exterior. Through cleaning and maintenance, the container meets these requirements for multiple uses.

- *Non-Reusable Packaging:* A cardboard box shipping liquids is weakened after the first use due to humidity or rough handling during transit. When it is reused, the original strength specifications no longer apply.

3. During its useful life, the packaging is repeatedly recovered, inspected, repaired and reissued into the supply chain for reuse.
   - *Reusable Packaging:* After flowing through the supply chain, a wood pallet is retrieved, inspected, repaired and reused. Reuse is enabled by pallet recycling companies and pallet pooling companies.
   - *Non-Reusable Packaging:* A wooden crate is shipped overseas, the end-user disassembles the crate and reuses the wood for another application.
4. There is an existing process for recycling and/or reuse of the packaging at end-of-life.
   - *Reusable Packaging:* Any reusable plastic, wood or metal pallet or container that can be easily recycled through standard industrial methods.
   - *Non-Reusable Packaging:* Packaging that is constructed in a manner that prohibits recycling through standard industrial methods.

The Reusable Packaging Association [6] provides a positive avenue to understand both the terminology as well as applications of reusable packaging methods that reduces environmental burden. "Europen" is the European Organization for Packaging and the Environment, and has developed 'Essential Requirements for Packaging in Europe'. This document provides a practical guide to using standards, and discusses the EN-13429 European standard on Reuse. In this discussion, it states that when reusability is claimed, the requirements are determined by a combination of the demands placed on the packaging itself and the nature of the reuse system in which it functions. For packaging to qualify as reusable the packer/filler must ensure the following:

- The packaging is intended to be reused for its original purpose
- It is possible to clean, wash and/or repair the packaging after emptying and to refill and reload it.
- A system which supports reuse of the packaging shall be available.

In the past year the International Standards Organization (International Organization for Standardization or *Organisation internationale* *de normalisation*) has initiated a new Technical Committee and Working Groups to develop new international standards for packaging and the environment, that include a working groups on "reuse".

Reusable packaging is advantageous for multiple industries including automotive, food, pharmaceutical, chemical, textile and several consumer goods. The advantages extends to reducing overall packaging costs, product damage, labor costs, inventory, cost per trip and improves transport efficiency through standardized loads, resulting in fewer trips and reduced fuel costs. It also reduces waste from entering the solid waste stream, green house gas emissions, energy requirement and demands on natural resources for raw materials. Reusable packaging is uniquely positioned to impact corporate sustainability initiatives in a meaningful way.

One way to measure the environmental impacts of different types of packaging is through Life Cycle Assessment studies. "A Life Cycle Assessment (LCA) is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying energy and materials used and wastes released to the environment and to evaluate and implement opportunities to affect environmental improvements." The principles and framework for conducting Life Cycle Assessments are outlined in International Standards Organization's (ISO) 14040. A LCA quantifies resource use, energy consumption, and environmental emissions to the air, water, and land for a given product system based upon the study boundaries established. Life cycle assessments compare the environmental impacts of single-use and reusable packaging [5].

Pallets have been widely used as material-handling platforms to assist in moving packaged products through the supply chain over the past seven decades. The growing trends and shifts to palletized handling over break-bulk handling of single parcel saves time and cost during cross-docking and loading/unloading processes in today's transportation environment. The design of this material handling structure called a "pallet" is important since it plays a role in transferring dynamic forces to the products loaded on these platforms during the transportation and handling environments [8]. Initial wood pallet designs introduced in the 1960's and 1970's used hardwoods and provided large deck coverage with stiff wood members (deck-boards and stringers). However over the last three decades the quality and bending stiffness of wood members continues to go down as cost and weight of these structures goes down. Alternate pallet materials such as plastics and corrugated fiberboard also reduce the stiffness of pallet decks. In addition the fastening systems (nails and screws) used to combine various members of the pallet (deckboard, blocks or stringers) play a role in the structural stiffness of the final structure. During reuse, the fastening systems are pivotal in creating a "moving" or weaker structure that will transmit higher levels of vibration and shock energy to the product placed on top.

It has been well established in various research projects conducted by the researchers at Michigan State University that stiffer pallets transfer less dynamic force when subjected to vibration levels observed and measured in rail and truck transportation environments. The transmissibility levels go down as the stiffness or natural frequency of the palletized load goes up. Based on this fundamental premise Michigan State University Center for Distribution Packaging Research engaged in this research project that is evaluating a new wood based pallet developed by Miller-Dowel Company, Inc. that uses stiffer wood members and combines them using a patented technology with dowels that allow for very little "loosening" and "softening" of the overall pallet structure during transportation and reuse.

The study compared two types of pallets as shown in Figures 1 and 2. Figure 1 shows the newly developed "BISON" pallet to a commonly

Figure 1. *BISON pallet.*

Figure 2. *GMA pallet.*

used wood pallet termed as a "GMA" pallet as it meets the requirements of the Grocery Manufacturers Association. The Bison pallet has a size of 48 × 40 × 5.5 inches and weighs 49 lb. The GMA pallet has a size of 48 × 40 × 4.75 inches and a weight of 48 lb.

In this study pallets that are loaded with a range of food and beverage products, and are subjected to transportation vibration levels in accordance with ASTM test methods. Packaged items include aluminum beverage cans, metal beverage cans in corrugated shippers, and metal food cans in plastic shrink wrap corrugated trays. These systems (palletized loads) are sold directly through club stores such as Sam's Club and Costco.

The 2006 Food Manufacturers Institute and Grocery Manufacturers Association (FMI/GMA) Unsaleables Benchmark Report highlighted the 2005 industry averages for "warehouse delivered" products to Manufacturers and Retailers as follows:

- Manufacturer reported weighted average = 0.81% of sales $ = $2.05 billion
- Retailer reported weighted average = 0.97% of sales $ = $2.45 billion

Figure 3. *Damage from fork-trucks, bad deck-board, and protruding nails.*

Figure 3 shows damage attributed from damaged pallets to the bottom layer of packaged products. A portion of the total damage is attributed to the interaction of the top of the pallet to the bottom layer of stacked product. Poor quality can result in damage to both primary and secondary packaging.

MATERIALS AND METHODS

The vibration levels that are transmitted to the secondary and primary packaging components that are stacked on the pallet loads are compared between the types of Bison pallets and other GMA pallets currently being used. This study looked at three different types of palletized load structures that were unitized and stretch wrapped on both types of pallets:

1. Paperboard cartons containing aluminum beverage cans
2. Corrugated boxes with steel cans containing juice
3. Shrink wrapped corrugated trays with canned vegetables

These three palletized configurations are shown in Figures 4–7.

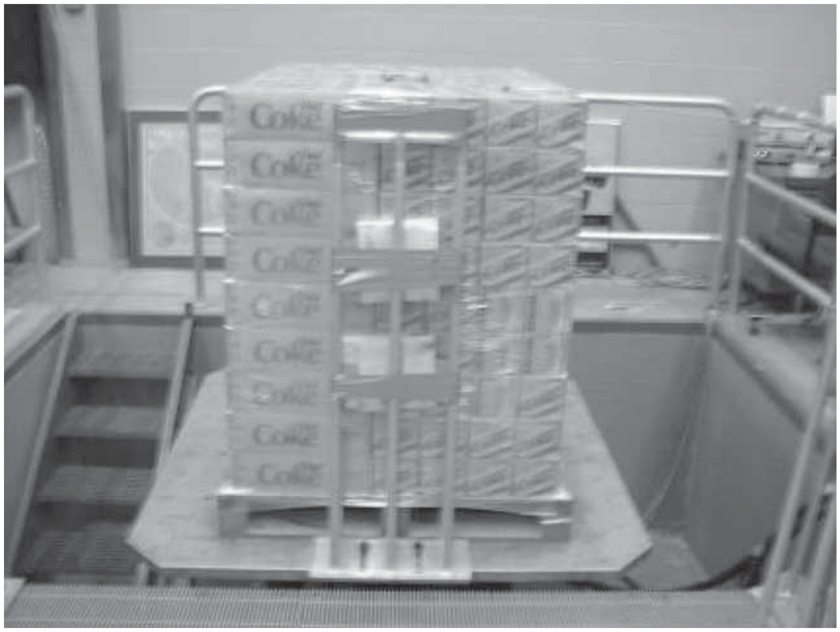

Figure 4. *Unitized load of beverage cans in paperboard cartons on BISON pallet.*

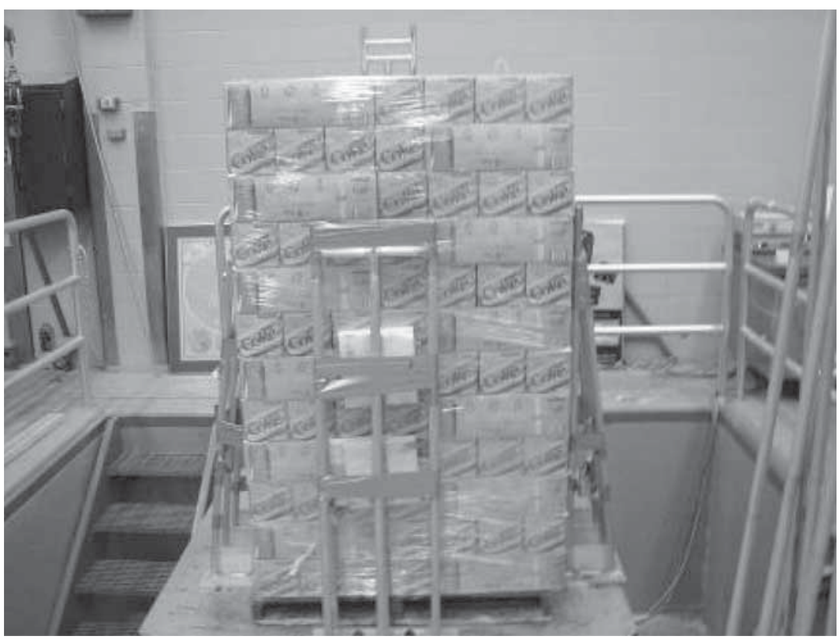

Figure 5. *Unitized load of beverage cans in paperboard cartons on GMA pallet.*

Figure 6. *Unitized load of corrugated boxes with steel cans containing juice on BISON pallet.*

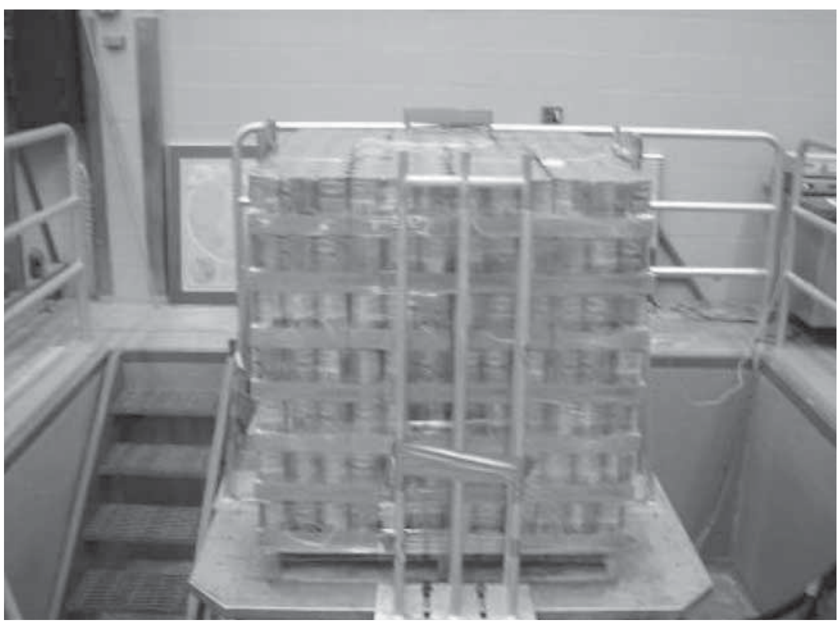

Figure 7. *Unitized load of shrink wrapped corrugated trays with steel cans containing porocessed vegetables on GMA pallet.*

Figures 4–7 show the various palletized loads that are placed on electric-hydraulic vibration tables that can be programmed to produce random vibration to simulate the transportation environment. For this study ASTM D4728 [9] test method was used to produce the random vibration for testing the various loads. Three different stretch wrapped unitized loads were tested on two different types of pallets. The vibration table was programmed to use a truck composite spectrum as described in ASTM D4169 [9], at an Assurance Level II, and with a G_{rms} of 0.519 g. The various palletized loads were placed on the vibration table for testing for at last 30 minutes. In addition two different accelerometers were mounted on the upper section of the unitized loads and at the input to the vibration table. The response spectrum was monitored over a period of time. This was saved and then a “transmissibility” function representing the average of the two response spectrums was compared to the input drive spectrum. The “transmissibility” function is the response of the response spectrum divided by the input vibration spectrum.

It is clear that if this new pallet system can attenuate vibration levels, it will lead to a reduction in damage, thereby reducing the amount and need of secondary packaging being used, which can help meet packaging sustainability targets.

RESULTS AND DISCUSSION

The study compared transmitted vibration levels to the products on GMA pallets versus BISON pallets. The results from these tests are shown briefly in Figures 8 shows the Power Density Spectrums (PDS) from testing done using the BISON pallet with a unitized load of the paperboard cartons with beverage cans. The demand spectrum used was the ASTM D4169 truck composite spectrum. Channel 1 (input) describes the actual power density spectrum at a given instant that represents the input vibration history. Channel (output) is the response spectrum analyzed from the vibration history at that instant on the top of the palletized load. Figure 9 describes the transmissibility function and is the ratio of Channel 2 divided by Channel 1.

Similarly Figure 10 describes the power density spectrums that were analyzed based on the test with the GMA pallet using the paperboard cartons containing aluminum beverage cans. Figure 11 provides the corresponding transmissibility function for the GMA pallet. Figures 12-15 shows data from tests for the other two palletized loads on BISON

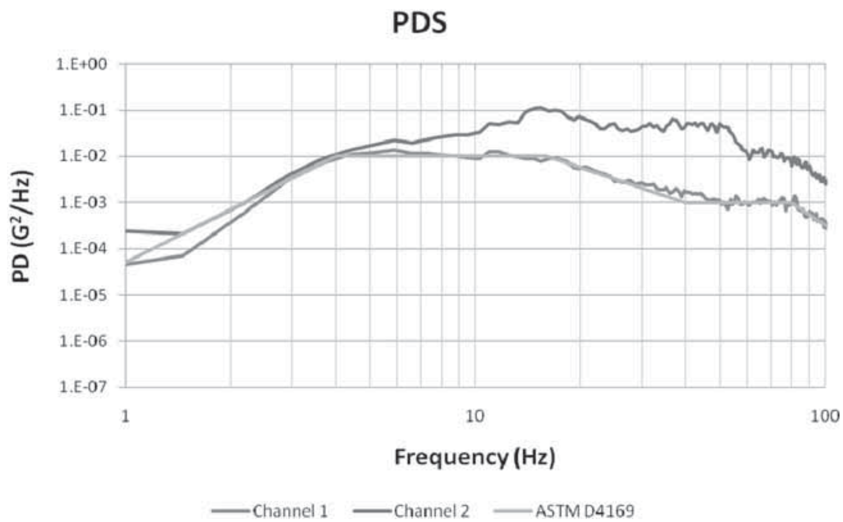

Figure 8. *PDS from BISON pallet test with paperboard cartons of beverage cans.*

pallets. The data from Figure 9 is compared to data from Figure 11 in Figure 16. Figure 16 therefore provides a comparison of transmitted vibration by the two pallets over a frequency range.

It should be noted that the orientation of stacked loads (column versus inter-locking) can change the natural frequency and the corresponding transmissibility levels. All stacked vibration tests were done using

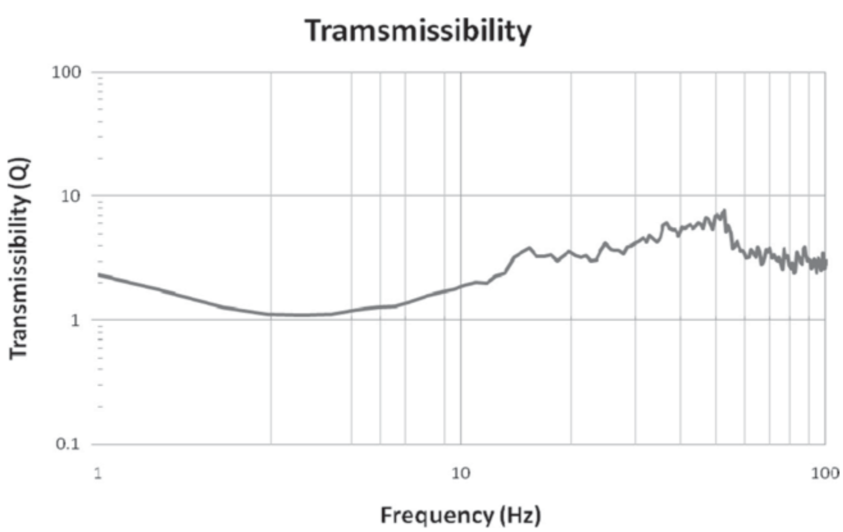

Figure 9. *BISON pallet transmissibility function for beverage cartons.*

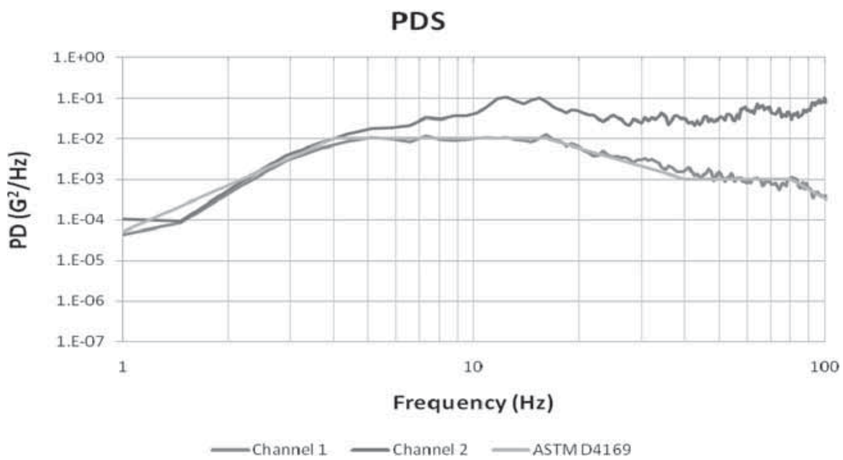

Figure 10. *PDS from GMA pallet test with paperboard cartons of beverage cans.*

fully unitized loads on these pallets that were stretch-wrapped and have been shown in Figures 4–7. The entire loads were subjected to preconditioning at standard conditions of 23°C and 50% relative humidity for at least 72 hours prior to test in accordance with ASTM D4332 [9]. The vibration testing was also performed at these standard conditions. It should be noted that long term vibration effects on paper corrugated structure will result in some crushing of the flutes and thereby make this structural material "stiffer" thereby also increasing the natural frequency.

The results of this study and later described in the conclusions ap-

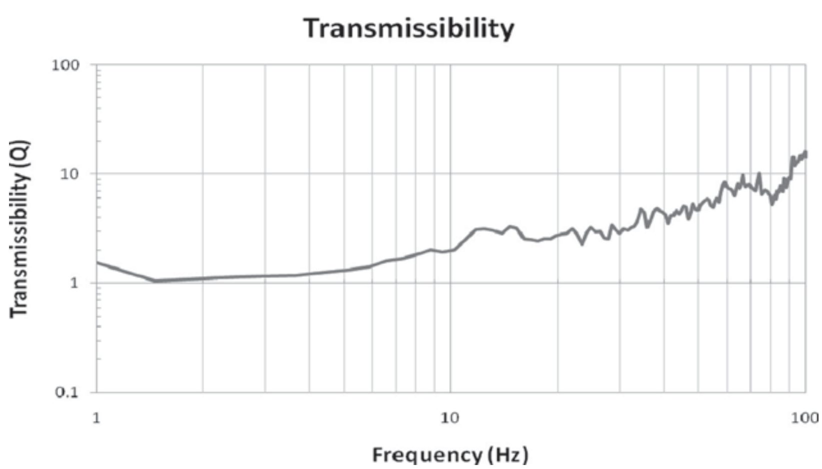

Figure 11. *GMA pallet transmissibility function for beverage cartons.*

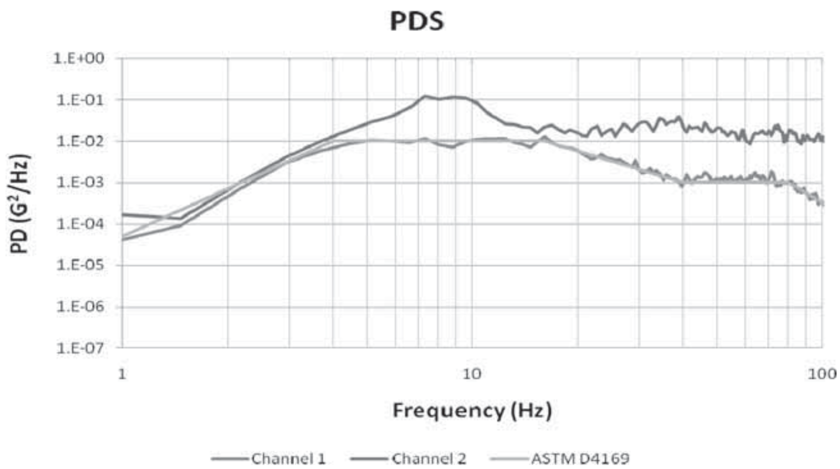

Figure 12. *PDS from BISON pallet test with corrugated boxes with steel cans of juice.*

ply to the type of "packaged" palletized and unitized loads of beverage cans, food cans, and liquid containing bottles. Results and outcomes can vary if the type of load is different such as machinery items, appliances, etc., that can have different load bearing regions as compared to product shipped by the Grocery Manufacturers Association.

This study also did not perform any individual tests on the different types of wood pallets as described in ASTM D1185 [9] such as impact, drop and corner drops, etc. Such testing has been previously done by other researchers [4].

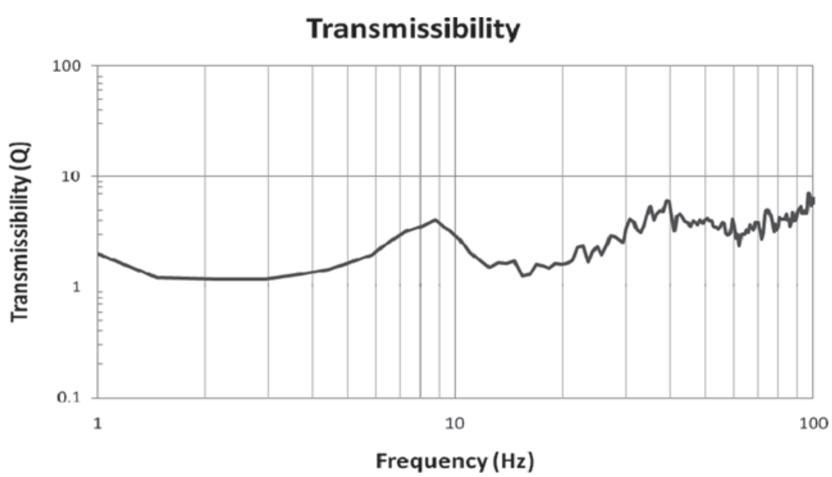

Figure 13. *BISON pallet transmissibility function for corrugated boxes with steel cans of juice.*

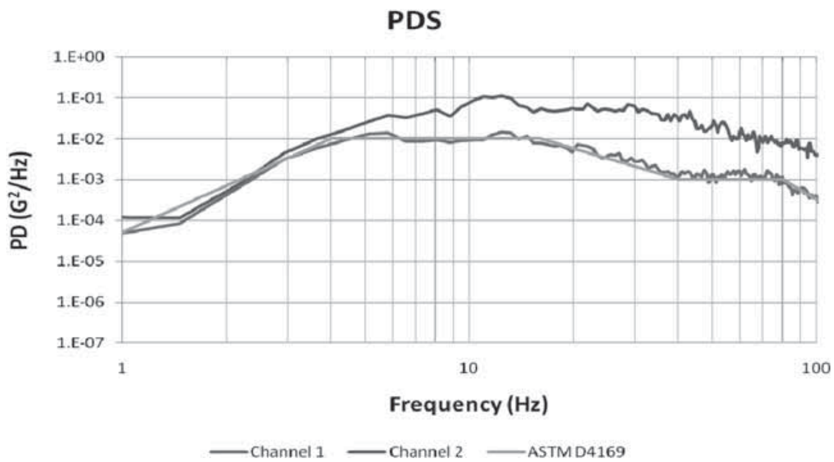

Figure 14. *PDS from BISON pallet test for shrink wrapped trays of canned vegetables.*

In a most recent review of sustainability, Kalkowski [10], cites the results from a major survey done by Packaging Digest [10] and the Sustainable Packaging Coalition, that drew 630 responses from the gamut of packagers, material and machinery suppliers, consumer packaged goods companies (CPGs) and retailers. Result show that nearly two-thirds of respondents say sustainable design in packaging decisions has become an important factor. The respondents to the survey also cited Wal-Mart as the leader among retailers, and Procter & Gamble among

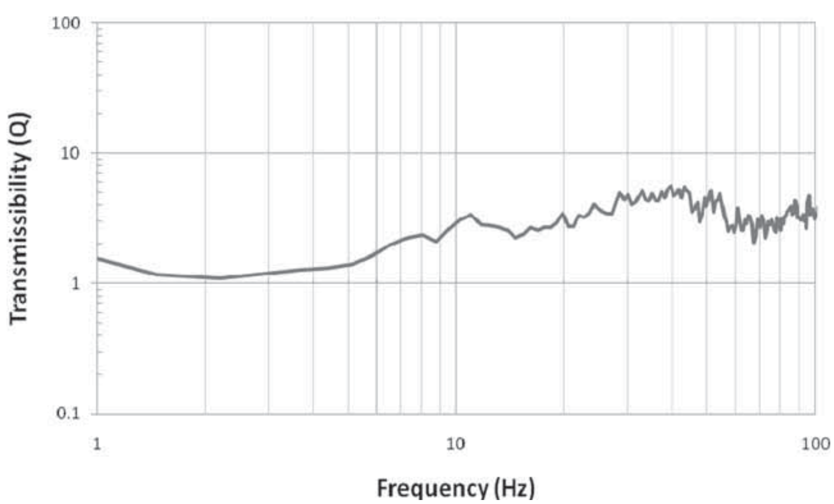

Figure 15. *BISON pallet transmissibility function for shrink wrapped trays of canned vegetables.*

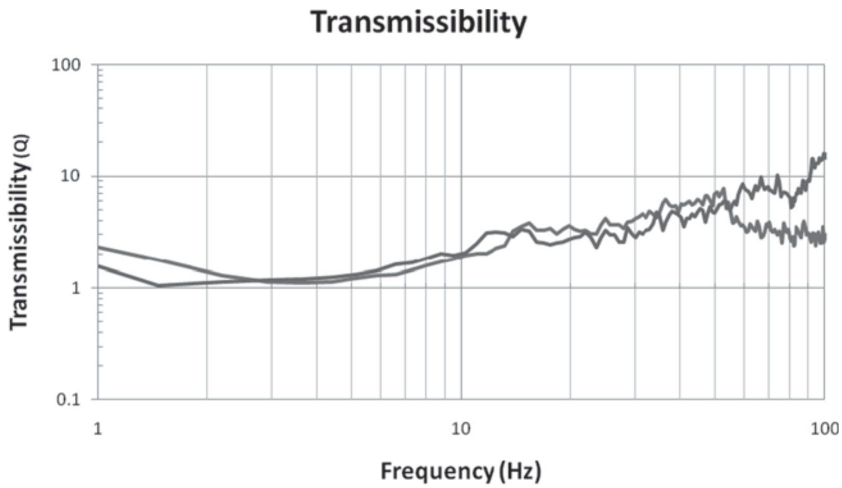

Figure 16. *Comparison of transmissibility function between Pallet 1 and Pallet 2 for beverage cans in paperboard cartons.*

consumer product companies. 87% respondents wrote in that they felt no single supplier company demonstrated leadership in sustainability. 81% of participants stated too many companies are "green-washing" their packaging by making false or unproven claims on their products environmental benefits. One respondent points out that *"Greenwashing has become so saturated that the sincerity of companies'* and developed a new term *'green exhaustion.'*

Kalkowski's [10] based on the survey described above shows that the most popular guidelines included in the sustainable packaging policies include are energy consumption (62%), recycled content specifications (54%), design guidelines (49%), and bans or limits on specific materials usage (43%). Nearly 67% of the survey respondents say that sustainability efforts have been difficult to advance during the current economic downturn. Respondents say the biggest challenges to making their packaging processes more sustainable include: raw materials costs (49%), lack of alternative materials (38%), ability to produce comparable-quality packaging (35%) and compatibility with existing systems (24%).

A major outcome of these efforts with leading global manufacturers and retailers is the development of new standards on *Packaging and the Environment* by ISO. This effort was initiated in Stockholm in 2009 and plans to have final ISO standards developed in several areas by 2012.

Results show that in all three cases, the BISON pallet reduces the amount of transmitted vibration to the product due to the stiffness and less shifting of product during transit. As a result of this the amount of primary and secondary packaging needed to protect contents during shipping and handling can be reduced. The transmitted Power Spectral Density plots have been compared between 3–10 Hz which causes predominant displacement in the vibrating loads and is attributed to damage and corresponds to suspension and structural responses. Data is also compared in the 1–100 Hz range. The data shows that there is a significant reduction (10–20%) in transmitted vibration between the GMA wood pallets and the BISON pallet. The pallet significantly reduces the amount of energy transmitted to the load. Based on this premise the amount of primary and secondary packaging can be reduced when using these new pallets. Furthermore the absence of nails reduces additional damage to primary packaging.

CONCLUSIONS

Packaging design incorporates all components of packaging: primary, secondary and tertiary. It is therefore clear that to reduce primary (bottles, cartons, cans, etc) and secondary packaging (corrugated shippers, trays, etc.), importance must be given to the tertiary packaging components (pallets, unitization methods, etc.). Stiffer pallets will reduce transmitted vibration and therefore require a reduced level of package protection. In addition this contributes to less damage to the product (e.g. fresh produce, cereal, crackers, etc.) and requires less strength for primary and secondary packaging, namely shipping containers such as boxes, and primary packaging containers made from plastic, glass and metal.

In addition pallets that are absent of nails, and made of rigid and sturdier deck-boards, will result in both reduced vibration, as well as a reduction in damage attributed to protruding nails and damaged wood splinters. This also makes recycling of wood pallets made from a single material into a future life as wood chips easier as there is no separation required of metal nails or staples.

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A Novel Method Predicting the Compressive Strength and Lifetime of Corrugated Fiberboard Shipping Containers

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ABSTRACT: Creep buckling of corrugated fiberboard due to stacking loads is frequently observed during storage. The damage has a great influence on the corporate activities. Consequently, it is essential to improve the accuracy of the estimation of the lifetime of corrugated fiberboard containers at their design stage.

For this study, creep experiments and compression experiments were conducted using corrugated fiberboard boxes. Estimation of the lifetime of corrugated fiberboard boxes was attempted using data obtained from compression experiments. Results reveal a formula to estimate the lifetime of corrugated fiberboard boxes exactly based on the relation between the static load and buckling time, as derived from results of creep experiments and compression experiments.

1. INTRODUCTION

STRENGTH degradation of corrugated fiberboard boxes under storage in a warehouse results from the creep phenomenon because of the stacking load (static load) and increased moisture contents of fiberboard resulting from higher atmospheric humidity. The buckling of corrugated fiberboard boxes attributable to strength degradation causes the collapse of stacked packaging containers in warehouses and causes damage to contents. Consequently, packaging design demands knowledge of the relation between static loading and buckling time (lifetime) and of the relation between moisture and compressive strength.

Numerous studies of the relation between static load and buckling time have been conducted, not only by Kellicutt [1] but also by many other researchers [2–5]. However, to obtain the relation for corrugated fiberboard

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of various kinds, many new samples and a long time would be required because the relation is dependent on the corrugated fiberboard material.

For this study, creep experiments and compression experiments were conducted for the corrugated fiberboard boxes. Their materials were C170/SCP120/C170. Their sizes were those of typical orange fruit boxes. The relation between the buckling time and static load was examined through creep experiments. In addition, the relation between compression speed and compressive strength was examined in compression experiments. Furthermore, the relation between static load and hypothetical compressive speed, which [6] is defined as the ratio of deformation of the box at the buckling to buckling time, was examined. Results of compression tests yielded estimates of the lifetime of corrugated fiberboard boxes based on these relations. Finally, to analyze the effect of corrugated fiberboard moisture on the compressive strength of corrugated fiberboard boxes, we conducted compression experiments for other materials, other sized boxes, other atmospheric humidity and temperature conditions, and other compression speeds.

2. EXPERIMENTAL METHOD

2.1 Correlation of Creep Experiments and Compression Experiments

2.1.1 Sample and Conditioning for Testing

The material is C 170/SCP 120/C170. The type of the stage is an A-flute, double faced corrugated fiberboard box with interior dimensions of 363 × 302 × 258 mm. Table 1 presents data related to the performance of the liner and corrugating medium of the corrugated fiberboard. The conditioning for testing was performed under 20°C and 65%RH for 24 hours. Measurement of moisture m (%) was conducted using the following methods. First, the mass of the corrugated fiberboard was measured after the test was finished. That value was recorded as (M_1). Secondly, after removing the sample after 24 hours at the 105 ± 3°C, the mass (M_2) was measured. It can be expressed as $m = 100 \times (M_1 - M_2)/M_1$. The sample moisture was calculated as 9.5% based on the given sample.

2.1.2 Creep Experiments

Because applying large loads one at one time is difficult, load ampli-

Table 1. Performance of Liner and Corrugating Medium.

	Ring-crush Load (N)		
	With-machine Direction	Across-machine Direction	Basic Weight (g/m^3)
Liner	325	213	171
Corrugated medium	172	115	122

fication equipment was designed and manufactured on a lever principle for creep experiments, as presented in Figure 1.

Weight for balance (Figure 1) is set next to the supporting point in order to balance the moment of the right bar and the left. Weight for static load is set at the edge of the left bar in order to generate the moment that is equivalent to the load applied to the sample.

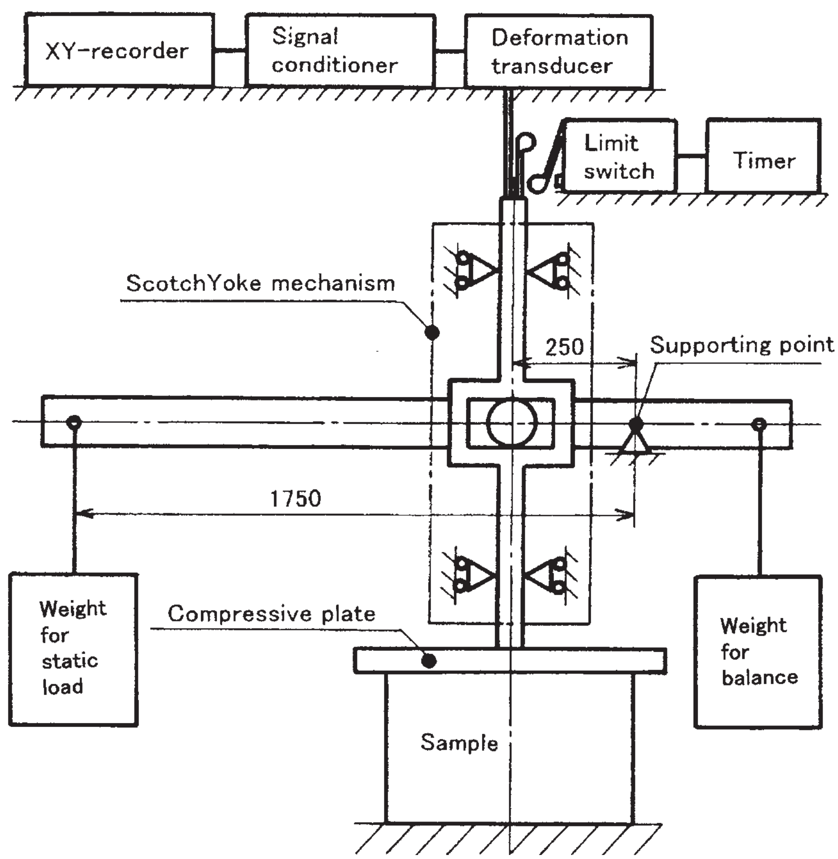


Figure 1. *Schematic of apparatus for creep test.*

When the corrugated fiberboard box is loaded, a scotch yoke mechanism—a mechanism that converts the rotary motion into simple harmonic motion—was adopted to prevent the load direction from affecting the rotation direction of the lever arm. Thereby, the load direction affects only the vertical direction. By installing a limit switch on the scotch yoke mechanism's vertical movement division upper end division, measurement of the displacement magnitude and of the creep experiment for the buckling time was done. The deformation length and buckling time were measured.

The experiment was conducted as described below.

First, while applying a 196 N load, the time deformation length was recorded. Second, the 196 N load was unloaded. Third, measurement by the timer of the deformation length by static loading started with the 196 N load in the tip. The box perfectly measured the time up to the beginning of buckling (buckling time), as presented in Figure 2.

The static loads used for the 10 samples in experiments were 1176 N, 1274 N, 1372 N, 1470 N, 1568 N, and 1666 N.

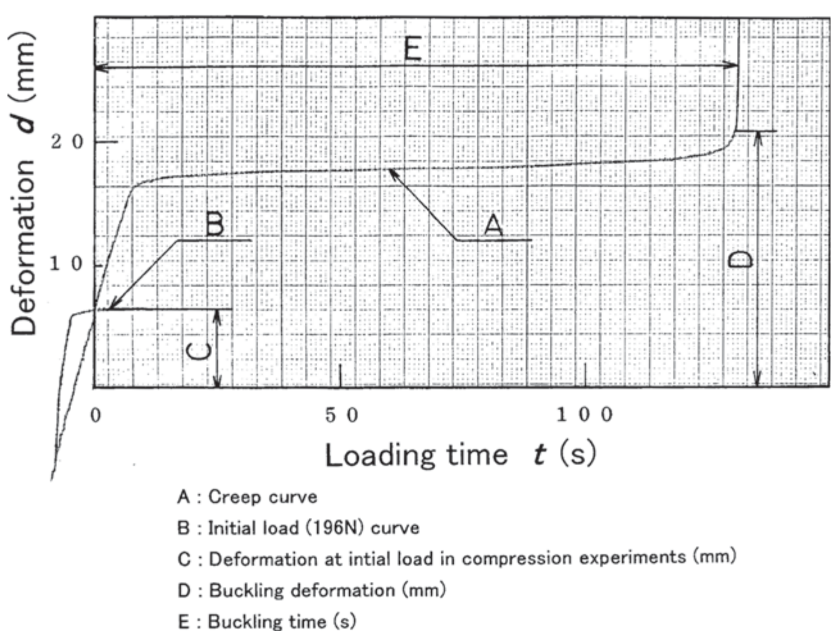


Figure 2. *Typical behavior of corrugated fiberboard containers under static load.*

2.1.3 Compression Experiments

Testing equipment for compression experiments (Autograph AG5000B special type; Shimadzu Corp.) was used to assess rates of compression in four conditions of 0.1, 1, 10, 100 (mm/min), and to measure compressive loads and deformation lengths of the five samples. This study applied compressive loads up to the maximum level, at which the corrugated fiberboard box buckled, thereby indicating the boxes' compressive strength, with data related to the time deformation length with compressive deformation.

2.2 Compression Experiments Using Different Materials, Dimensions, and Conditions

2.2.1 Sample and Conditioning for Testing

Data related to the performance of the liner and corrugating medium of the corrugated fiberboard are shown in Table 1. Samples A–G have 363 × 302 × 258 mm internal dimensions. The material and stage type are shown in Table 2. The sample was left for 24 hours under temperature and humidity conditions of 20°C/65%RH, 20°C/90%RH and 40°C/90%RH. In addition, samples A and D were dipped in 10°C water for 1 minute. Sample E was dipped for 3 minute in 10°C water. Samples H–O are A-flute double-faced corrugated fiberboard boxes of B220/GS125/B220 with the internal dimensions shown in Table 3. Testing was carried out at 20°C and 65%RH for 24 hours. Although their specifications are completely identical, samples A and H have different manufacturing lots.

Table 2. Board Composition and Flute Size of Samples A–G.

Sample	*Board Composition*	*Flute Size*
A	B220/GS125/B220	A-flute
B	K280/GS125/K280	A-flute
C	C170/GS125/C170	A-flute
D	B220/GS125/B220	B-flute
E	B220/GS125/GS125/GS125/B220	AB-flute
F	B220/DK200/B220	A-flute
G	B220/FKM115/B220	A-flute

Table 3. Internal Dimension of Samples H–O.

Sample	*Internal Dimension (mm) (Width × Depth × Height)*
H	363 × 302 × 258
I	363 × 302 × 792
J	363 × 302 × 525
K	363 × 302 × 180
L	732 × 302 × 258
M	300 × 302 × 258
N	250 × 302 × 258
O	610 × 363 × 258

2.2.2 Compression Experiments

Compression experiments used four rates of compression with 0.1, 1, 10, 100 (mm/min), measuring the respective compressive loads and deformation lengths of five samples. Testing was carried out at the condition of 20°C and 65%RH.

Using a 900 × 800 × 0.04 mm polyethylene bag on the sample with temperature and humidity conditions of 20°C/90%RH and 40°C/90%RH, the compression tests were conducted for respective samples.

3. RESULTS AND DISCUSSION

3.1 Correlation of Creep Experiments and Compression Experiments

3.1.1 Creep Experiments

The times for buckling caused by static load in creep experiments were ranked with mean value μ (arithmetic mean) and standard deviation s following a normal distribution. The mean value μ_{LE} (geometric mean) and with standard deviation s_{LE} following a log-normal distribution are presented in Table 4. The suitability of the probability distribution is examined because a large difference exists in cases where the representative values of an experimental value were assumed in arithmetic means and in cases where it is assumed in the geometric mean. The Kolmogorov–Smirnov test (K–S test) is used as a method for examining suitability in cases of few samples. For buckling times in the case of the 1176 N static load, the K–S test results are expressed

Table 4. Buckling Time at Static Loads (unit; s).

Rank	Static Load					
i	1176(N)	1274(N)	1372(N)	1470(N)	1568(N)	1666(N)
1	630	191	48	17	9	5
2	4838	310	84	17	10	5
3	17640	414	183	46	13	6
4	22128	2130	190	52	16	16
5	24970	2140	254	65	18	17
6	35887	2228	432	129	69	22
7	55866	3235	1203	200	126	23
8	63735	4140	1494	363	305	23
9	90576	8740	1723	501	335	72
10	433524	48335	19225	1227	1712	93
μ	74979	7186	2484	262	261	28.2
s	129034	14675	5915	376	524	29.9
μ_{LE}	26142	2065	497	110	59.0	17.8
s_{LE}	5.80	5.22	5.82	4.19	6.16	2.76

μ = Arithmetic mean
s = Standard deviation
μ_{LE} = Geometric mean
s_{LE} = Standard deviation (for logarithmic distribution)

to show the suitability in Figure 3, Figure 4, and Table 5. The threshold value $D(n,a)$ is a one-sided test variable using a K–S test table with 0.323 for the $a = 0.1$ level of significance for $n = 10$ samples.

Figure 3 shows the buckling time on the normal scale: $F_0(t)$ is the matching line required based on μ and s; the decision-limiting line $F_0(t) \pm D(10,0.1)$ in the K–S test is shown in the figure. The point of hoops of two is coming out on the outside of the decision line. Figure 4 shows the buckling time on a log-normal probability scale; $F_0(t)$ is matching line required based on μ_{LE} and s_{LE}. A decision-limiting line $F_0(t) \pm D(10,0.1)$ for all points exists in the K–S test when showing the buckling time. Table 5 shows data used to produce Figure 3 and Figure 4. The case of $D_{max} = 0.352$, in which the buckling time is the normal distribution in Table 5, was assumed to be larger than that of $D(n,a)$, and the case of $D_{max} = 0.212$, for which it was assumed that the logarithmic normal distribution is smaller than that of $D(n,a)$. For each D_{max}, it is assumed that the buckling time followed a log-normal distribution for static loads smaller than $D(n,a)$. However, each D_{max}, assuming that the buckling time followed normal distribution for the static load except for 1470 N ($D_{max} = 0.265$), is greater than $D(n,a)$. The geometric mean is taken as a

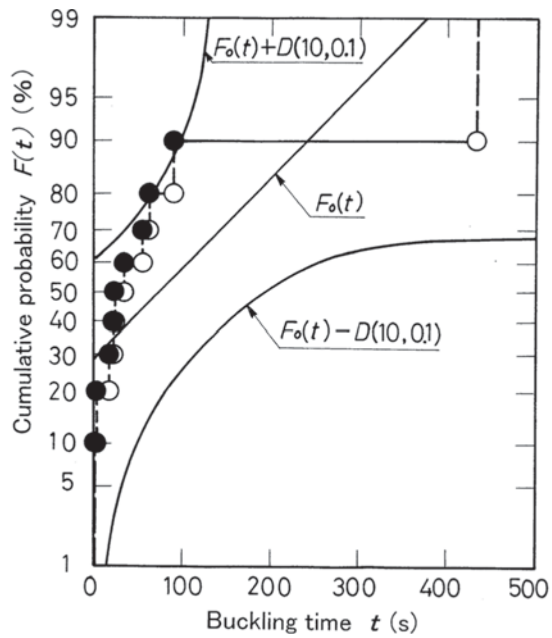


Figure 3. *K–S test for creep buckling time at 1176 N; normal probability scale.*

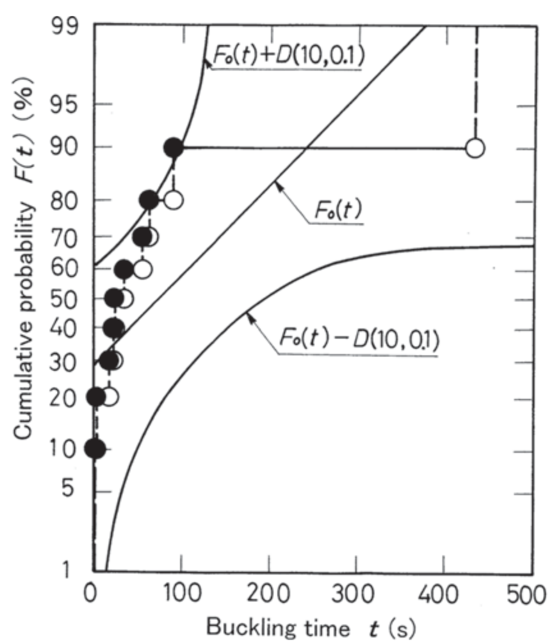


Figure 4. *K–S test for creep buckling time at 1176 N: logarithmic-normal scale.*

Table 5. Buckling Time at Static Loads (unit; s).

Rank				Normal Distribution		Logarithmic-normal Distribution	
i	*i* -1 / n	*i* / n	Buckling Time (s)	*F* (*xi*)	*D*	*F* (*xi*)	*D*
1	0.0	0.1	630	0.282	0.282	0.017	0.083
2	0.1	0.2	4838	0.293	0.193	0.169	0.069
3	0.2	0.3	17640	0.328	0.128	0.412	**0.212**
4	0.3	0.4	22128	0.341	0.059	0.462	0.162
5	0.4	0.5	24970	0.349	0.151	0.490	0.090
6	0.5	0.6	35887	0.381	0.219	0.572	0.072
7	0.6	0.7	55866	0.441	0.259	0.667	0.067
8	0.7	0.8	63735	0.465	0.335	0.694	0.106
9	0.8	0.9	90576	0.548	**0.352**	0.760	0.140
10	0.9	1.0	433524	0.997	0.097	0.945	0.055

D(10,0.1) = 0.323
F (xi) = Cumulative distribution function

representative value for the buckling time of each load because the logarithmic normal distribution implied by the distribution of the measured value for buckling time for a static load follows a normal distribution.

The relation between the static load P_s and the buckling time t is presented in Figure 5. The decrease in the static load is related directly to the logarithmic increase in the buckling time.

$$P_s = 1823 - 156 \log t \tag{1}$$

The correlation coefficient is –0.98, showing a strong negative correlation.

The load ratio C (%) is defined as the ratio of the compressive strength of corrugated fiberboard box and the stacking load. The relation between the buckling time t (day) and the load ratio C (%) is shown in Figure 6. Compared this study's results with other researchers', the similar tendency is shown in Figure 6.

3.1.2 Compression Experiments

The values for compressive strength, as assessed using the compression speed in compression experiments, are ranked by the arithmetic mean μ and standard deviation s following a normal distribution. The geometric mean μ_{LE} and the standard deviation s_{LE} in the following log-normal distribution are presented in Table 6. Compressive strength for

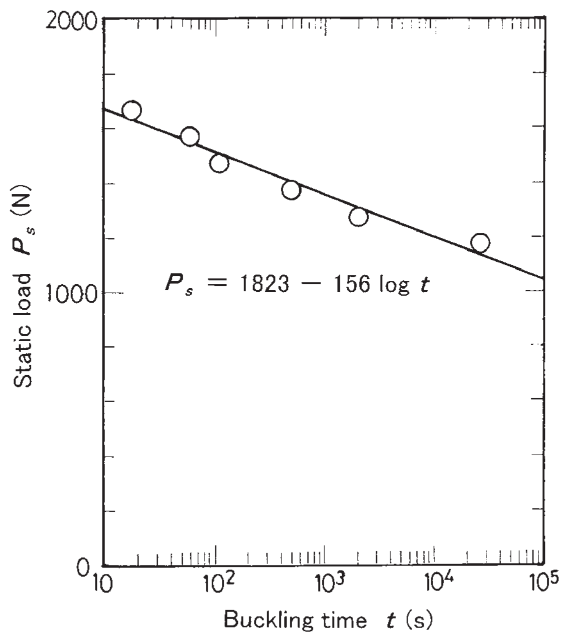


Figure 5. *Relation betwen static load and buckling time in creep experiments.*

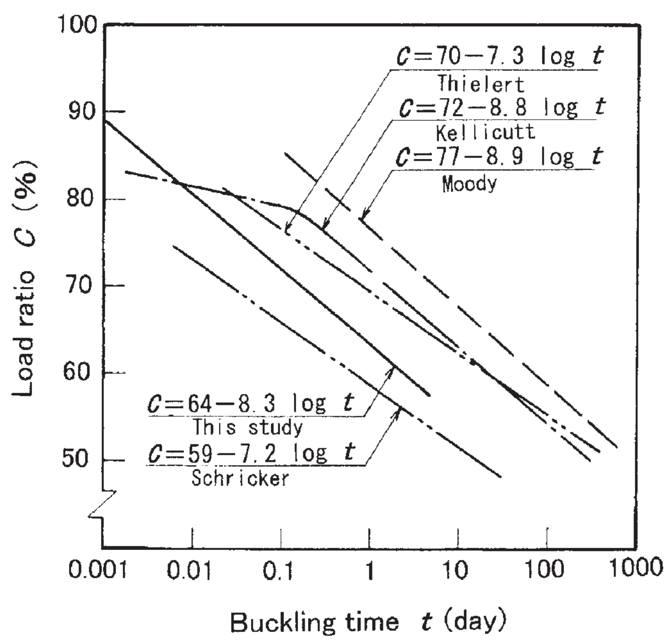


Figure 6. *Relationship between load ratio of creep test and buckling time [5].*

Table 6. Compressive Strength at Compressive Speeds (unit; N).

Rank	Compressive Speed			
i	0.1 (mm/min)	1 (mm/min)	10 (mm/min)	100 (mm/min)
1	1411	1597	1617	1833
2	1441	1597	1715	1921
3	1499	1607	1725	2009
4	1509	1627	1764	2019
5	1607	1627	1793	2097
μ	1493	1611	1723	1976
s	75.4	15.2	66.9	101.3
μ_{LE}	1492	1611	1722	1974
s_{LE}	1.05	1.01	1.04	1.05

μ = Arithmetic mean
s = Standard deviation
μ_{LE} = Geometric mean
s_{LE} = Standard deviation (for logarithmic distribution)

0.1 mm/min compressive speed is shown in Figure 7 and Table 7 to examine the suitability by K–S test. The threshold value $D(n,a)$ is that shown by a one-sided test of the K–S test table with 0.447 for the a = 0.1 level of significance for n = 5 samples. Figure 7 shows the compressive strength on a normal scale: all points on the decision limiting line $F_0(t) \pm D(10,0.1)$ exist in the K–S test showing the compressive strength.

The case of D_{max} = 0.218, in which the compressive strength is a normal distribution in Table 7, was assumed as smaller than that of $D(n,a)$. For D_{max} = 0.211, it was assumed that the normal distribution was smaller than that of $D(n,a)$.

Table 7. K–S Test for the Compressive Strength at 0.1 mm/min.

Rank				Normal Distribution		Logarithmic-normal Distribution	
i	$\frac{i-1}{n}$	$\frac{i}{n}$	Compressive Strength (N)	*F* (*xi*)	*D*	*F* (*xi*)	*D*
1	0.0	0.2	1411	0.137	0.137	0.132	0.132
2	0.2	0.4	1441	0.243	0.157	0.243	0.157
3	0.4	0.6	1499	0.530	0.130	0.541	0.141
4	0.6	0.8	1509	0.582	**0.218**	0.589	**0.211**
5	0.8	1.0	1607	0.934	0.134	0.931	0.131

D(10,0.1) = 0.323
F (xi) = Cumulative distribution function

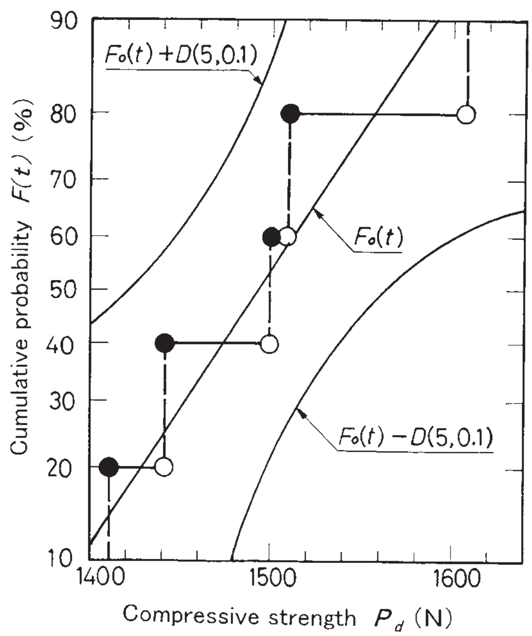


Figure 7. *K–S test for compressive strength at 0.1 mm/min; normal probability scale.*

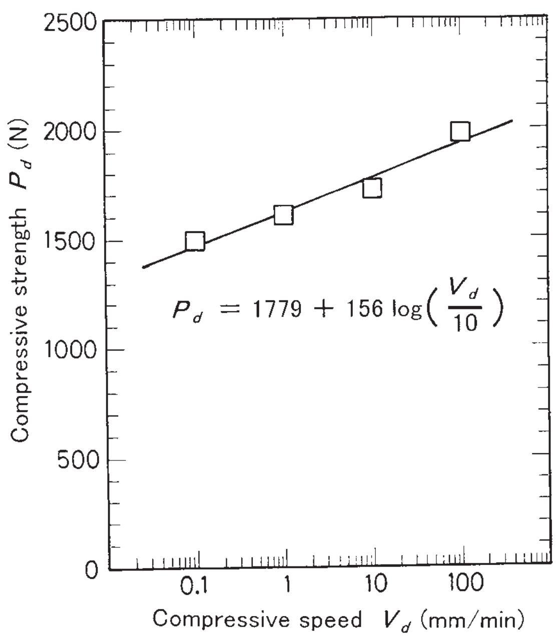


Figure 8. *Relationship between compressive strength and compressive speed in compression experiments.*

The arithmetic mean was taken as a representative value of the experimental value because the compressive strength for the compressive speed seems to follow a normal distribution. It also enables comparison with other data for compressive speed.

The relation between the compressive speed V_d (mm/min) and the compressive strength P_d (N) is expressed in Figure 8. The decrease in the compressive strength is proportional to the logarithmic increase in the compressive speed.

$$P_d = 1779 + 156 \log\left(\frac{V_d}{10}\right) \tag{2}$$

The correlation coefficient is 0.98, showing a strong positive correlation.

3.1.3 Correlation of Creep Experiments and Compression Experiments

The following equation was obtained when the hypothetical compressive speed V_s (mm/min) in creep experiments is assumed as a ratio of the buckling time t (s) and buckling deformation d_s (mm) [6].

$$V_s = \frac{d_s}{t/60} \tag{3}$$

The relation between the compressive rate V_d (mm/min) and the compressive deformation d_d (mm) in the compression experiments is shown along with the relation between static load P_s (N) and buckling deformation d_s (mm) in the creep experiments. The compressive deformation is fixed as about 16.7 mm even though the speed of the compressive speed and buckling deformation is fixed as 20.3 mm, irrespective of the mass of the static load used for testing, as presented in Figure 9. For the following reasons, $d_s > d_d$: d_s is the deformation that occurred as the buckling of creep experiments finished, although dd represents buckling of the corrugated fiberboard box beginning in compression experiments by deformation at the maximum compressive load. Buckling in both experiments apparently begins later than the buckling at the equivalent deformation. Estimation of the progress of the creep of corrugated fiberboard box was made according to results of compression experiments for relating the creep experiments to compression experiments. Equation (3) consists of the following, for which it is assumed that $d_s = d_d$ =16.7 mm.

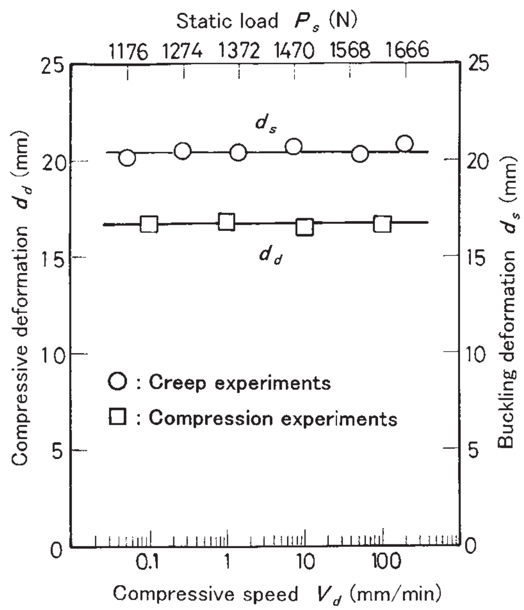


Figure 9. *Compressive deformation and buckling deformation.*

$$V_s \fallingdotseq 1002/t \tag{4}$$

In Figure 10, the relation between the static load P_s (N) and the hypothetical compressive speed V_s (mm/min) of Equation (4) is shown. The decrease in P_s is proportional to the logarithmic decrease in V_s from Figure 10. The following formula was obtained empirically when the relation between V_s and P_s was approximated as a logarithmic function using least-squares regression.

$$P_s = 1512 + 156\log\left(\frac{V_s}{10}\right) \tag{5}$$

The correlation coefficient is 0.98, showing a strong positive correlation.

In Equation (2), $P_d = P$, $V_d = V$, and the coefficient are used respectively with $\alpha_d = \alpha$ and $\beta_d = \beta$. In Equation (5), $P_s = P$, $V_s = V$, and the coefficient are used respectively with $\alpha_s = \alpha$ and $\beta_s. = \beta$. Equation (2) and Equation (5) can be expressed as in Equation (6).

$$P = \alpha + \beta \cdot \log\left(\frac{V}{10}\right) \tag{6}$$

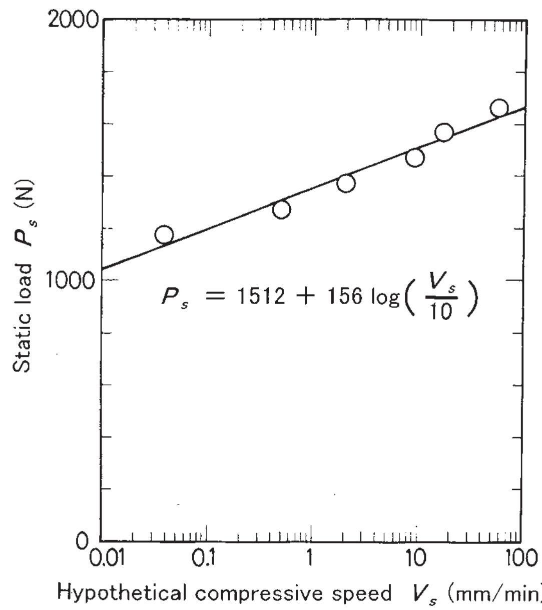


Figure 10. *Relation between the static load and hypothetical compressive speed.*

The compressive speed 10 mm/min [7] was inferred from Equation (6), so that the value of second term of the right-hand side might become 0. In addition, α is called the standard compressive strength [8]. The second term of the right-hand side of the Equation (6) is designated as β with the speed corrected strength because it becomes intense, depending on the compressive speed. It becomes equal, as $\beta_s = \beta_b = 156$ for the speed-corrected strength in the creep experiments and compression experiments shown in Equation (6). Additionally, $\alpha_s = 0.85\alpha_d$ from $\alpha_s = 1512$ N, $\alpha_d = 1779$ N. The value was about 85% for compression experiments and in the creep experiments, with correlation for creep experiments and compression experiments.

3.2 Compression Experiments Using Different Materials, Dimensions, and Test Conditions

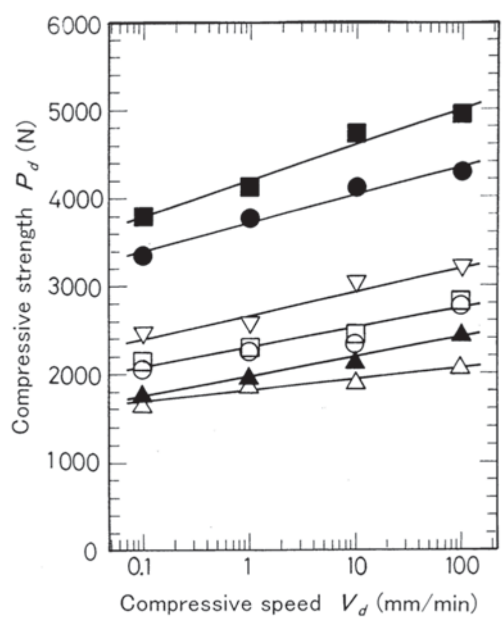
3.2.1 Compressive Strength and Compressive Deformation

In the load–deformation curve, the first peak of the compressive load was made the compressive strength. The deformation volume was inferred as the compressive deformation. For the following reasons, the first peak load was judged as the compressive strength. There were 65 boxes in 140 = (7 × 4 × 5) boxes on the sample with more than two for peak loads in 20°C 65%RH temperature and humidity conditions. There were 25 boxes in 20°C/ 95%RH and 9 boxes in 40°C 95%RH. The proportion of the sample in which there is only one peak load results from the increase because the compressive deformation of the first peak load becomes equivalently any fact and high-temperature and humidity condition.

3.2.2 Creep Prediction of the Corrugated Fiberboard Box

3.2.2.1 Material Effect of the Corrugated Fiberboard Box

The relation between the compressive strength P_d (N) and the compressive speed V_d (mm/min) of samples A–G, which had been pretreated at 20°C 65%RH, is presented in Figure 11. That figure also shows



Sample	Symbol	Regression function	Correlation coefficient
A	○	$P_d = 2460 + 217 \log(V_d/10)$	0.96
B	▽	$P_d = 2930 + 265 \log(V_d/10)$	0.97
C	△	$P_d = 1940 + 124 \log(V_d/10)$	0.96
D	□	$P_d = 2530 + 223 \log(V_d/10)$	0.97
E	■	$P_d = 4600 + 404 \log(V_d/10)$	0.99
F	●	$P_d = 4030 + 316 \log(V_d/10)$	0.98
G	▲	$P_d = 2200 + 222 \log(V_d/10)$	0.99

Figure 11. *Relationship between compressive strength and compressive speed (Samples A–G at 20°C 65%RH).*

that the compressive strength decreases concomitantly with compressive speed, irrespective of the corrugated fiberboard box material. The relation between the compressive speed and the compressive strength is as presented in Equation (7).

$$P_d = \alpha_d + \beta_d \bullet \log\left(\frac{V_d}{10}\right) \tag{7}$$

Although the formula is derived under the condition of 20°C /65%RH, but it also can apply the situation at 20°C /90%RH and 40°C/ 95%RH.

3.2.2.2 Effect of Moisture on the Corrugated Fiberboard Box

The relation between the compressive strength and compressive speed of sample A in which the pretreatment condition differs is presented in Figure 12, which also shows that the compressive strength de-

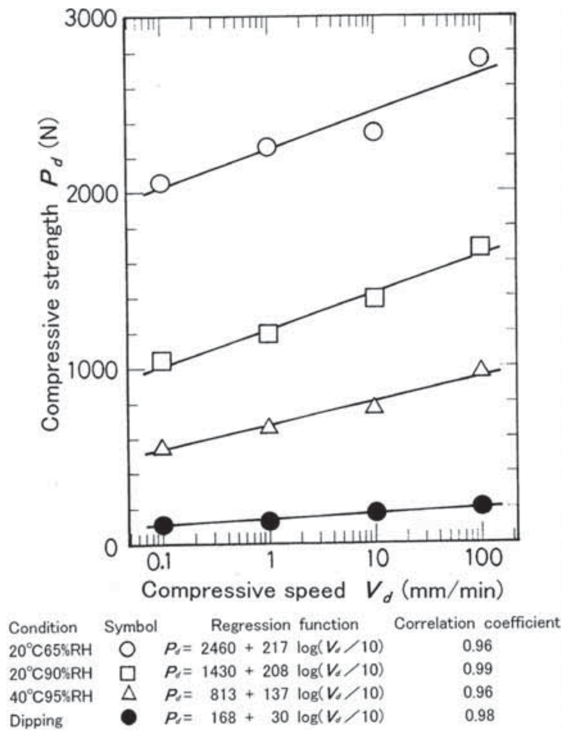
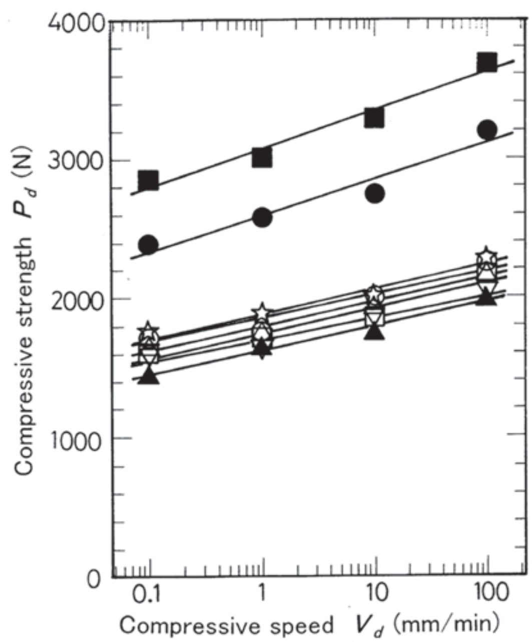


Figure 12. *Relationship between compressive strength and compressive speed for Sample A.*

creases when the compressive speed slows, irrespective of the moisture of the corrugated fiberboard box. The relation between the compressive speed and the compressive strength is as shown in Equation (7). This relation can be stated similarly for samples B–G.

3.2.2.3 Effect of the Corrugated Fiberboard Box Dimensions

The relation between the compressive strength and the compressive speed of sample H–O with pretreatment at 20°C/65%RH is presented in Figure 13. That figure also shows that the compressive strength decreases when the compressive speed decreases, irrespective of the corrugated fiberboard box dimensions. The relation between the compressive speed and the compressive strength is as shown in Equation (7).



Sample	Symbol	Regression function	Correlation coefficient
H	○	P_d = 2020 + 166 log(V_d／10)	0.95
I	□	P_d = 1920 + 179 log(V_d／10)	0.97
J	△	P_d = 1970 + 175 log(V_d／10)	0.99
K	☆	P_d = 2060 + 182 log(V_d／10)	0.99
L	●	P_d = 2850 + 258 log(V_d／10)	0.97
M	▲	P_d = 1800 + 172 log(V_d／10)	0.99
N	▽	P_d = 1850 + 155 log(V_d／10)	0.97
O	■	P_d = 3340 + 275 log(V_d／10)	0.98

Figure 13. *Relationship between compressive strength and compressive speed for samples H–O, 20°C 65%RH.*

3.2.2.4 Standard Compressive Strength and Speed-corrected Strength

The relation between the standard compressive strength α_d (N) and the speed-corrected strength β_d (N) of the sample and different corrugated fiberboard box materials, moisture levels, and dimensions is presented as Figure 14. Next, the empirical formula was obtained through least-squares approximation of the relation between β_d and α_d in the linear function.

$$\beta_d = 47.2 + 0.0754\alpha_d \tag{8}$$

The correlation coefficient was 0.93. It represents a high and positive correlation. Results show that compressive strength of all corrugated fiberboard boxes of which material and moisture and dimensions for optimal compressive speed differ can be estimated because β_d is approximately proven if α_d is proven.

3.2.2.5 Creep Estimated Formula of the Corrugated Fiberboard Box

Equation (9) is obtained by substituting Equation (8) into Equation (6).

$$P = \alpha + (47.2 + 0.0754\alpha)\log\left(\frac{V}{10}\right) \tag{9}$$

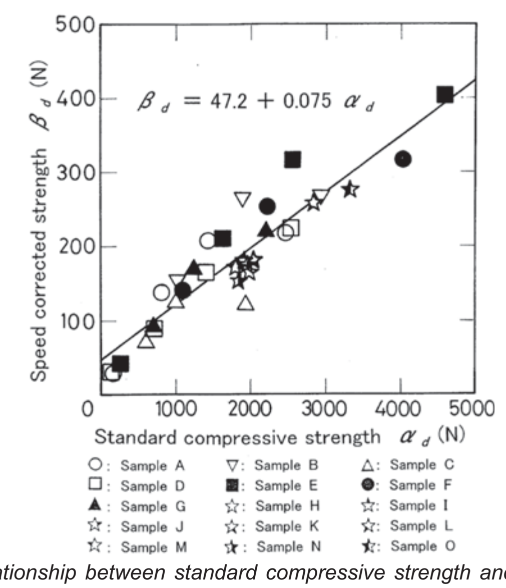


Figure 14. *Relationship between standard compressive strength and speed-corrected strength.*

First, $\alpha_s = 0.85\alpha_d$ is substituted in α of Equation (9) because the standard compressive strength of creep experiments is 85%. Next, the static load P_s(N) can be represented as Equation (10), when it is arranged considering the hypothetical compressive rate V_s (mm/min), which is a ratio incorporating buckling deformation d_s (mm) (Pd_d (mm)) and the storage period (buckling time) T (day).

$$P = 0.583\alpha_d - 196 + (47.2 + 0.0641\alpha_d)\log\left(\frac{d_d}{T}\right) \tag{10}$$

From Equation (10), the stacking load can be estimated if the storage period is given because compressive strength and compression quantity were proven through compression experiments.

Concretely, when the storage period is 1 month ($T = 30$), the stacking load as the standard compressive strength (compressive speed 10 mm/min) is 1960 N. The compressive deformation of 20 mm is calculable as occurring from 916 N. Furthermore, when the storage period is 1 year, it is possible to obtain the stacking load for the standard compressive strength of 1960 N. The compressive deformation is 20 mm with 729 N.

Next, Equation (10) is arranged in the storage period as shown in Equation (11).

$$T = \exp\left(\frac{0.583\alpha_d - P_s - 196}{20.5 + 0.0278\alpha_d} + \ln d_d\right) \tag{11}$$

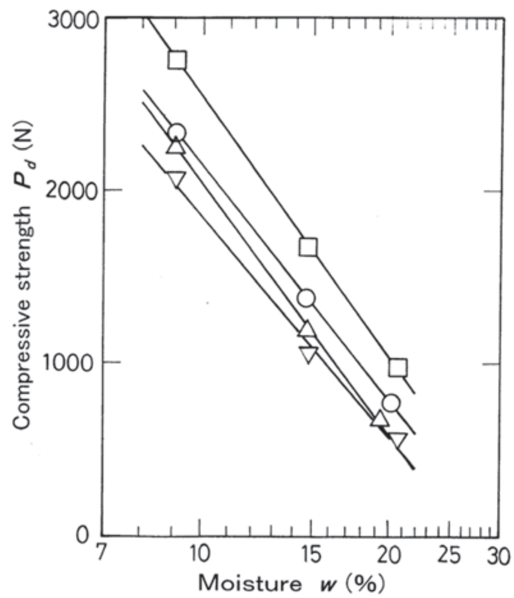
From Equation (11), the storage period can be estimated if the stacking load is given because compressive strength and compression quantity were evaluated through compression experiments.

3.2.3 Degradation of the Corrugated Fiberboard Box by Moisture

The relation between the compressive strength P_d (N) and the moisture m (%) of sample A is depicted in Figure 15, which also shows the resultant empirical formula. The compressive strength decreases if the moisture increases. This relation is approximated by a logarithmic function using least-squares approximation.

$$P_d = \gamma - \delta \cdot \log m \tag{12}$$

Figure 16 presents the relation between γ(N) and δ(N), showing that δ is also increased if γ increases. This fact was also apparent for samples



Compressive speed	Symbol	Regression function	Correlation coefficient
100	□	P_d = 7560 − 5016 log *w*	−1.00
10	△	P_d = 6677 − 4527 log *w*	−1.00
1	▽	P_d = 6904 − 4857 log *w*	−1.00
0.1	○	P_d = 6105 − 4249 log *w*	−1.00

Figure 15. *Relation between compressive strength and moisture, Sample A.*

B–G. The following empirical formula is obtained when least-squares approximation of the relation between δ and γ is done of the linear function.

$$\delta = -136 + 0.71\gamma \tag{13}$$

The correlation coefficient becomes 1.00, showing a high and positive correlation.

It is derived from arrangement through the substitution of Equation (13) in Equation (12) in γ, as in Equation (14).

$$\gamma = \frac{P_d - 0.136 \cdot \log m}{1 - 0.71 \cdot \log m} \qquad (8 \le m \le 21) \tag{14}$$

The corrugated fiberboard box, which has 1960 N standard compressive strength, takes in 9% moisture in this example. In this case, γ consists of Equation (14) with 5675 N; δ consists of Equation (13) with 3890 N. To calculate the compressive strength with moisture of this corrugated fiberboard box of 20%, the compressive strength becomes

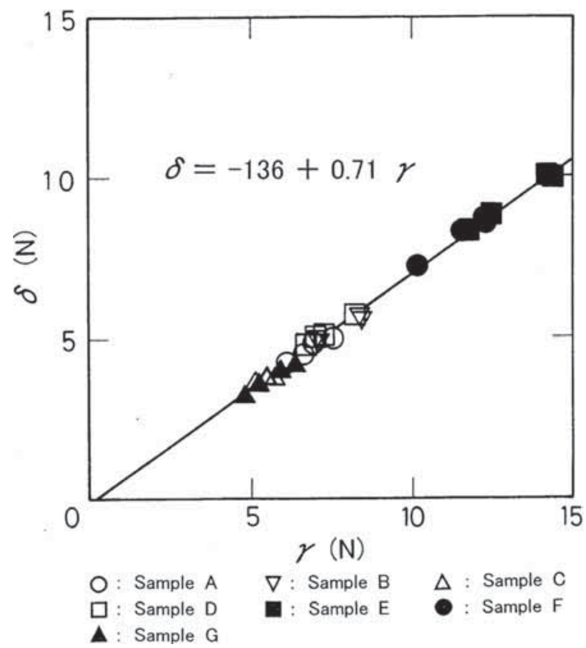


Figure 16. *Relation between γ and δ.*

613N when γ = 5665, δ = 3890, and m = 20 are substituted into Equation (12). As described above, degradation of the corrugated fiberboard box by the moisture is easily calculated.

4. CONCLUSIONS

The relation between compressive strength of corrugated fiberboard boxes and their lifetime was clarified using compressive experiments and creep experiments.

Results reveal a formula to estimate the lifetime of corrugated fiberboard boxes exactly based on the relation between the static load and buckling time, as derived from results of creep experiments and compression experiments.

The following equation was obtained.

$$T = \exp\left(\frac{0.583\alpha_d - P_s - 196}{20.5 + 0.0278\alpha_d} + \ln d_d\right)$$

In that equation, T (day) signifies the lifetime of a corrugated fiberboard box under a static load P_s (N). Furthermore, α_d (N) and d_d (mm) respectively represent the compressive strength and deformation, as obtained using standard compression experiments.

Results show the possibility of estimating the lifetime from the stacking load and of estimating the stacking load from the lifetime when the compressive strength, compressive deformation, and moisture of corrugated fiberboard are measured. Moreover, it was possible to estimate the degree to which the fiberboard moisture degrades the box strength.

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Packaging Requirements for Less-Than-Truckload Shipments to Reduce Damage—Furniture, Appliances and Boxed Freight

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ABSTRACT: This paper provides results from a major damage assessment study that analyzed challenges products endure during shipping and handling in the less-than-truckload logistics environment. The study shows the various package forms, handling and loading challenges that carriers experience when shipping a multitude of mixed products as part of daily shipments, and recommendations to reduce or avoid damage and avoid personal injury. This paper presents findings for furniture, appliances and boxed freight and is the second of a series of three papers. The paper reviews findings from various shipments, and provides recommendations on both packaging and loading methods based on product type to safely load and transport less-than-truckload shipments, and to reduce damage claims without compromising safety of personnel handling and performing loading and unloading functions.

1.0 INTRODUCTION

EVERY day thousands of tons of commodities are transported around the country via motor carriers. A large majority of this freight is moved through the less-than-truckload (LTL) distribution environment, which has very unique characteristics that are inherent to how the system functions. This paper is the second paper in a series of three papers. The authors have retained the same introduction and results of the LTL survey in all three papers so readers can review the background information on LTL shipments and damage independently with each paper.

Freight moving via LTL motor carrier is handled frequently, with multiple loading and unloading points during transit. During distribu-

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tion, freight may be mixed with a wide variety of commodities, which impacts how and where in the trailer it is loaded. Packaging plays a significant role, not only in protecting the freight, but also making it easier to handle and stow with other freight. Carriers are faced daily with the challenge of optimizing the available space in the trailer with the largest number of shipping units that can be shipped without causing damage and compromising safety. This is sometimes a difficult task if the carrier does not truly comprehend the protective capabilities and the integrity of the package that has been placed in shipment with other packages from other customers, all moving in the same truck. One leaking pail, or broken glass products, can compromise several other packages in their vicinity, and so damage is often progressive in LTL shipments.

Previous studies conducted in collaboration with Michigan State University School of Packaging have shown that LTL shipments will be susceptible to damage due to a lack of proper packaging and improper loading methods [1, 2]. Vibration levels measured in LTL shipments have also shown that these levels are significantly higher than those in other types of truck shipments [3, 4]. Results from recent studies have shown that vibration levels measured in LTL trailers and pup-trailers are higher than those recommended for truck shipments [5, 6] and in industry standards [7]. As a result the International Safe Transit Association (ISTA) developed a new test method that used the new vibration data to better represent this unique shipping and handling environment [8]. This test method “Project 3B: Packaged-Products for Less-Than-Truckload (LTL) Shipment” is a general simulation test for packaged-products shipped through a motor carrier (truck) delivery system, where different types of packaged-products, often from different shippers and intended for different ultimate destinations, are mixed in the same load. Project 3B is appropriate for four different types of packages commonly distributed in LTL shipments: Standard 200 lb (91 kg) or less, Standard over 200 lb (kg), Cylindrical, and Palletized or Skidded [8]. Requirements may include atmospheric conditioning, tip-over, shock and impact, random vibration with top load, concentrated impacts, and fork lift handling.

Packaging requirements, for freight transported via LTL, are defined in the *National Motor Freight Classification (NMFC)*. Each commodity description in the *NMFC* specifies minimum packaging requirements to ensure the products can be handled and protected in the motor carrier environment. The descriptions may be as simple as “in boxes,” “in drums,” “in boxes, crates, or on a lift truck skid or pallet”. The *NMFC*

Figure 1. *Vibration levels in LTL shipments compared to truck load test methods [7].*

does not stipulate what interior packaging is required, since that is dependent on too many factors that are inherent with a particular product. It is the shipper's responsibility to develop interior packaging that will protect and contain the product during handling and distribution.

However, despite the *NMFC's* minimum packaging requirements, there are a variety of commodities that are inherently difficult to handle or stow, susceptible to damage, highly fragile, or problematical to develop packaging that is appropriate to adequately protect it from the rigors of this distribution environment. The goal when setting the minimum packaging requirements for commodities is to provide proper containment. When freight is damaged, a damage claim is often filed against the carrier by the shipper or consignee of the freight. The shipper or consignee generally determines the value of the damaged freight and will request the carrier to reimburse all or a portion of the monetary value of the freight. Obviously, the payment of damage claims to shippers can become very expensive for many carriers.

In trying to understand how packaging and different loading methods can affect damage claims, six LTL motor carriers were surveyed and asked the questions mentioned in the next section regarding their company's history. Overall, the survey has proven that there are some commodities that are generally more susceptible to damage and have more liability factors than other commodities. Packaging can play a very important role in not only preventing damage to the products, but also facilitate in the safe handling and stowing of the products for carriers. This study contains pictures from "actual" LTL shipments that depict the type of freight and packaging that is commonly seen in the LTL environment for paint, copiers and televisions.

2.0 MOTOR CARRIER SURVEY AND RESULTS

Six LTL motor carriers were surveyed and asked the following questions regarding their company's history and practices. The responses received from these six carriers varied, mainly due to the size and coverage area of the company. For confidentiality purposes, the companies are only identified as A, B, C, D, E, or F.

1. What are the top three commodities or commodity groups (as described in the NMFC) with the most claims?
2. Approximately what percentage of all claims does each of the commodities or commodity groups named in number 1 represent?
3. Approximately how much money does your company spend each year in claims?
4. What is your company's claims ratio?
5. What percentage of claims does your company pay and deny?
6. How often does insufficient packaging account for the denial of a claim?
7. What is the most common reason for damage claims rejections?

The six carriers were very forthcoming with proprietary information regarding the information requested. These six carriers spend approximately $50 million combined each year in claims that range from $33,000 to $31 million. Three companies' claims-ratio ranged from 0.76% to 1.30%, with an average of 1.02%. Claims-ratio is calculated by dividing the dollars paid in claims by total overall revenue generated for all shipments. On average, these six carriers pay 65% of the claims filed, while denying only 35%. For one company over 80% percent of all claims were related to furniture alone.

Based on this survey, furniture was found to be the most frequently damaged commodity group, as four out of the six carriers named this as their top issue and concern. Furniture, as a whole, can be very fragile, large, and can be awkward in size and shape. The NMFC provides for specification-based packages for most furniture types, as well as Item (Rule) 181, which is a test procedure that simulates the LTL environment and was designed specifically for furniture and furniture parts. However, shippers often do not utilize these standards and use a minimal amount of packaging which may not help protect the products from scratches, dents, and scuffs. Company C reported that furniture represents 81% of all their damage claims, while Companies D and F indicated that furniture was responsible for about 11 percent of their damage claims. Of Company C's 81% of all claims, 60% of the claims were denied due to insufficient packaging. Additionally, many types of furniture can be expensive and have a high value per pound.

Electronics, electrical equipment and supplies, and machinery were also identified by the carriers as commodities with the most claims. Not unlike furniture, some of the products can also be quite fragile. However, the fragility is often determined by a particular component within the product. These products may also be very large, which would hinder the manufacturer from developing packaging that can sufficiently protect the entire unit.

Companies C and F indicated that certain types of paper goods are also liable to damage due to a lack of packaging. Company C denies 100% of damage claims on these goods based on insufficient packaging. While paper goods are dense freight with few negative handling and stowing issues, when they are not packaged properly the product can be subjected to damage from handling and the external environment. Company A reported 20% and Company E reported 29% denial of claims due to insufficient packaging. In the case of Company A, this is the most common reason for claim denial. Of the 84% of Company E's claims are filed for damage, while 16% is for loss of product.

Overall, this survey has proven that there are some commodities that are generally more susceptible to damage and have more liability factors than other commodities. The packaging can play a very important role in not only preventing damage to the products, but also facilitate in the safe handling and stowing of the products for carriers. Unfortunately, as depicted by the figures that follow, manufacturers are not always packaging their commodities in a way that is appropriate for the LTL environment. In many instances, the pictures prove why the numbers presented by the carriers in the survey are accurate and representative of the issues carriers face on a daily basis.

3.0 DAMAGE ISSUES AND PREVENTIVE METHODS WITH SHIPMENTS OF FURNITURE

Furniture, as indicated in the motor carrier survey results, is the commodity group that has the highest damage claims for many carriers, due to its inherent fragility and, often, lack of appropriate packaging. Some types of furniture may also be more susceptible to damage due to the inclusion of glass or other fragile materials to enhance the aesthetic features. Packaging requirements for furniture are very specific in the National Motor Freight Classification (NMFC). Unlike most other freight which only specify the minimum packaging requirements, the furniture section primarily consists of the numbered packages, "F" and "S" packages, which are all specification-based packaging guidelines. These guidelines are defined for almost every type of furniture from chairs, to tables, to desks.

Many types of furniture such as sofas and chairs are shipped in fiberboard boxes, as shown in Figures 2(a), 2(b), and 2(c). Manufacturers use various types of interior packaging and dunnage materials in order to protect against damage, which can be as simple as a plastic bag or wrap to prevent abrasion and dust, or Kraft paper, such as those shown in Figures 2(d), 2(e) and 2(f). Certain items require complex solutions such as custom molded foam cushions. When proper cushioning is not used, the furniture may be susceptible to movement within the box, which can cause damage during handling. While the paper or plastic bag will protect the furniture from scuffing against the inside of the box, manufacturers in many cases may relying solely rely on the box to protect the product from impacts and vibration. The box utilized in Figure 2(a) does benefit the manufacturer by conforming to the shape of the chair to eliminate the use of excess packaging by using a box that is too large for the chair. However, the shape does not increase the density for the shipper since the density is calculated by the outer most dimensions. Also, since the box is multi-level, a carrier may try to load freight on the lower part, to utilize the space lost by the unique package design.

Over the years, manufacturers have been finding ways to cut costs and reduce packaging, which can dramatically affect the protection of the furniture. As shown in Figures 2(g) through 2(i), plastic wraps and limited fiberboard are more common for packaging of chairs. However, this lack of packaging drastically increases the potential for damage. Figures 2(d), 2(e), and 2(f) are upholstered chairs which should be protected from damage not only from handling, but also from the exter-

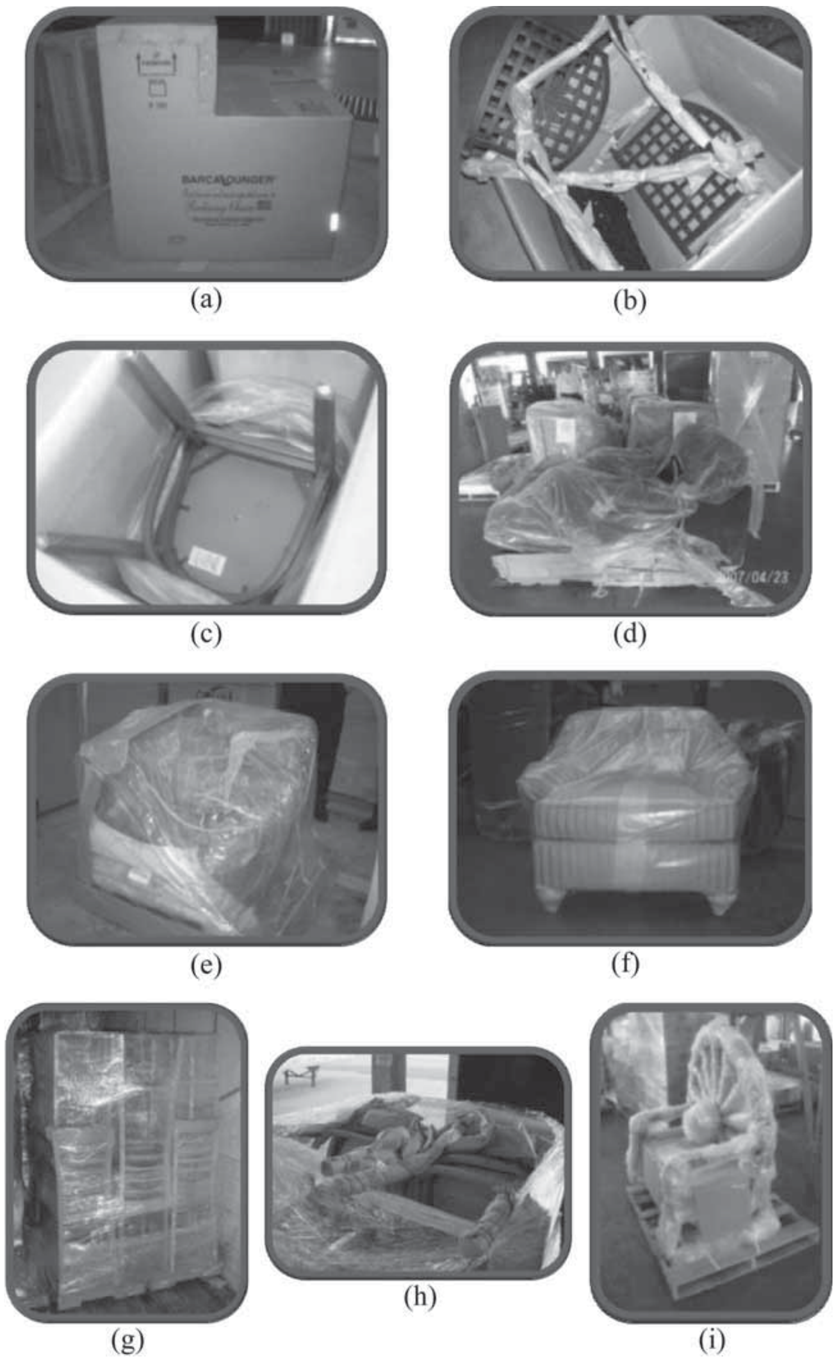

Figure 2. *Shipments of furniture.*

nal environment prevalent due to other products in a LTL shipment. The upholstery can easily be stained or soiled by grease, oil, water, etc. Additionally, the upholstery could be punctured through the plastic by equipment or other freight. While manufacturers may be saving money, they are also increasing the *risk of damage.*

Figure 2(g) is of wood dining room chairs that are stacked and wrapped with plastic wrap on a pallet. While the pallet does help to facilitate handling and the chairs are unitized, the chances of the plastic wrap keeping the chairs unitized during changes in temperature and during handling and vibration on the truck are not very good. If the chairs begin to shift during transit, the plastic wrap may loosen, which would compromise its integrity. The manufacturer of the chairs in Figure 2(h) did wrap the legs and backs with Kraft paper to help prevent any damage that would not be prevented by the plastic wrap. However, if the load were to fall or be impacted, the paper would not do much to prevent major damage.

Figure 2(i) is a bench that is also tendered on a pallet, however, the shipper utilized bubble wrap to protect it. Bubble wrap is not commonly used as an interior packaging for these types of products and should not be used as the primary package, as it was designed as cushioning for within packages of fragile products.

4.0 DAMAGE ISSUES AND PREVENTIVE METHODS FOR SHIPMENTS OF APPLIANCES

Household appliances, such as refrigerators, freezers, washers, dryers, and dishwashers used to be commonly packaged in fiberboard boxes, sometimes on pallets, depending on the size and weight of the product. However, over the last few years, manufacturers have been reducing their packaging costs on these items by utilizing plastic wrap packages and trying to address sustainability initiatives by reducing packaging. These packages generally consist of foam or fiberboard corner and edge protectors, strapping, pallets, paper and plastic wraps. Units are generally attached to a pallet and the faces of the products do not have any protection other than the plastic wrap making them susceptible to damage on contact with other freight. Examples are shown in Figures 3(a), 3(b), and 3(c). Motor carriers have indicated that the reduction in packaging materials has compromised the integrity of the packages and leave appliances more susceptible to damage.

Figures 3(b) and 3(c) are of refrigerators, one in a damaged fiber-

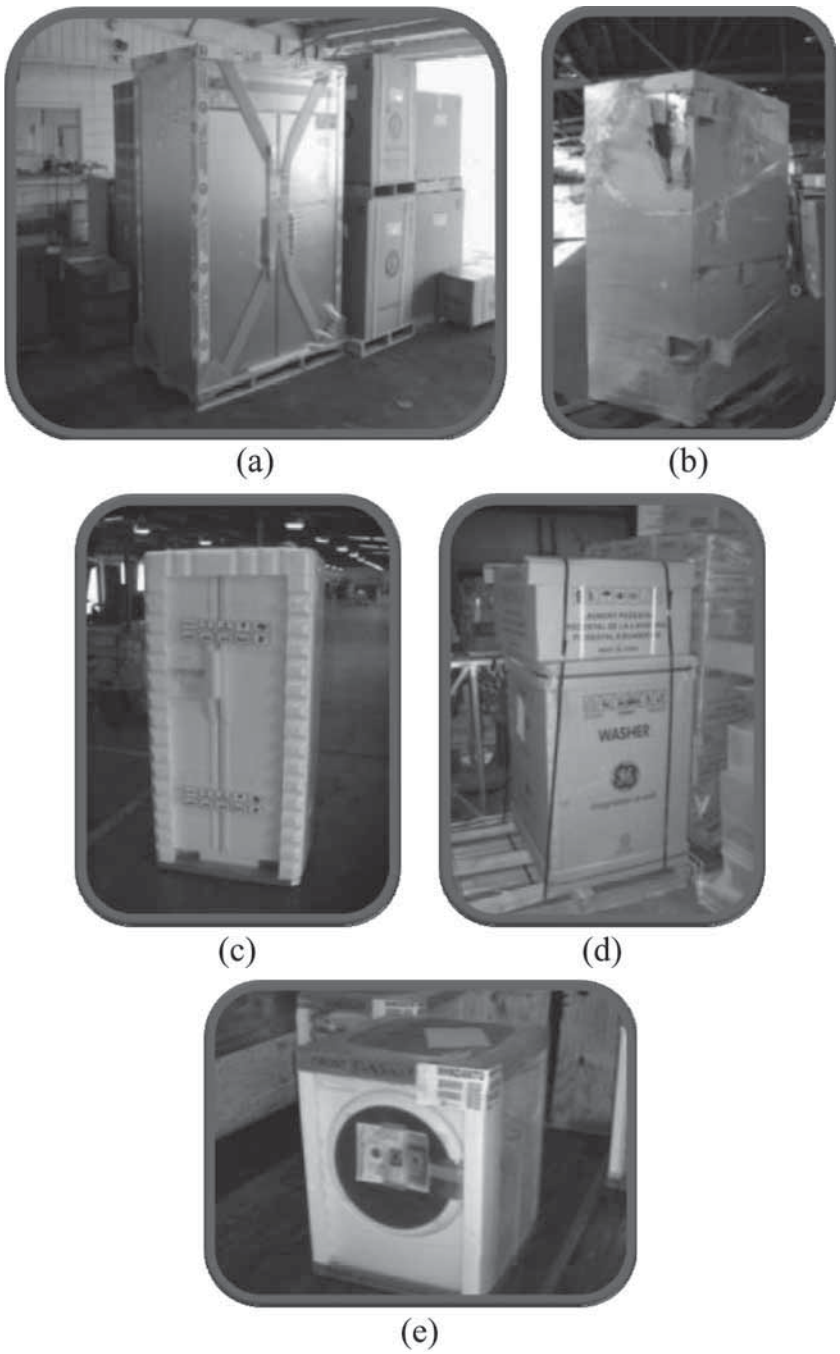

Figure 3. *Shipments of appliances.*

board box and the other in a plastic wrap package. While the box is ripped and the refrigerator *may* be damaged, if that unit had been shipped in a plastic wrapped package, there is little doubt that the refrigerator would not have suffered severe damage. One of the important functions of a package is to protect the product, even if it is ripped and damaged, as in Figure 3(b), as long as the product itself is not damaged. One of the benefits in utilizing the plastic wrap packages is that they are generally shipped on pallets, which facilitate mechanical handling with minimum manual or human interaction. When shipped in boxes and not on pallets, handling with mechanical equipment such as fork trucks is difficult.

The washer shown in Figure 3(d) is packaged in a fiberboard box and strapped to a pallet. However, the pallet is too large for the washer, so there is a lot of unused space on that pallet, and the pallet is not constructed in compliance with Item (Rule) 265 of the *NMFC.* Additionally, the load is not centered on the pallet causing it to be off balance and difficult to handle. Therefore, the carrier may load freight on that pallet in order to utilize the space or may have issues with safe handling. Since the washer is in a box, the washer is better protected from damage by freight loaded adjacent to it. However, if freight that is sharp is loaded next to the washer as shown in Figure 3(e), the plastic wrap will do very little to protect against that freight and the washer sides may be dented or scuffed.

Additionally, there are very few commodities in the *NMFC* that permit shipment in plastic wrap packages. Therefore, if manufacturers are utilizing this method of packaging and not complying with the minimum packaging requirements of the *NMFC*, they may be subject to denials of damage claims based on insufficient packaging or different tariff rates and classification.

5.0 DAMAGE ISSUES AND PREVENTIVE METHODS FOR SHIPMENTS OF BOXED FREIGHT

Fiberboard boxes are probably the most commonly used forms of transport packaging today. Boxes may be used as primary, secondary, or even tertiary packages due to their strength and flexibility for many applications. *NMFC* Item (Rule) 222 defines the construction, strength, and marking requirements for fiberboard boxes and is considered one of the industry accepted standards for truck shipments. The *NMFC* does not, however, specify how freight should be stacked and unitized on

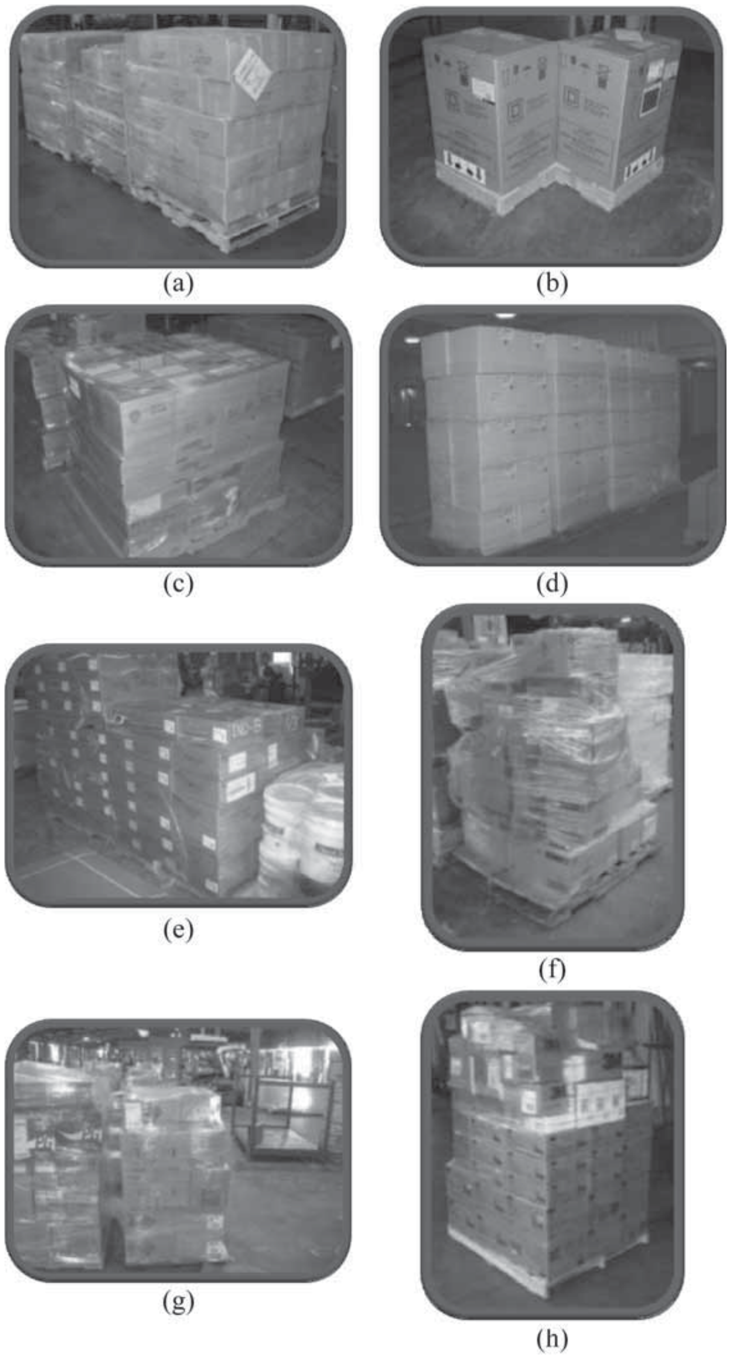

Figure 4. *Shipments of boxed freight.*

pallets for easy stowing. One thing that has been reiterated throughout this document is the importance of flat load-bearing surfaces so that carriers can stack freight and utilize as much of the trailer as possible. However, in the LTL environment, manufacturers do not always ship nice, square pallets of boxed freight due to the variation in product shapes and sizes that are to be delivered to different customers.

Figures 4(a), 4(b), and 4(c) show how unitized boxed freight approximately four to five feet in height, enables a carrier to stack other smaller freight on top of them. While the units in Figures 4(a) through 4(c), provide a flat top surface, the height can restrict the type of freight that can be loaded safely on top of them.

On the other hand, the units depicted in Figures 4(d), 4(e), and 4(f) are representative of how many manufacturers ship out their products, based on their customers' needs. It's easier to unitize everything, even if it creates a pyramid-shaped pallet, rather than splitting the freight up. However, this type of stacking causes inherent stowing issues for the carriers. They are not able to stack freight on top and they may not be able to load that unit on other freight, depending on the total height and available space.

The improper use of plastic wrap can greatly hinder the integrity of a unitized load. The units in Figures 4(g) and 4(h) show plastic wrap holding the freight together. However, if the plastic wrap does not fully enclose all of the freight and the pallet, the unit can easily shift during handling and transit, or slide off the pallet altogether. When stacking boxes four feet and higher, it is imperative that appropriate means are used to insure the freight will not shift or the unit will not fail (collapse) for the safety of handlers, as well as preventing damage to the freight.

6.0 CONCLUSIONS

The study concludes the following:

- Packaging and loading methods are critical in reducing damage and injury during transportation and handling of LTL shipments.
- LTL shipments must be properly blocked and braced with other packages or using load securement methods such as straps, retaining bars, air-bags, or dunnage.
- Loads will shift in LTL shipments if void spaces exist in filled trailers. Proper sized pallets of appropriate strength should be used for unstable loads.

- LTL shipments produce significantly high level of vibration during transport as compared to fully loaded trailers, and as such must be tested to higher levels of pre-shipment testing.
- Stretch-wrap should be applied integrally with the pallet to prevent unitized load from shifting off the pallet.

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Effect of Varying Sled Configurations on the Coefficient of Static Friction for Corrugated and Solid Fiberboard Using the Incline-Plane Method

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ABSTRACT: Amongst one of the most important physical properties of paper based packaging substrates is their resistance to normal forces when two of these surfaces rest on each other. This property known as the coefficient of friction (COF) is described as the measurement of resistance to friction. Standard test methods have been developed to measure COF values to obtain consistent results. Though sled configurations are recommended by various standards for the incline-plane method of measuring COF, studies reporting the effect of variations for the same are lacking. The purpose of this investigation was to compare static COF of corrugated fiberboard and linerboards obtained from several sled configurations using the incline-plane method. This study considered nine different sled configurations and two sample orientation angles to determine coefficient of friction for three types of materials—C and E-flute corrugated fiberboard and a linerboard. The results indicate that the material type, sled dimension and weight did not have a significant effect on the coefficient of friction values, obtained from incorporating different sled configurations during testing. The orientation of sample material in relation to the sled had a significant contribution in affecting the coefficient of friction value for both E-flute and linerboard material.

1.0 INTRODUCTION

THE various properties of paper based substrates for packaging applications can be summarily categorized as physical, optical and strength related. While properties such as basis weight, caliper, dimensional stability, friction and smoothness fall under the physical characteristics; brightness, fluorescence, gloss, opacity and color are commonly included in the optical characterization [1]. Properties such as

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burst strength, compression strength, hardness, tear resistance and wet strength are included in the strength category of material properties [1].

Amongst one of the most important physical properties of paper based packaging substrates is their resistance to normal forces when two paper, paperboard or corrugated fiberboard surfaces rest on each other. This property known as the coefficient of friction (COF) is described as the measurement of resistance to friction as related to the effect of how smooth or rough a surface is to prevent material from slipping across the surface [2]. It is the ratio of the friction force resisting movement of the surface to the force applied normal to that surface i.e., the weight of the material above that surface. Static and kinetic friction are the two commonly measured components of friction. While static friction is the force resisting the initial motion between surfaces, kinetic friction is the force resisting motion when sliding at constant speed is already underway.

The COF of packaging materials is indicative of how packages made from these materials will perform during several critical applications. There can be several problems due to the COF being too high, too low or inconsistent. These problems could include roll winding and rewinding problems, rolls telescoping during transit, problems with web tracking and print registration, registration errors in die cutting or converting, corrugator runnability problems, undesired sliding on conveyor belts, stack and pallet instability, etc [3].

Depending upon the end use, paper is treated to two categories of coatings—pigmented and functional [1]. Pigmented coatings are usually applied in-line with the papermaking machine to offer glossy, white and smooth surface for printing. The functional coatings, on the other hand, provide a barrier of lacquer, varnish or plastic and are applied post the papermaking process. While the lacquer and varnish are applied after printing to improve ink gloss, contrast and image detail, plastic extrusion coatings typically provide gloss and improved moisture barrier and heat sealability. Though sizing agents included in the furnish preparation prior to papermaking increase liquid resistance of paper, they are not referred to as functional coatings but are classified separately simply as sizing [1].

Frictional characteristics of paper are also important when designing a package. Packages are usually shipped stacked on top of one another and the orientation of the paper determines the friction. According to Maltenfort, corrugated box surfaces need to be designed to have an optimum smoothness so that they can be unitized without sliding off of each other and causing damage not only to the boxes but also to the products carried within [4]. Technical Association of the Pulp and Paper Industry (TAPPI) states that a high COF of one surface of paper or paperboard (containerboard) to itself means that containers having that surface will tend to resist sliding in unit-loads, while a low COF may indicate potential problems with the packages slipping from the load [2].

Friction may also increase in printed paper as corona discharge treatment in air is found to produce a marked increase in COF of newsprint due to surface oxidation effects [5]. To help reduce slippage, frictionizing agents may be added to the paper to increase friction. This is done when paper or corrugated boards are subjected to slick surfaces or high angles of incidence. Factors that change the COF on paper are moisture, the chemical composition of the surface or material, the weight being applied, and any flaws in the orientation of the grain [1].

Coatings are used in the paper and corrugated industry frequently for various applications, to replace non-recyclable wax coatings as an example [6]. Coatings are used to protect and enhance the external surface of the package and alter the appearance of the package by making it stand out. An optimum coating protects the package from the rigors of assembly, shipping and distribution, safeguarding it from fingerprints, abrasion and scuffing. The most common coatings used in the packaging and paper industry are ultraviolet and aqueous coatings [7]. The coatings are used as a protective layer and the type of application determines which of the two coatings is the most suitable. The coatings can be sprayed on during the manufacturing of the paper based product, and dry almost instantaneously.

The composition of aqueous coatings is 60% water and 40% solids [7]. During the drying process of this coating, the liquids evaporate or are absorbed by the substrate, leaving the solids to form a thin film [8]. This is a clear film that is smooth and enhances the properties of the external surface of the package and increases hardness. Aqueous coatings are used for applications such as food packaging, in-line seal blister packaging, primer and seal coating, and items which will be written on [8]. Though aqueous coatings are generally cheaper than the ultraviolet variety the latter provides better characteristics and benefits.

Ultraviolet (UV) coatings are 100% solid solution and instead of heat drying are light cured [7]. The solids in this coating cross link to form a durable plastic film that provides unparalleled gloss and hardness [8]. This coating also offers a broader range of finishes than aqueous coatings, including options such as metalized flakes or pearlized pigments.

The coating can be applied during the production of the package or later on at a different stage. The benefits of applying the coat during production are reducing cost, increasing finish quality, and increasing the rate to finish the material. As stated earlier, UV coatings are more expensive than aqueous, but are more beneficial in applications such as those requiring ultimate gloss, ultimate hardness, non-absorbent print surfaces, point-of-sale displays for the enhanced appearance and for spot coating. UV coatings can be applied over ink to protect the color and appearance and can provide various degrees of smoothness.

Whenever a material or coating is added to the surface of a paper based material the COF is altered. Although smoothness and glossiness of packages are beneficial to the package appearance, it also makes the package more susceptible to slide during shipping, and the contents of the package can be damaged. Coatings can protect the contents from the environment, abrasion, and from scuffing. The COF varies by coating used, the thickness of that coat, and the surface the material is in contact with. Coatings can be made to have a certain COF based on the customer requirements and standards. This is beneficial for shipping and the different environments the paper based material will encounter.

The standard approach to measuring friction as related to paper based substrates involves two fundamentally different methods—the horizontal-plane and incline-plane methods. In the former method, a sled is pulled horizontally on a table by a string. The COF is measured using this method from the equation $\mu = F/N$, where F is the force in the string and N is the normal force [4]. For the incline-plane method, a sled is placed on a flat surface and the surface is inclined gradually with a constant angular velocity till the sled begins to slide. The COF in this case is measured as $\mu = \tan a$, where a is the angle at which the sled begins to slide [2].

Though little work has been reported for friction as related to paper, studies related to the impact of sled footprint and mass for the incline-plane methodology are even scarcer. This study focuses on this aspect. Table 1 lists some of the common standard methods for the paper industry used to measure friction for paper.

As is apparent from Table 1, there are a variety of test conditions available amongst the test methods listed. The two sled related characteristics important in determining the coefficient of static friction are its mass and footprint. While the former is relevant to the normal forces, the latter is related to the contact area between the two surfaces. Sled footprints and weights as recommended by various standard test proto-

Table 1. Common Standard Test Methods for Friction Measurement for Paper.

Method	**ASTM 3247**	**T 815**	**T 816**	**T 549**
Material	Corrugated & solid fiberboard	Paper, corrugated and solid fiberboard	Corrugated & solid fiberboard	Writing & printing paper
Sled's Apparent Contact Area (mm × mm)	62.5 x 62.5	90 x 100	63.5 x 63.5	63.5 x 63.5
Surface Pressure (kPa)	3.44	1.4	3.5	0.48
Backing	Hard	Soft	Hard	Soft
Sliding Distance (mm)	62.5	25	63.5	130
Pulling Rate (mm/s)	2.54	1.5°/s	2.5	2.5
Slidings				
Number	3	3	3	1
Static or Kinetic	3rd static value	3rd static value	3rd static value	static & kinetic

cols for different applications vary. For example, TAPPI T815 recommends an 89 mm × 102 mm footprint and 1300 g mass for fiberboard whereas ASTM D202 recommends a 64 mm × 76 mm footprint and 235 g mass for electrical insulating paper.

This study evaluated the effect of varying sled contact area or footprint as well as the mass of the sled on the COF for corrugated and solid fiberboard using the incline-plane method.

2.0 EQUIPMENT, MATERIALS AND METHODS

The scope of this study involved studying the effect of varying sled footprint and mass on the COF values for corrugated and solid fiberboard using the incline-plane method. TAPPI test method T815 was used for the study.

2.1 Equipment

A Model 32-25 coefficient of friction tester (Figure 1) from Testing Machines Inc. (Ronkonkoma, NY, USA) was used for this study. The equipment conforms to the TAPPI T815 standard and allows the incline-plane to move between 0° to 80° angle and increase at the rate of 1.5° ± 0.5° per second. The incline-plane is automatically stopped as the test block begins to slide through a photo-optical sensor mechanism.

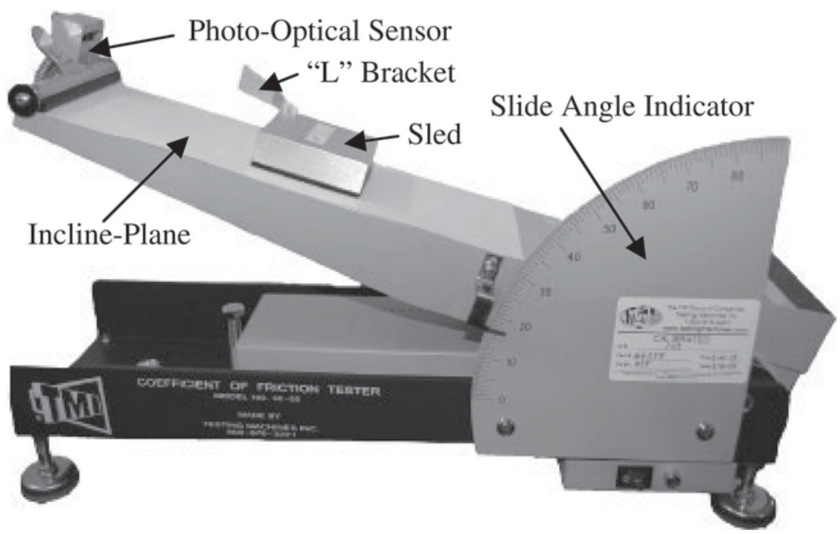

Figure 1. *Model 32-25 Coefficient of Friction Testing Machine.*

2.2 Materials

Nine different sleds varying in footprint and mass were constructed (Table 2 and Figure 2) to study the effect of variations in footprint and mass on the COF values. These sleds were machined to within ± 0.1 grams of the designated weight. The base sleds (A-1, B-1 and C-1) were equipped with precision ground, 0.64 cm (diameter) by 2.54 cm (height) dowel pins (Figure 2) to stack additional plates to increase the overall weights, in 25% increments, of the sleds. As shown in Figure 2 the base sled (M1) represented a sled weight 25% lower than standard sled weight (M1 + M2). Similarly, a sled weight of 25% higher than standard sled weight was represented by base sled (M1) mounted with additional weights (M2 + M3). One 2.54 cm aluminum "L" bracket (Figure 2) was attached to the sleds to ensure proper triggering of the photo-optical sensor on the friction tester. A 3 mm thick silicone rubber pad was attached to lower surface of the base sleds as per the requirements of TAPPI T815 (Figure 2). Unbleached C-flute (4.76 mm caliper) and E-flute (1.59 mm caliper) corrugated fiberboard and solid fiberboard (0.51mm caliper) were used as the samples for this study.

2.3 Methods

All test specimens were preconditioned at 30% ± 2% relative humid-

Table 2. Sled Specifications for the Study.

Sled	Footprint	Mass
A-1	64 mm x 127 mm	703 g (25% lower)
A-2	64 mm x 127 mm	938 g (standard)
A-3	64 mm x 127 mm	1173 g (25% higher)
B-1	51 mm x 102 mm	561 g (25% lower)
B-2	51 mm x 102 mm	749 g (standard)
B-3	51 mm x 102 mm	937 g (25% higher)
C-1	38 mm x 76 mm	419 g (25% lower)
C-2	38 mm x 76 mm	560 g (standard)
C-3	38 mm x 76 mm	702 g (25% higher)

ity (RH) and 23 ± 1.0°C for 24 hours and conditioned at 50.0% ± 2.0% RH and 23.0 ± 1.0°C for an additional 24 hours. The testing atmosphere was maintained the same as for conditioning. This was in accordance with TAPPI T402 [10].

The outcome of interest was the COF. The predictors of interest were sled dimension (three levels: 38 mm × 76 mm, 51 mm × 102 mm, and 64 mm × 127 mm), sled weight (three levels: standard, 25% lower than standard, 25% higher than standard), and orientation angle (2 levels: 90° and 180° for flutes in corrugated fiberboard samples and machine/cross directions for solid fiberboard) of the material to the sled. According to TAPPI T815 to maintain data precision it is recommended that

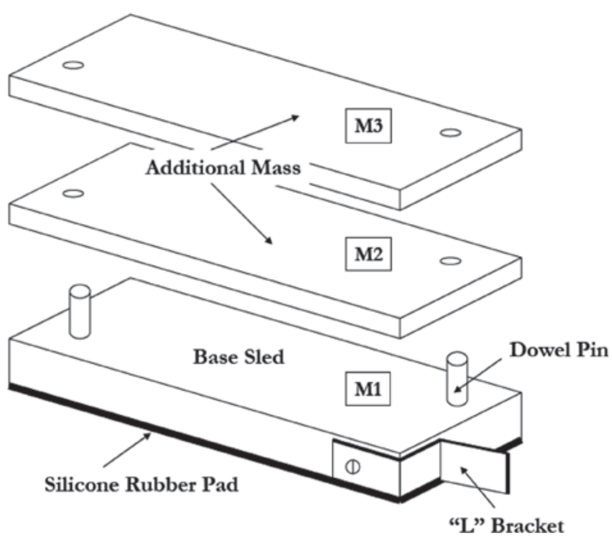

Figure 2. *Experimental sleds used in the study.*

COF measurements should be an average of five replicates. Coefficient of friction measurements for C-flute corrugated and solid fiberboard were replicated eight times for each sled combination (Table 2) and orientation angle. Whereas, COF measurements for E-flute corrugated board were replicated six times for each sled combination (Table 2) and orientation angle. The data for the three materials (linerboard, E-flute, and C-flute) were analyzed separately using analysis of variance. TAPPI T815 test procedure was followed for conducting all coefficients of static friction tests [11].

3.0 RESULTS AND DISCUSSION

Standard test methods as seen in Table 1 have been developed to measure COF values to obtain consistent results. Irrespective of the method implemented to determine COF values, it has been reported that there could be a difference in COF values as high as 50% between lab to lab facilities [3]. Inconsistencies may also arise in data collection as a result of sled foot print and sled mass utilized during testing. The standard test method by TAPPI T815 makes a note that COF values is a ratio between frictional force and the normal force being applied by the mass (sled weight) therefore COF values are independent of the sled weight [11]. However it is recommended that a mass of 1300g with sled dimensions of approximately 90 mm × 100 mm be utilized during testing to obtain consistent COF values. Therefore, it remains to be identified if varying sled weight varies the measured COF values of the same paper material. Another critical component of interest, in relation to measuring COF values for corrugated fiberboard and linerboard, is the orientation of the flute and/or grain direction in relation to the sled. It is expected that the COF values may differ when the sled is placed in the same direction of the flute or grain compared to a sled placed at a right angle to the flute or grain direction.

The incline-plane test method by TAPPI T815 does not mention the recommended sled orientation in relation to the flute direction of corrugated board or grain direction of a liner board. For that reason it is necessary to determine if the sled orientation in relation to the flute and/or grain direction is of any consequence, while measuring COF of a paper based material. Some studies report that surface roughness may or may not affect COF. A study has indicated that a rough paper surface leads to higher COF than a smooth paper surface [12]. On the contrary some studies reported that COF is independent of surface roughness

[13, 14]. This suggests that while determining COF of paper based material the surface properties may not be necessarily the only component contributing towards COF. There seems to be a collective effect of various paper properties and experimental setup while determining the COF values of a paper based material. Therefore the three components, sled dimension, sled weight and orientation of flute or grain direction in relation to the sled, was the focus of interest in this study, to verify their effects on COF values of three different materials.

Prior to analyzing the collected data it was expected that increasing contact area between the sled and sample material would produce a substantial variation in the COF values irrespective of the type of material. Conversely, it was inferred from Figures 3(a), 4(a) and 5(a) that varying contact area between sled and sample material does not necessarily produce inconsistent COF values for each material type. This suggests that increasing or decreasing the contact area by altering the sled dimensions may not have a considerable effect on the COF values. Similarly by varying the sled mass it was anticipated that COF values may differ for the same material. However, according to Figures 3(b), 4(b) and 5(b) the COF values did not vary considerably with increasing sled weight. This ascertains that COF values are independent of the sled weight, as it is a ratio between frictional force and the normal force being applied by the mass.

A separate analysis of variance was performed for the three materials (linerboard, E-flute, and C-flute), with COF as the dependent variable. The three predictors selected were sled dimension (64 mm × 127 mm, 51 mm × 102 mm, and 38 mm × 76 mm), sled weight (standard, 25% lower than standard, 25% higher than standard), and orientation angle of the material to the sled (90° and 180° for flutes in corrugated fiberboard samples and machine/cross directions for solid fiberboard).

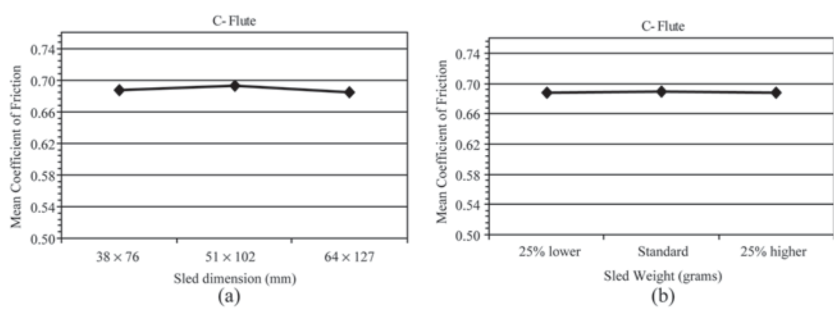

Figure 3. *Effect of sled dimension (a) and sled weight (b) on COF values of C-Flute corrugated board.*

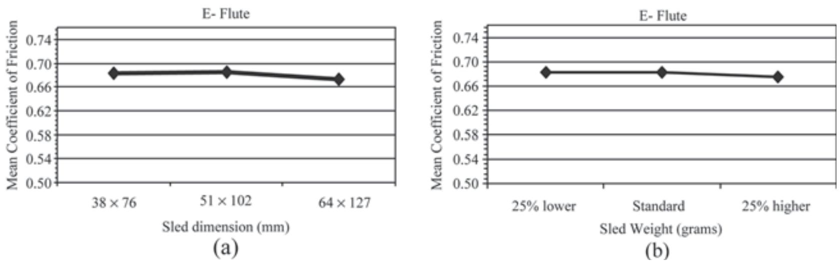

Figure 4. *Effect of sled dimension (a) and sled weight (b) on COF values of E-Flute corrugated board.*

Sled dimension and sled weight did not have a consequential effect on the COF values for all three materials. Coefficient of friction for both linerboard and E-flute were found to be significantly affected by the orientation angle ($p < 0.05$) (Tables 3 and 4). Whereas, the sled dimensions and sled weight did not contribute as significant predictors of COF as shown in Tables 3 and 4 ($p > 0.05$). It was observed that the 90° orientation had a higher mean COF than the 180o orientation for both linerboard (Figure 6) and E-flute materials (Figure 6). The mean COF for linerboard was between 0.16–0.18 higher ($p < 0.05$) for the 90° orientation than the 180° orientation. Similarly, for E-flute, the mean COF for the 90° orientation was higher than the 180° by 0.10–0.13 ($p < 0.05$). However, for C-flute sled dimension, sled weight and orientation angle did not have any significant effect on the COF ($p > 0.05$) (Table 5).

4.0 CONCLUSION

This study was undertaken to investigate the effect of varying sled footprint and mass on the coefficient of friction values for corrugated and solid fiberboards using the incline-plane method. All testing was

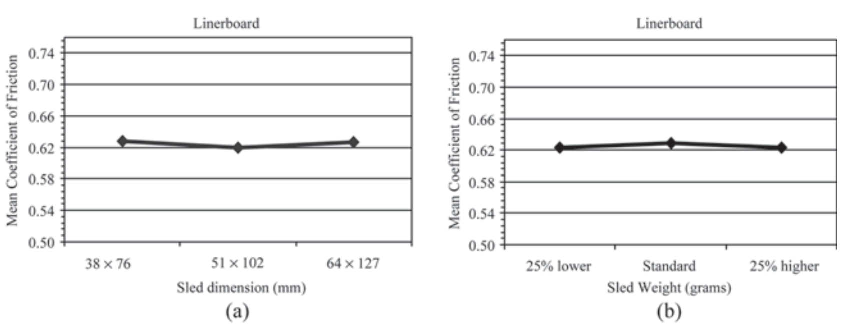

Figure 5. *Effect of sled dimension (a) and sled weight (b) on COF values of linerboard.*

Table 3. Parameter Estimates from Analysis of Variance for Factors Predicting Coefficient of Friction, for Linerboard; N = 144.

	Estimate	SE (Estimate)	p-value
Constant	0.624	0.003	< 0.0001
Sled dimension (Reference = 64 mm x 127 mm)			
38 mm x 76 mm	0.003	0.005	0.512
51 mm x 102 mm	–0.005	0.005	0.250
Sled weight (Reference = standard + 25%)			
Standard – 25%	–0.002	0.005	0.656
Standard	0.004	0.005	0.412
Material orientation to sled (Reference = 180°)			
90°	0.085	0.003	< 0.0001

conducted as per the TAPPI T815 test methodology except for the recommended sled specification. The purpose of this investigation was to compare static COF of corrugated fiberboard and linerboard obtained from several sled configurations using the incline-plane method. This study considered nine different sled configurations and two sample orientation angles to determine coefficient of friction for three types of materials. The materials considered for this study were C and E-flute corrugated fiberboard and a linerboard. The results indicate that irrespective of the material type, sled dimension and weight did not have a significant effect on the coefficient of friction values, obtained from incorporating different sled configurations during testing. The orientation of sample material in relation to the sled had a significant contribution in affecting the coefficient of friction value for both E-flute and linerboard material. This variation was observed in all nine sled con-

Table 4. Parameter Estimates from Analysis of Variance for Factors Predicting Coefficient of Friction, for E-flute; N = 108.

	Estimate	SE (Estimate)	p-value
Constant	0.679	0.0005	< 0.0001
Sled dimension (Reference = 64 mm x 127 mm)			
38 mm x 76 mm	–0.007	0.007	0.310
51 mm x 102 mm	0.005	0.007	0.485
Sled weight (Reference = standard + 25%)			
Standard – 25%	0.002	0.007	0.729
Standard	0.003	0.007	0.637
Material orientation to sled (Reference = 180°)			
90°	0.059	0.005	< 0.0001

Table 5. Parameter Estimates from Analysis of Variance for Factors Predicting Coefficient of Friction, for C-flute; N = 144.

	Estimate	SE (Estimate)	p-value
Constant	0.688	0.003	< 0.0001
Sled dimension (Reference = 64 mm x 127 mm)			
38 mm x 76 mm	–0.001	0.004	0.814
51 mm x 102 mm	0.004	0.004	0.234
Sled weight (Reference = standard + 25%)			
Standard – 25%	–0.0003	0.004	0.925
Standard	0.001	0.004	0.833
Material orientation to sled (Reference = 180°)			
90°	0.003	0.003	0.274

figurations using the incline-plane test method. However, coefficient of friction values for C-flute corrugated board was not significantly affected by the various sled configurations and orientation angle of sample material during testing. These findings suggest that varying sled configurations to measure static coefficient of friction may not generate substantial variation in the results using the incline-plane test method. The orientation angle of test material must be reported while stating the

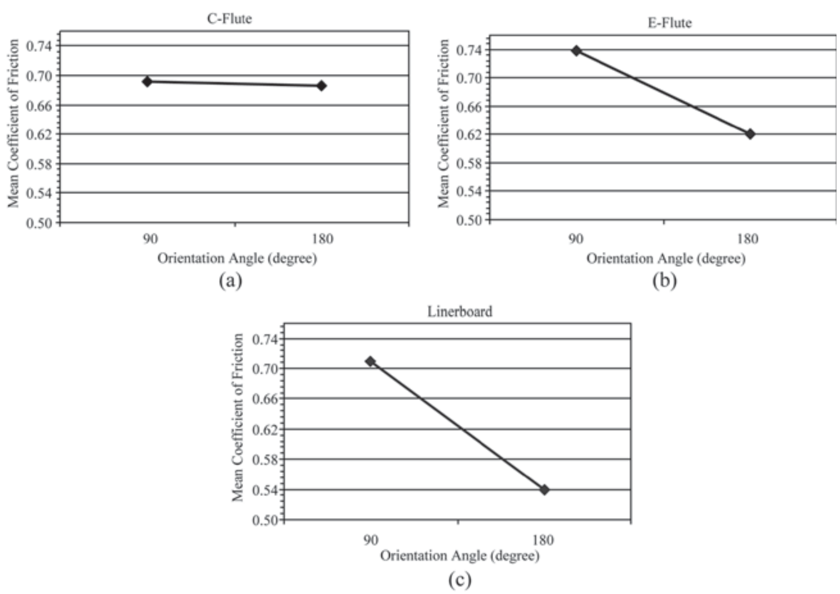

Figure 6. *Effect of sled orientation in relation to flute and grain direction on COF values of C-Flute, E-Flute corrugated boards and linerboard.*

static coefficient of friction value of a paper based material as it can affect the obtained results.

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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 = 14	285	53

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