Shock Transmissibility of a Palletized Load Caused by Forklift Truck Handling

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Abstract

There is an exhaustive amount of research done on vibration transmissibility. However there is a lack of information about shock transmissibility. There currently is no research or studies to prove how shock affects the contents of a unitized pallet load of products, until now. Millions of dollars in damages are pointlessly thrown away each year due to improper forklift handling of products. Similarly, agricultural products are highly susceptible to damages and bruising which leaves the product undesirable to consumers, leading to its eventual disposal. This paper aims to study exactly how agricultural products are damaged when a unitized pallet load is struck, dropped, or similarly mishandled by a mechanical forklift truck. The study utilized state of the art real time data recorders to analyze a variety of standardized shock tests commonly found in distribution test cycles published by ASTM and ISTA.

Shock values have been recorded and compared to one another to determine exactly how and where products are being damaged. The study compared the shock dampening potential of full and half-sized pallet configurations. The study determined that the half sized pallet configuration has better potential to dampen mechanical handling in all axes than the full sized configuration. Likewise, the study has also determined that shock travels more in the direction that it was sustained. Lastly, the study has determined that the pallet facing the forklift truck is also considerably more likely to experience damaging levels of acceleration than the side facing away.

Acknowledgements

We would like to send our sincerest gratitude to our technical advisor, Dr. Jay Singh, for his guidance throughout the completion of this project as well as Mr. Patrick Blizinski of Lansmont Corporation for training us on the data recorders operation as well as providing technical support whenever a question regarding the proper instrument operation arose.

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Section I. Introduction

Problem Statement:

Much has been said and written about shock transmissibility and its effects on products and packages. However, this report will serve to examine shock transmissibility and its effect directly on palletized product loads, more specifically, agricultural high volume consumer products such as lettuce, spinach, tomatoes etc. The shock that this report will study is that from direct and indirect forklift truck mechanical handling.

This report will serve to examine three important factors. The primary purpose of this report is to study and map how a shockwave transfers or is transmissible through palletized load. Will a shock wave originating at one corner of the pallet load transfer shock to all components equally or will there be locations of increased response and areas of attenuation or dampening etc? The secondary purpose of this report is to examine the differences in shock transmissibility regarding the two most common palletized shipping configurations. Will one prove more resistant to forklift truck mechanical handling? The tertiary purpose of this report will review which of the ASTM and ISTA mechanically handling simulations has the most severe impact on palletized products.

This data will prove invaluable to warehouse stores, corrugated converters, and the distribution environment as a whole. There is currently no study that examines exactly how each particular location within a palletized load is effected by different shock impulses. The data that is gathered will give these sectors a better understanding of how different components of the product pallet system are affected. Theoretically, the data collected in this study could prove to change the way product and shippers are stacked in a palletized load.

Needs:

The end user of this data needs to have a clear understanding of how mechanical shock originating on the side, corner, vertical edge, and vertical face of a pallet transfers energy throughout the combined volume of a palletized unit including each face, side, and corner of the shippers involved. The end user of this data similarly needs to have a clear understanding of how the full sized pallet load footprint and half size pallet load foot print differ in their ability to transfer and dampen/attenuate shock originating on the side, corner, vertical edge and vertical face of a pallet. The end user of the data will also have a clear understanding on how each type of commonly used impact test effects the two most commonly used pallet shipping orientations (full-sized and half-sized).

Identified Need	**Weight of Importance (1-4)**
Understanding of how shock travels through a palletized load	4
Understanding of how pallet stacking patterns are effected differently	4
Understanding of how different mechanical shocks effect palletized loads differently	3

Related Work:

In the mid 1990's D. C. Slaughter, R. T. Hinsch, J. F. Thompson performed a similar study regarding vibration transmissibility through a palletized load of Bartlett Pears. Their data provided interesting conclusions in that vibration can actually be amplified through a paperboard pallet load at certain frequencies. Their data showed that the boxes that were higher up on the stack, or a higher tier became airborne and experienced more acceleration and damage at certain frequencies around 40 Hertz. The team also tested traditional column stacking and cross stacking pallet configurations. Their research is encouraging as it proves that much can still be learned about how these invisible forces interact with products in ways that contradict what we traditionally assume. Their data proved extremely valuable for all parties involved in the distribution of pears as packaging could then be developed to attenuate the given frequencies and thus preventing bruising in transit.

Objectives:

By the end of this report the reader will have a definite understanding of how different mechanical shocks are transmissible throughout the two most common types of palletized load. The data will be of significant importance and value to any person or entity that deals with the packaging and distribution of palletized loads.

Contribution:

This data will contribute to reducing the amount of product damage to any palletized commodity. This data will allow corrugated converters and corrugated designers to develop better means of packaging and protecting products while in transit that can dampen specific shocks and protect the pallet system as a whole.

Scope of Project:

The scope of this project will focus primarily on high volume agricultural products such as tomatoes, spinach, and lettuce as well as more expensive agricultural commodities such as mangoes, papaya, pineapple, etc. The high volume agricultural products are packaged in the standard "full-sized" secondary shipper and the more expensive products in a variant of the "half-sized" secondary or primary shipper.

The project will use test inputs from ASTM and ISTA specified mechanical forklift truck impacts. The type of commonly used impacts will be compiled and tested in comparison to one another. The impacts effects of shock transmissibility will be recorded using multiple tri-axial accelerometers. The individual transmissibility of each type of shock in both shipping patterns will be recorded. From the data we will be able to draw conclusion in regard to how shock actually transfers through a palletized load.

In addition to the test, two systems must be developed. The first system that must be developed is a means to suspend the accelerometers in the geometric center of a CFBC. This system may include foam and a metal support structure. The second system that must be contained is a means to match each shipper to a commonly observed product weight. The system may utilize sand and or lead shot to simulate the product weight as closely as possible.

Section II. Literature Search

Shock Explained

Shock theory is a subject in which there is a wealth of research and detailed information. Shock theory applies to almost every technical field in one way. For the scope of this project however, the report will keep the elements of shock theory as practical and approachable for all readers as possible. The following will serve as a review of shock theory: Shock is a term that originates from the French Choquer or to “strike against”. As the term implies, shock can be generated by any two or more entities colliding; either accelerated by gravity or another form of mechanical energy. It is defined by the Webster Online Dictionary as a violent shake or jarring concussive occurrence, or the effect of the occurrence.

For the scope of this project the term shock will be defined as a “disturbance in the equilibrium” (Tustin, 2005) of a package-product system resulting from mechanical handling (more specifically from a forklift truck). Shock is experienced as a rapid positive and negative acceleration in a short period of time or duration. Unlike sinusoidal vibration, which may excite one resonant frequency of a package-product system, shock excites all natural frequencies simultaneous. (Tustin, 2005)Following an impact, a system must respond at its resonant frequency, this is a fundamental scientific phenomenon that is inherent to all things. The resonant frequency in which the system responds is dependent on the mass, volume, and density of the system.

Shock Pulse

A shock pulse is characterized by a rapid positive and negative acceleration in a given duration (Optics Arizona, 2010). The most common type of shock pulse observed is the half sine shock pulse in which the object is accelerated and decelerated at near the same rate, with no dwell at peak acceleration. There are other types of shock pulses however such as rectangular, trapezoidal, and triangular pulses which can all be recreated using specialized shock table programmers and equipment.

Transmissibility

Transmissibility is the ratio of dynamic shock output from an object to the dynamic shock input of an object (Optics Arizona, 2010). Typically, the output will be significantly less than the input due to the dampening effect the object has on the impulse. At resonance however, the output can be considerably larger than the input. This can cause catastrophic failure such as the Tacoma Narrows bridge incident in Washington.

Measuring Shock

Shock can be measured in a variety of ways. These methods range from the purely mechanical shock trip indicators to the more elaborate piezo accelerometer/transducer based technologies. The mechanical indicators are typically low cost alternatives to the latter. Mechanical indicators go by the trade names of ShockWatch®, Tip-N-Tell, Tilt(N)Watch®, Drop(N)Tell etc. (Each indicator serves and individual purpose to alert the shipper or receiver of rough handling in transit. Each indicator is typically designed for single use applications and to definitively trip at a certain predetermined peak g threshold of abuse. The mechanical shock trip indicators cost between $1.00-5.00 depending on complexity and quantity of order (U-line 2010). There are also significantly more elaborate mechanical indicators using graphite coated ball bearings to indicate the direction of the shock. Some use dial indicators and spring loaded mechanisms.

Figure 1

Taken From: DbPackaging.com

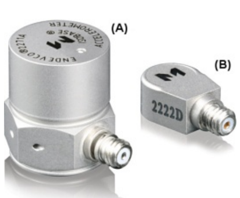


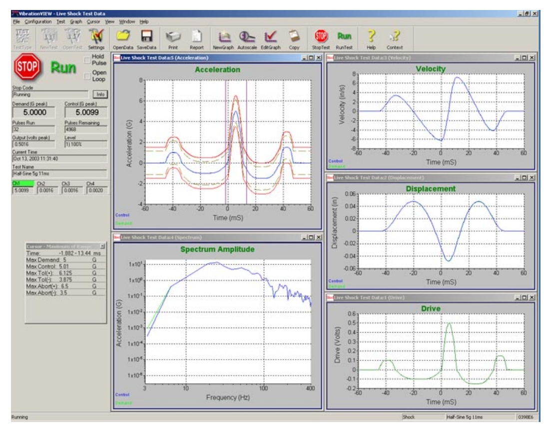
Figure 2

Taken From: SensorMag.com

Peizoelectric (PE) accelerometers are much more complicated. The basic science behind the PE accelerometer is that there is a small preloaded piezo chip that is forced to deform under acceleration. (Tustin, 2005) As the piezo deforms, it emits an electrical charge. The charge can then be amplified and measured. The charge is typically in the millionth of a coulomb range. By dividing the charge by the amount of acceleration experienced, one can determine the sensitivity of the accelerometer in pC/g. Once the accelerometer's sensitivity is determined it can then be used to measure shock and vibration. This is a form of transduction, or converting one form of energy into another. In this case mechanical shock is being transduced to electrical potential energy and then measured for scientific research. [4] Accelerometers come in a variety of different sensitivities. This is useful for obtaining the proper resolution of a shock pulse. The operator should choose the accelerometer with the sensitivity correctly suited for the application or range of peak g's.

For our project we will be using Tri-axial accelerometers. As the name implies the accelerometers will measure acceleration in 3 axes. A Tri-axial accelerometer is actually three highly sensitive single axis accelerometers arranged in different orientations to accurately measure shock in multiple directions (X, Y, Z).

The signal that an accelerometer produces is amplified either by an amplifier or coupling mechanism. Once the gain is increased, the signal can be processed by a data recorder and converted into a waveform using computer software (Lansmont Test Partner). The wave form is a graph of the acceleration (g's) experienced for a given duration (milliseconds). The most commonly observed shock pulse is the half sine waveform. There are other forms of shock pulses which can be recreated using plastic and gas programmers on a shock table; these include trapezoidal, square and triangular wave forms. [7]The collected data is then filtered to produce a cleaner, more defined shock form. This shock form is used to guarantee that a shock test has been performed to customer specifications, or it can be used to simply measure an unknown shock value, which is the case for this project.



Research

Data Recorders

Data recorders are self-contained units that serve a variety of functions. They often contain at least three accelerometers to measure shock and vibration. They also contain the necessary hardware to process and store the information onboard. Instead of having an accelerometer tethered to an amplifier data processor and computer, one can simply place the data recorder in or on the specimen and retrieve the data on a later date. Many data recorders are also capable of measuring temperature, humidity, and time as

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well. The Lansmont Corporation has set the standard for testing equipment and data recorders. Their Saver™ 9X30 is the current industry leading data recorder capable of measuring Tri-axial acceleration, temperature, and humidity in real time for up to 30 days. (Lansmont Corp. 2011) Data recorders offer a convenient self contained, self powered solution to recording almost any type of environmental occurrence.

Shock Test Standards

Almost all package distribution testing has some element of shock testing that the specimens are subjected to. This section will review the commonly used methods to perform shock testing and the type of environments they are used to represent.

Easily the most common type of shock testing is the drop test. In a drop test a package or package product system is dropped from a predetermined height in a certain orientation onto a specified test surface (usually steel or hardwood). These tests are performed in cycles and certain faces, edges, or corners are specified. A pneumatic piston driven drop test machine is typically used to help ensure that human interaction has little effect on the way the package falls. The drop test machine is also vital in ensuring that test results stay consistent between packages and between operators. For example ASTM D 4169-05 uses initial drop testing at the beginning of its test schedules and final drop testing toward the conclusion to simulate packages being mishandled by human hands being picked up and taken to distribution facilities, and packages being delivered. (ASTM International, 2005)Manual handling drop tests are predominantly not monitored with an accelerometer unless specified for a specific application. The client determines the pass fail criteria for their own package product system.

Manual handling drop shock testing however is usually only performed on single package-product systems or less than truck load quantities. If a palletized load of products is to be tested as a single unit, there is a special set of test standards that apply. When discussing the handling of a palletized load as single unit, one is most likely speaking about mechanical handling, as forklifts, order pickers, and cranes may be necessary to move these systems. While a single package may be in the unstable hands of a delivery person, a palletized load is often subjected to mechanical brutalization by the hardened steel tines of a forklift. There are different tests accordingly.

The test standard that has been found to be the most relevant to our project is the ISTA 2 Series. Elements of ISTA2 (ISTA 2J) were specifically designed for palletized quantity loads for warehouse stores such as Sam's club, Costco, food-4-Less, etc. It deals with testing a large quantity of individual systems as a singular palletized load and involves the following types of shock tests (International Safe Transit Association, 2010)

Edge Drop

In an edge drop, the specimen is dropped from a specified height onto an edge. The edge is to make contact with a level surface. A block of wood is in most situations placed under the edge to be tested and then swiftly removed to allow for a free fall. Other methods include propping up the opposite side of the specimen with pieces of wood as well to guarantee the edge of the specimen makes contact as opposed to the under surface.

Corner Drop

A corner drop is similar to an edge drop, only that a corner is propped up instead of an edge. Like in the edge drop, a piece or pieces of wood are used to elevate the corner being tested and the opposite sides of the specimen to allow for direct contact.

Horizontal Impact

In horizontal impact, the test specimen is either accelerated into the test surface, or the test surface is accelerated into the specimen. This can be accomplished with a horizontal impact machine, or by simply driving the specimen into a rigid wall at a specified velocity. The specimen can also be rammed by a forklift that is traveling a specified velocity. Unlike the Edge and Corner drop, gravity has little effect on the horizontal impact test.

Incline Impact

Similar to horizontal impact, incline impact is performed by accelerating the test specimen down an incline into a rigid wall. This is typically performed using an inclined impact test machine. Unlike the horizontal impact test described above, gravity does play a large role in the acceleration of the test specimen. Gravity's affect is directly related to the degree of incline that the test is performed.

Why Forklifts?

Forklifts are the focus of this study, because they are massive immensely powerful machines that have the potential to cause millions of dollars in damage each year. There are almost 40,000 forklift accidents each year in the United States resulting in close to 100 fatalities (OSHA, 2011). According to the Industrial Truck Association (ITA), 90% of the 855,900 forklifts in the United States will be involved in at least one serious injury in their 8 year service life (Industrial Truck Association, 2011). The forklifts' inherent danger is due to their increased structural mass. Forklifts are typically made from cast steel and iron components that can weigh in excess of 5000 lbs (Industrial Truck Association, 2011). Because of the extra mass, a forklift has the potential to cause severe damage at relatively low speeds. A forklift traveling at 5mph can generate the same shock levels as a sedan traveling a 30mph. This being said, forklifts are operated by humans, and as long as there is a human element, mistakes will be made.

Forklift Mechanics

For this study we will be looking specifically at the commonly seen and recognized forklift truck style forklift. This style is also known as the counterbalance forklift truck. It is categorized by its large cast steel frame with the weight stack and hydraulic chain driven lifting tines located on the front end. The forklift truck is driven by a single operator similar to an automobile with a few critical differences (Forklift Briefing UK, 2011)

1) Forklifts are steered by their rear wheels:

By placing the steering wheels at the rear of a forklift, the operator gains a much smaller turning radius that if the wheels were in the front. This tight turning radius is crucial for maneuvering packaged loads through the confined aisles of a warehouse. However, there is a downside to this tight turning radius, it makes the forklift much more unstable in high-speed turns.

2) Forklifts use hydraulic inching pedals instead of clutches.

Forklifts use an inching pedal to disconnect the motor from the transmission. The inching pedal allows the operator to divert engine power to the lifting tines for heavy loads. While the inching pedal is engaged, the brake is engaged simultaneously. This prevents the truck from being moved while the load is being lifted. A dangerous situation can occur if there is a load in the air and the operator unknowingly disengages the inching pedal causing the forklift truck to jerk forward.

3) The forklift center of gravity is variable because the location of a forklift's mass is constantly changing depending on the height and placement of the load and tines, the center of gravity is variable. The higher the forklift tines are in the air, the higher the center of gravity. As the center of gravity of the forklift is increased, the more likely it is to tip over. The variability of the center of gravity in regard to forklift trucks is known as the stability triangle.

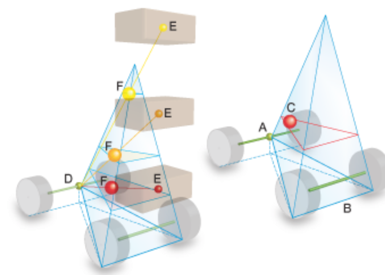


Figure 5

Taken From: ForkliftBriefing.com

With these small but critical differences between an automobile and a forklift truck it is easy to understand how an operator may become comfortable and complacent on the job. It is in these moments of relaxed daily occurrences that a mistake can be made, jeopardizing the safety of the individuals involved and the products they are moving.

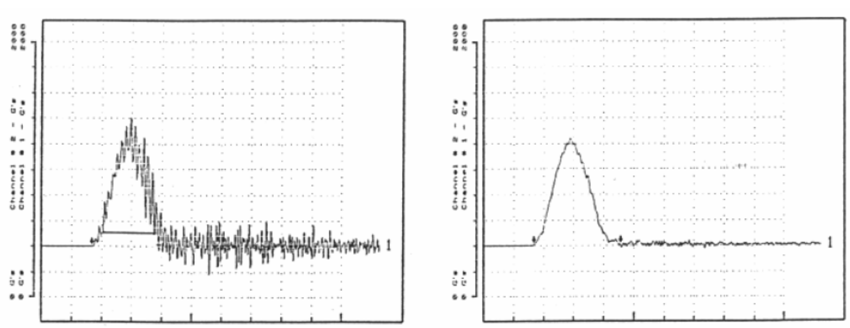
Accelerometer Fixture Issues

Proper accelerometer fixture design will be a critical task in the successful and accurate completion of this study. In order to properly analyze a shock wave traveling through a palletized load, the accelerometers will have to be mounted in a way that accurately records the strength and duration of the force for the area in which they are located. If these criteria are not met, the entire study would be considered inaccurate, unreliable, and of no contribution to the packaging industry.

Huzel, et. al. (1992) states that some of the most important issues to consider when designing a fixture are rigidity and the effect the placement of an accelerometer has on the package characteristics (i.e. weight, rigidity). The first consideration the authors elaborate on is the mounting rigidity of the accelerometer to the package being tested. In other words, the forces being experienced by the packages must be the same forces that are being experienced, and recorded, by the accelerometers. The accelerometers should be mounted to a flat and smooth surface on any axis that the accelerometer will be recording information about. The intention to use tri-axial accelerometers in this study would require that the accelerometers be mounted on flat surfaces on all sides of the accelerometers. Through this method, the accelerometers would not be allowed to rotate or shift, and skew the data recorded.

Another point Huzel, et.al. mentions is how an accelerometer and fixture can have a tremendous effect on package characteristics. Firstly, stiffening in the area in which the accelerometer is mounted to can occur. The more flexible the fixture contact area is, the greater the chance of this becoming an issue and altering the true data. Another way that the accelerometer and fixture combination can affect package characteristics is through adding extra mass and artificially weighting the specimen. By increasing the mass of the package, the force experienced by the specimen will be linearly increased. To reduce the effect of increased mass, the fixture should be made of the lightest material possible that still exhibits the desired rigidity characteristics.

Schueneman (2011) also states some issues that must be considered when designing a fixture for an accelerometer. The largest issue the author identified was the importance of making the accelerometer completely rigid and in sync with the specimen. If the accelerometer is not mounted in such a way that the movement in relation to the specimen is limited, data "chattering" can result. Figure 6 shows the difference in waveforms between a rigidly mounted accelerometer and a loosely mounted accelerometer that is allowed to "chatter".



(Source: Westpak, Inc.)

Figure 6

Schueneman (2011) states that if chattering is not able to be eliminated through a rigid mounting method, software based filters may be used to reduce some of the chattering that is shown on the waveform once the data is recorded. However, filtering can lead to less accurate results and should therefore be avoided if possible. In other words filtering is a quick fix that may get you rough data, but it is not a replacement for a well thought out fixture design that will give reliable and accurate data.

Transmissibility Theory

Transmissibility theory can be applied to many different types of force applied to a broad array of products and packages in the world today. The purpose of this research project is to analyze how a shock wave might transmit through a palletized load of a common commodity product moved by forklift trucks throughout the distribution environment. According to The American Heritage Dictionary (2009), transmissibility can be defined as the ability to convey force or energy from one part of a mechanism to another. In the case of our study, the force that would be conveyed would be a force caused by the collision of part of a palletized load with another object or surface in the distribution environment due to forklift truck handling. The mechanism in the case of this study would be a palletized load of mock club store product.

Many of the past studies done in the area of transmissibility change the type of force, or the mechanism that experiences the force. For example, instead of a shock wave, the force initiated on the specimen could be a vibration frequency, and, instead of a palletized load of club store product, the specimen could be a large medical imaging device.

In a similar study conducted by the United States Department of Agriculture (USDA), the resonant vibration transmissibility characteristics of palletized top loading corrugated containers were analyzed. According to Godshall (1971), one of the largest factors to consider when analyzing the transmissibility of vibration through a palletized load would be the dampening characteristics of the system (i.e. the palletized load.) If there is no dampening in the system, the transmissibility of the system will be infinite. In other words, the force applied to one edge or face of the system will be the exact same force experienced by any other part of the system. Although this concept is being applied to a vibration force in the USDA study, it is reasonable to also apply this concept to studies involving shock forces such as our own. Through the completion of the study of the shock transmissibility of a palletized load due to forklift truck handling, we will gain insight into the amount of damping that occurs in typical palletized loads in the club store environment. Through understanding the degree of transmissibility that occurs in palletized club store load, packages and pallet patterns can be optimized to provide the most desirable combination of damping performance and cost efficiency.

Types of Corrugated Containers

One of the most critical aspects in the testing procedure proposed is the type of corrugated container that is used to hold the accelerometers and be stacked on the pallets. There is truly a plethora of container styles, fluting medium, and sizes. In this section, the most common corrugated containers will be explained, including their uses, advantages, and disadvantages. This information can then be used to help determine the best container for use in the proposed study.

The most common type of corrugated container used to transport commodity goods in the world today is the regular slotted container (RSC). This container is a one piece box that, when folded, has eight flaps of equal width that fold to enclose the container. The fact that all the tabs have an equal width cause the RSC style of box to be one of the most efficient containers to be formed because there is less than 5% wasted corrugate to cut a RSC blank. This type of container requires the use of a manufacturers tab, which can be glued, stitched, taped, or stapled. Similarly, the flaps on the top and bottom of the container are also enclosed in the same ways. The determination for the type of sealing mechanism includes the environmental conditions that the container will be exposed to, the product that the container will be enclosing, and the rigor of the distribution environment that the container will experience. For example, if the container is going to experience very humid conditions or getting wet, adhesive glue would not want to be used because the adhesive is a water soluble polymeric compound. In this case, taping or stitching the manufacturer’s joint and flaps would be a more appropriate solution. (Scheuneman, 2011).

The RSC also acts as the base model for many other types of corrugated containers known in the family termed as slotted containers. Some of these containers would include the overlap slotted container (OSC), the full overlap slotted container (FOL), the center-special slotted container (CSSC), the center special overlap slotted container (CSO), and the center special full overlap slotted container (SFF). These different variations of slotted containers can be used to help add cushioning, strength or a quality image to a container (Scheuneman, 2011).The only difference between any of the many types of slotted containers is the lengths of the top and bottom flaps. The flaps can be made to both meet in the middle, both overlap completely, only partially overlap, and any other combination of these criteria. Due to the versatility in characteristics and the efficiency of production, slotted style boxes are widely used throughout the consumer goods market.

Although slotted containers are a common choice in the distribution market, they are not the only option. Another very popular type of corrugated shipping container used in the distribution of consumer goods, especially non-durable consumer goods, is the bliss box. Although, it is often regarded as a "box" it is actually more correctly defined as a tray because the top is left open. Corrugated bliss containers are made of three pieces of corrugate: One forming the bottom of the tray along with the length sides of the container, and the other two pieces form the width sides of the container. Through the use of three separate pieces of corrugate in the construction of the container, the corners are reinforced resulting in a significant increase in compression strength compared to the slotted containers. Also, to further increase strength, the containers can use a lighter type of material in the center while also utilizing a heavier corrugate board on the edges to further increase compressive strength while also maintaining a relatively low increase in cost (Montague, 2007). The Bliss Style of container is most commonly used in the agricultural industry to package fruits and vegetables (UNCTAD/WTO, 1993).

Just as there are many styles of corrugated containers, there are also many variations in container size and fluting medium. The size of corrugated containers are often made to a standardized footprint (this will be discussed in detail in the following section), however, there are factors specific to different products that will encourage deviation from these standard sizes. Another variation in corrugated containers, the fluting medium, is usually dictated by the strength requirements of the product being packaged. Some of the most common fluting types include A, B, C, E, F. Although all types are used in the industry, C-flute is the most common in the commodity product market (UNCTAD/WTO, 1993).

The wide variety in styles, sizes, and fluting types of corrugated containers commonly used to package commodity goods makes it possible for shock damping, and consequently shock transmissibility, of a palletized load to vary from pallet to pallet. Even though they may be carrying similar products, a pallet loaded with one type of container style will vary in terms of shock transmission from another pallet with a different style of container.

Common Palletized Load Footprints

In an effort to increase the efficiency of the entire distribution cycle, the packaging industry developed common footprints for palletized loads. Created at the turn of the millennium, the Corrugated Common Footprint (CCF) created standardized container footprints as well as interstacking features to help increase efficiency during the loading, warehousing, and shipment of fresh fruits and vegetables on a standard 48-40 pallet (Corrugated Common Footprint, 2011). The CCF is based around the greatest cube efficiency on a standard Grocery Manufacturers Association (GMA) pallet without overhang. Two footprint styles were created. The first, known as a half size configuration, includes 10 containers per tier, with outside footprint dimensions of 15 11/16" x 11 11/16". The second, known as full size configuration consists of 5 containers per tier with outside footprint dimensions of 23 1/2" x 15 11/16". The CCF does not indicate a standard for container heights. This will be determined by the products specific needs. Figure 2 shows the standardized pallet footprints in the half and full size configurations (Corrugated Container Footprint, 2011).

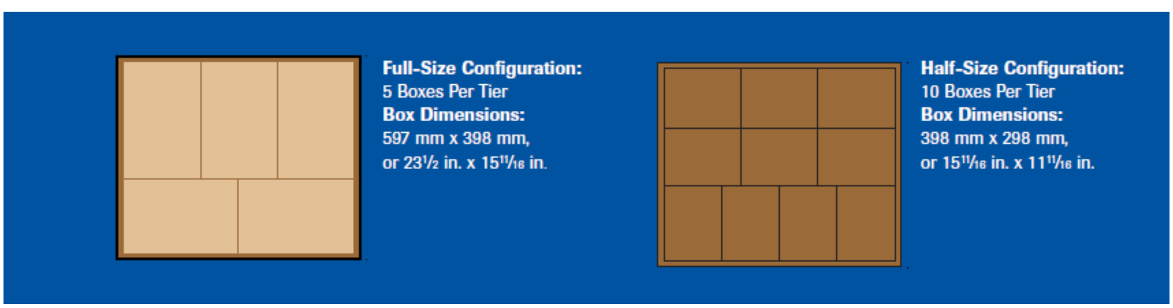


Figure 7

Although the compliance to the standards laid out by the CCF is completely voluntary, it is a widely accepted and practiced standard due to its many benefits. Through a standardized container as proposed through CCF, equipment costs, labor training costs, and shipping costs are all reduced. Also, palletized loads are able to be made more stable and accurate containers are more consistently produced by many different corrugate container manufacturers. Not only does the standardization of containers make local business more efficient, the CCF has also been made in cooperation with European Federation of Corrugated Board Manufacturers (FEFCO) European box standards accepted worldwide. This greatly increases the possibility of international trade and commerce.

Commodity Industry Volume

The usefulness of the proposed study is largely based around the volume of product that it could have an effect on. In order to accomplish this, several bulk commodity product suppliers were researched and volume figures stated. All figures were drawn from Hoover's Company and Industry Database Software.

Costco Wholesale Corporation

2010 Annual Sales (Mil)	$77,946
Number of Warehouse Stores Nationwide	565

Safeway, Inc

Number of Retail Stores	1695
2010 Annual Sales (Mil)	$41,050

Save Mart Supermarkets

Number of Retail Stores	245
2010 Annual Sales (Mil)	$4,900

The Kroger Co.

Number of Retail Stores	3,620
2010 Annual Sales (Mil)	$82,190

Wal-mart Stores, Inc

Number of Retail Stores	8400
2010 Annual Sales (Mil)	$408,214

Section III. Alternatives/Solutions

This experiment is intended to gain a better understanding of the following ideas related to packaging: the experiment aims to definitively prove how a rapid shock pulse travels through a palletized load of agricultural consumer product. The experiment aims to determine which palletized configuration (full or half) attenuates shock better than the other. Finally the experiment aims to examine which of the most common shock simulations or tests proves to be the most detrimental to the palletized product.

Alternative Methods

Standards organizations realize the capabilities of different laboratories are not equal. Therefore, both ASTM 4169 and the ISTA 2series offer a variety of means of completing the same test. For example, a horizontal impact test may be done with the heel of a forklift traveling at a particular velocity, or a horizontal impact test machine, or an incline test machine. The nature of this flexibility allows the project significant fails safes in the event that one or more systems are unavailable. The following is a brief description of methods and their alternatives that could be included in the context of this project.

Horizontal Impact

In horizontal impact, the test specimen is either accelerated into the test surface, or the test surface is accelerated into the specimen. Both methods are acceptable. This can be accomplished with a horizontal impact machine, or by simply driving the specimen into a rigid wall at a specified velocity. The specimen can also be rammed by a forklift that is traveling a specified velocity if the tines are taken off and the heel of the truck is used. Unlike the Edge and Corner drop, gravity has little effect on the horizontal impact tests, so velocity at which impact occurs is much more important than a specified height or distance. Some operators have preferences to the way they perform the test and some customers likewise have a preference to how they want the test performed. For our test, we will most likely be accelerating the forklift into a stationary palletized product-package system. However, in the event of machine failure, we will have a contingency plan in place to switch to another means of testing.

Incline Impact

Similar to horizontal impact, incline impact is performed by accelerating the test specimen down an incline into a rigid wall. This is typically performed using an inclined impact test machine. Unlike the horizontal impact test described above, gravity does play a large role in the acceleration of the test specimen. Gravity's affect is directly related to the degree of incline that the test is performed. Incline testing can usually be substituted for horizontal testing and vise versa. This is useful in that the packaging dynamics laboratory has recently had an incline tester donated.

There are a number of ways to perform these tests. We will start with basic forklift operations if possible, to simulate the damage to the package system as realistically as possible. If there is a problem with the forklift, and it is unable to procure another forklift, we will be able to switch to incline plane or horizontal impact testing.

Pallet Drop Test

In the event that both of the above options are unavailable, it may be possible to substitute a palletized load drop test to generate the shock inputs. A palletized drop test machine holds the pallet similar to a forklift, and then accelerates the specimen flat onto a steel bottom plate. The shock would be traveling from the base of the pallet up, but the nature of the shock transmission should be the same regardless of where the shock originates. In the event that the machine to perform these tests is unavailable, and freight to a nearby test lab is unrealistic, the palletized load can be lifted with nylon webbing or similar rigging equipment and dropped by means of a quick release flat onto the ground or a steel plate from a specified height.

Statistical Model

Experts were contacted to make the experiment statistically sound. The first individual contacted was Dr. Ignatova of the statistics department. Dr. Ignatova assisted in determining the number of boxes, the placement of boxes, and the placement of the data recorders. The second individual contacted was Lansmont instrument specialist Patrick Blizinski. Blizinski spoke from his experience that the best position to place a total of four data recorders would be in opposing corners of the palletized load.

The major independent variable of the experiment is the pallet configuration, either full or half style. The stacking pattern and the higher quantity of smaller boxes are estimated to have more of an effect on shock transmissibility that the type of shock pulse itself. The secondary variable to be tested on both full and half sized configurations is the type of shock (edge, corner, or horizontal.)

Plan for Interpreting Data

The internal clocks on the four data recorders were synchronized to the computer and a stop watch. Synchronizing allows the operators to keep track of what test event is occurring at a given time. Once the tests have been performed and their shock values recorded, it will be our job to interpret the data in an intelligent way. There will be four groups of twelve test sets with three events per set. This data is being generated from the four data recorders in opposing corners. From the data collected by the data recorders closest to the point of impact the severity of the shock can be established. From the data recorders located in the opposing corner from the point of impact we can determine the amount of shock attenuation (absorption) that occurred throughout the palletized load. This model will be followed for edge drop, corner drop, and horizontal impact for both the full and half sized configurations. A minimum of 3 repetitions will be performed for a total of 18 impacts. The data will be input into a spread sheet for organization and formation of graphs and visual aids to supplement our findings.

Means of Recording Data

Lansmont 3X90 data recorders are being used to record all shock received by the palletized load. Each data recorder has a unique identifier to differentiate between them. The recorders can record in real time and for an extended period of time. The data will be transferred from the device to a computer for evaluation. Again, there will be 4 groups of 12 test sets with 3 events per group. The software analyses the shock event based on peak acceleration, duration, and average G. Using these numbers, it can be determined and which point in the pallet configuration the most shock was experienced. Likewise, by averaging the numbers we can determine which configuration saw the most shock, and which had the highest rate of attenuation; thus determining which configuration took the shock “better”.

Hypothesis

Shock is most severe at the point of impact and shock values decay the farther away from the point of impact the data is recorded. Shock travels equally in all directions. Horizontal impacts will be the most severe because a large surface area is contacted for a longer period of time.

Section IV. Results

Results were collected as sequential data events from each of the four 3x90 data recorders. The raw data was filtered at 500 Hz to satisfy the industry “rule of 10” that requires a given sampling rate to be filtered by a given frequency 1/10 its value. After the data was processed into an organizational spreadsheet, the spreadsheet was reviewed thoroughly to try and determine any patterns between events. In general, it was very difficult to clearly identify patterns between events. To review the test procedure, each test was performed three times. A test was separated into three shock events by the Lansmont software. The three events were observed separately amongst the four data recorders to determine intensity and transmissibility at and to different locations in the unitized load. Even with only three repetitions the unitized pallet load began to show severe signs of damage. It was the opinion of Blumer and Guadagnini With each subsequent repetition of the test the data would be less scientifically sound due to the rapid structural degradation of the corrugated board and unitized load.

The following is a review of primary results, occurrences, and patterns that were observed in reviewing the test results:

Half sized pallet configuration attenuates shock values better than the full sized pallet configuration. Shock transmissibility from the point of impact to the opposing side of the unitized load was less than the same results from the full-sized pallet configuration. To speculate, this is simply the result of there being more boxes and more material between the point of impact and the opposing side. The full-sized pallet configuration has fewer boxes, but larger, which results in their being less layers of corrugated board. The more boxes that are present, the better that impact is absorbed or attenuated by the unitized load. It is undetermined if size of the boxes is a contributing factor or simply the number of similar boxes.

In a unitized pallet load, shock travels in the axis of which it was sustained. A horizontal impact travels horizontally, an edge and corner drop mostly vertically, dependant on the angle of impact. The results of the edge and corner impact tests show that when an impact is sustained on the corner or edge of a pallet, shock transmissibility is higher in the vertical axis than in the horizontal even though the distance is near equal.

A pallet being carried by a forklift is most likely to see damage on the side against the forklift backrest. When conducting the horizontal impact, and the back rest impact, it was noted that the top most data recorder on the backrest side of the pallet configuration continuously saw the highest acceleration of the four data recorders.

Section V. Conclusion

Brief Summary of Project

This research project has given a basic view into the way in which a shock imposed on a palletized load by a forklift truck travels from the point of impact and throughout the rest of the pallet load. Through the construction of mock pallet loads, data collection has occurred on the two most common types of pallet footprints used in the wholesale distribution cycles, full and half size footprint configurations. Through a standardized test sequence that imposed the pallet loads to various shocks of different intensities and types, preliminary data was collected and analyzed to help come to a conclusion about shock transmissibility in these types of palletized loads.

Observations

After completion of the test sequences of both of the pallets, we were able to gather the data and analyze it to make some initial conclusions towards the question of how shock traveled through a palletized load. In many of the shocks imposed, a reliable pattern could be recognized. Also, a general pattern of how shock decay through a pallet load of a certain footprint configuration could also be recognized.

At first glance of our data, we noticed the amount of data we received from the full size pallet configuration compared to the amount of data received from the half size pallet configuration was very different. In many of the tests on the half size pallet configuration, especially the ones that were relatively mild in shock intensity, the data recorders that were away from the origin of the shock did not receive enough shock force to initiate the data recorder to record data. The values experienced at that location was under the specified acceleration value of 1 G. This situation was especially true with the backrest impact, corner drop, and edge drop. From this evidence, the conclusion that the half size pallet configuration is better at dampening the shock forces that it is subjected to. Although our project did not study why this occurred directly, one assumption that can be made as to why this is the case is the number of box to box interfaces in each of the pallet loads. In the half size configuration, there were many more joints when compared to the full size pallet configuration. It is not unreasonable to assume that much of the shock force may be lost in these interfaces and are not allowed to be transferred through the pallet load and affect the product or packages on the far end from the origin of the shock impact. This gives some credibility towards the statement that a half size pallet configuration may be more effective than a full size pallet configuration at dampening shock forces and subsequently reducing the amount of damage caused to the product or package during the distribution cycle.

Another pattern that can be seen repeated over many occasions in both types of pallet footprint configurations is a tendency for the shock forces to be transmitted at higher intensities in the direction in which the original shock force was transmitted. For example, a pallet that is exposed to a corner drop will show greater acceleration and velocity values in the corner vertical to the corner of impact rather than the corner horizontal to the corner of impact. Likewise, if the shock was initiated in a horizontal direction, such as in a left tine/right corner impact, the corners horizontal to the impact showed values of higher shock intensity than the corners that the shock had to travel vertically.

Another interesting conclusion that could be drawn from this study related to the duration of the shock forces at the different points in the palletized load. In almost all cases, the duration at the point of impact was much shorter than the duration at a point at which the force had to have been transmitted. However, although the duration was longer at these points, the intensity was usually much less. This trend agrees with the suggestion that as a shock force attenuates through a mass, the force will be spread over a greater amount of time and therefore be less severe.

In many cases, the different conclusions in which we were able to determine agree with the argument that a shock wave traveling through a unitized pallet load will travel very similarly to a shock wave traveling through any solid mass. The shock intensity is usually most severe at the point of impact and decays as the shock wave travels through the palletized load.

Project Limitations

Although it is believed that the data and conclusions that we have arrived at are sufficiently reliable, there were a few points that may have added a certain degree of variability to the study.

The first such limitation that can be identified is the level of repeatability that the shocks were exposed to. Efforts were made to expose the palletized load to the same level of shock during each trial, but this proved to be easier said than done. Although this variation makes it impossible to compare information from each data recorder across trials, it does not subtract from the ability to accurately compare data from different data recorders on the same trials. For this reason this can be considered a minor limitation.

Another limitation of this study is the exactness in which we were able to exert the forces on the unitized pallet load. In other words, if trying to exert a horizontal impact onto the pallet load, we tried to make to face impacting the wall as straight to the wall as possible, however, we had no exact way to do this. Although we were able to get the pallet close to the desired position, the method we used was purely subjective in nature. The four impacts that were setup in a subjective manner as described include horizontal impact, right face rotational impact, left tine/right corner impact, and the backrest impact. The other two impacts, edge drop and corner drop, were not subject to this limitation and therefore are slightly more reliable.

The third limitation that was experienced in the study was the number of data recorders that were used to collect points of data. Due to resource constraints during the time of the study, only four data recorders were able to be used. After consulting with Patrick Blizinski of Lansmont Corporation, we determined that the best way to utilize these four data recorders was to place them in the top and bottom of the opposite corners of the palletized load. Although Mr. Blizinski agreed with our thought that four data recorders would be enough to provide adequately reliable information, more data points would always prove to be more reliable and even more useful.

A final limitation of the project was our understanding and familiarity of the data recorders. The instruments that were used to carry out this study were the Saver 3X90 data recorders. Although the instruments have been accessible for research projects, they have not been incorporated in to general course curriculum. Due to this reason, the study was completed with less than a month of training on the data recorder hardware or software. Although we believe we used the instruments to their full capacity and reliability, this may not be entirely the case.

Elimination of the variables stated above would only further increase the reliability and usefulness of our data and conclusions for use in package development and distribution design.

Possible Project Extensions

Although this study does provide a good basis for understanding how a shock wave is transmitted through a unitized pallet load, there is room for additional studies to be done to further understand the subject at hand. Some possible extensions of this study includes doing more impact tests with data recorders in different areas in the palletized load, imposing shock forces with more repeatable means such as using an incline tester and pallet drop tester, and installing data recorders on random palletized loads that are in the actual distribution cycle. These are just a few of the ways in which this project could be extended.

Implementation of Results

The main facet of implementation of the data and conclusions reached in this study include making the study readily available to industry figures that would have a use for the conclusions reached. Some examples of industry figures that would highly benefit from the information found with this study include package designers, warehouse distribution managers, packers, as well as warehouse supervisors.

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Appendix A. Half Size Pallet Configuration Test Data

Data Filtered at 500 Hz

EDGE DROP

Edge Drop-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:35:45	36.5	13	153.93
2	4:37:01	22.77	34	138.33
3	4:42:50	26.32	32	154.51

Edge Drop-- Top of Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:35:45	7.57	32	68.88
2	4:37:00	11.23	47.8	92.34
3	4:42:50	6.84	39.8	75.48

Edge Drop-- Bottom Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:35:45	14.1	21	43.2
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

Edge Drop-- Top Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

CORNER DROP

Corner Drop-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:48:20	14.92	8	25.28
2	4:49:20	15.63	21	53.79
3	4:50:19	18.89	38	115.76

Corner Drop-- Top of Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:48:20	7.02	49	64.58
2	4:49:19	6.01	42.8	66.28
3	4:50:19	6.2	40.4	68.49

Corner Drop-- Bottom Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

Corner Drop-- Top Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

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HORIZONTAL IMPACT

Horizontal Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:53:25	16.13	44	95.36
2	No Data	No Data	No Data	No Data
3	4:54:41	20.78	43	118.3

Horizontal Impact-- Top Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:53:24	17.21	19	55.43
2	4:54:08	14.44	13	37.93
3	4:54:40	19.39	29	68.83

Horizontal Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:53:25	18.23	43	98.62
2	4:54:09	25.25	26	127.45
3	4:54:41	38.63	16	132.85

Horizontal Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:53:25	6.13	5.6	8.41
2	4:54:09	34.59	5.6	101.7
3	4:54:41	37.42	5.6	267.06

RIGHT FACE ROTATIONAL IMPACT

Right Face Rotational Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Top Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

LEFT TINE/RIGHT CORNER IMPACT

Left Tine/Right Corner Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

Left Tine/Right Corner Impact-- Top of Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	5:22:36	1.34	0	0.1
3	No Data	No Data	No Data	No Data

Left Tine/Right Corner Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

Left Tine/Right Corner Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

BACKREST IMPACT

Backrest Impact-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	5:17:27	28.66	9	100.73
3	5:18:25	17.7	35	91.8

Backrest Impact-- Top Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	5:16:39	10.28	8.6	23.61
2	5:17:26	4.23	2.4	2.59
3	5:18:25	16.41	12.6	35.33

Backrest Impact-- Bottom Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	5:16:39	20.58	27	80.26
2	No Data	No Data	No Data	No Data
3	5:18:25	12.57	33	80.93

Backrest Impact-- Top Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	5:18:24	12.44	16	35.86

Appendix B. Full Size Pallet Configuration Test Data

Data Filtered at 500 Hz

EDGE DROP

Edge Drop-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	3:48:55	28.72	24.4	126.25
2	3:49:44	34.34	10.4	103.87
3	3:51:04	38.97	18.8	107.96

Edge Drop-- Top of Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	3:48:55	6.39	55.2	78.35
2	3:49:45	3.22	15.8	13.31
3	3:51:05	2.78	14.2	12.01

Edge Drop-- Bottom Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	3:48:55	11.2	12.4	24.85
2	3:49:45	7.46	9.6	13.46
3	3:51:05	7.94	9.4	16.19

Edge Drop-- Top Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	3:48:55	3.43	23	20.68
2	3:49:45	5	28.4	34.78
3	3:51:05	5.06	46.8	44.48

CORNER DROP

Corner Drop-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:00:44	22.82	11.4	36.95
2	4:02:04	16.56	12.2	35.77
3	4:03:04	13.51	17	34.74

Corner Drop-- Top of Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:00:45	2.66	21.4	18.05
2	4:02:05	1.97	4.6	3.28
3	4:03:05	2.49	29.4	22.96

Corner Drop-- Bottom Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:00:44	3.97	3.8	3.8
2	4:02:05	3.33	2.2	2.29
3	4:03:04	3.75	3	3.36

Corner Drop-- Top Transmitted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:00:45	2.22	4.8	3.61
2	4:02:05	2.5	25.2	19.78
3	4:03:05	2.58	25.2	20.31

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HORIZONTAL IMPACT

Horizontal Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:06:04	42.89	5.4	103.09
2	4:06:37	30.58	15.2	88.63
3	4:07:08	20.94	15.2	55.72

Horizontal Impact-- Top Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:06:04	25.97	15	70.52
2	4:06:37	28.97	11.4	85.32
3	4:07:09	14.98	18	42.39

Horizontal Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:06:04	39.61	12.4	355.1
2	4:06:37	29.65	27.2	211.47
3	4:07:08	20.64	29.6	107.44

Horizontal Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:06:04	16.69	8.6	33.92
2	4:06:38	69.41	18.4	491.06
3	4:07:09	50.07	10.6	180.35

RIGHT FACE ROTATIONAL IMPACT

Right Face Rotational Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:10:47	7.8	13	23.29
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Top Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:10:48	2.71	31.6	25.74
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:10:46	1.86	2	1.43
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

Right Face Rotational Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:10:47	1.17	0	0.09
2	Cancelled	Cancelled	Cancelled	Cancelled
3	Cancelled	Cancelled	Cancelled	Cancelled

LEFT TINE/RIGHT CORNER IMPACT

Left Tine/Right Corner Impact-- Bottom Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:21:26	5.02	2.2	3.08
2	4:22:25	4.07	2	2.3
3	4:23:20	6.5	4.8	7.78

Left Tine/Right Corner Impact-- Top of Impacted Saver, Right

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

Left Tine/Right Corner Impact-- Bottom Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:21:25	4.88	2.6	3.65
2	4:22:24	7.61	7.6	10.62
3	4:23:19	6.25	5.4	9.42

Left Tine/Right Corner Impact-- Top Transmitted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	No Data	No Data	No Data	No Data
2	No Data	No Data	No Data	No Data
3	No Data	No Data	No Data	No Data

BACKREST IMPACT

Backrest Impact-- Bottom Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:14:39	13.22	24.2	59.49
2	4:15:02	3.25	4	4.13
3	4:15:24	13.07	28.4	50.84

Backrest Impact-- Top Impacted Saver, Left

Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:14:39	5.47	16	22
2	4:15:03	14.46	13.4	32.57
3	4:15:25	10.67	27.6	38.16

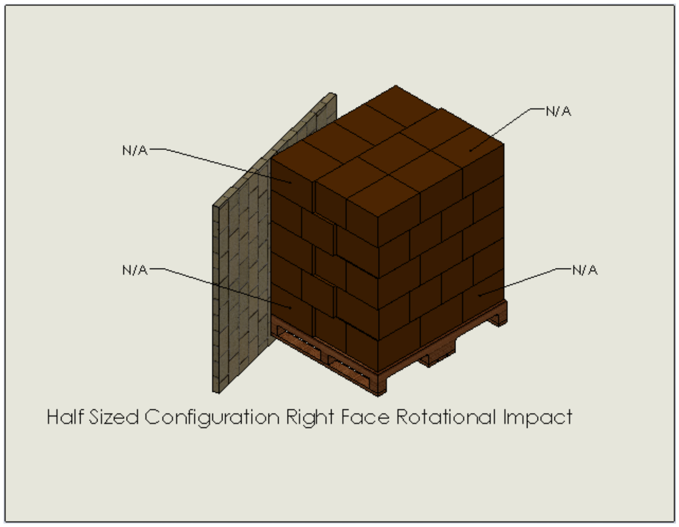
Backrest Impact-- Bottom Transmitted Saver, Right

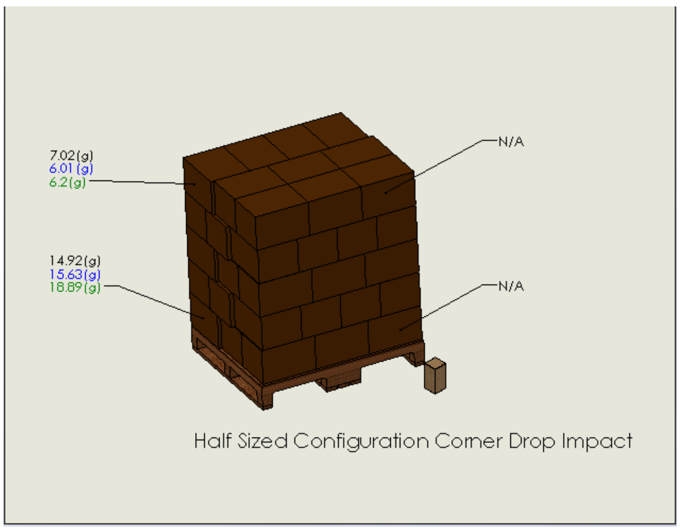
Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:14:39	15.89	38.2	82.29
2	4:15:03	5.13	25.6	34.53
3	4:15:25	7.32	29.2	58.31

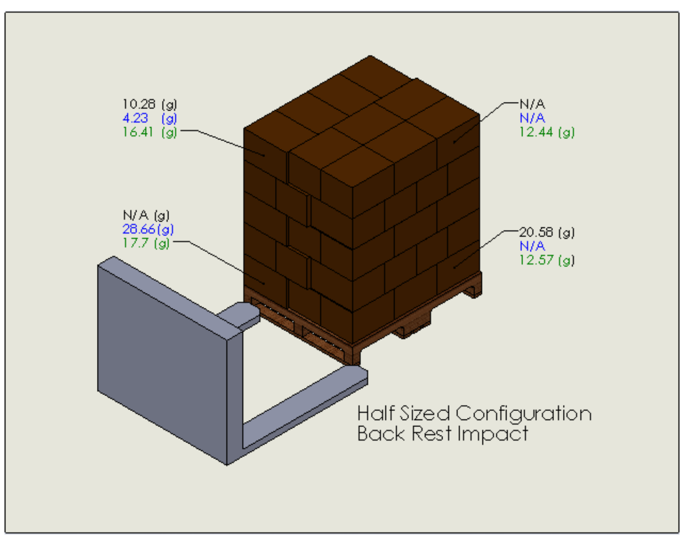
Backrest Impact-- Top Transmitted Saver, Right

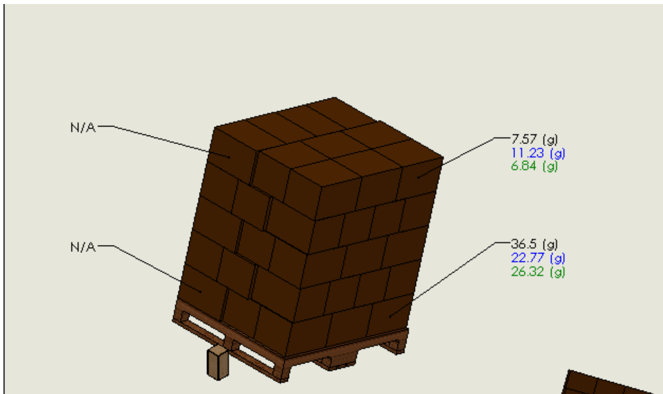
Event Number	Event time	Acceleration (g)	Duration (ms)	Change in Velocity (in/s)
1	4:14:39	10.18	11	25.53
2	4:15:03	3.54	12.2	12.99
3	4:15:25	14.67	10.4	30.67

Appendix C. Graphic Data Representations

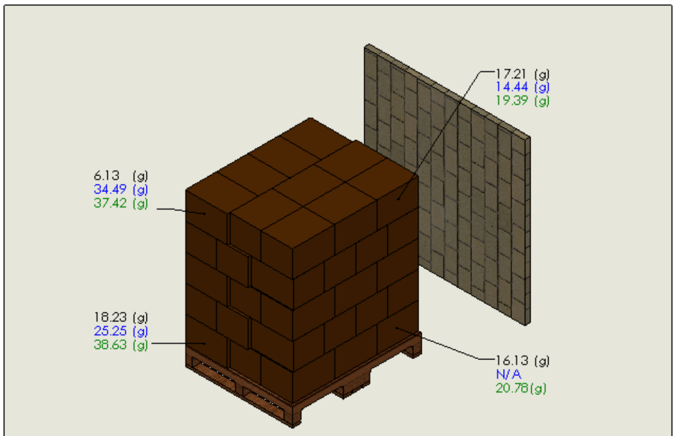




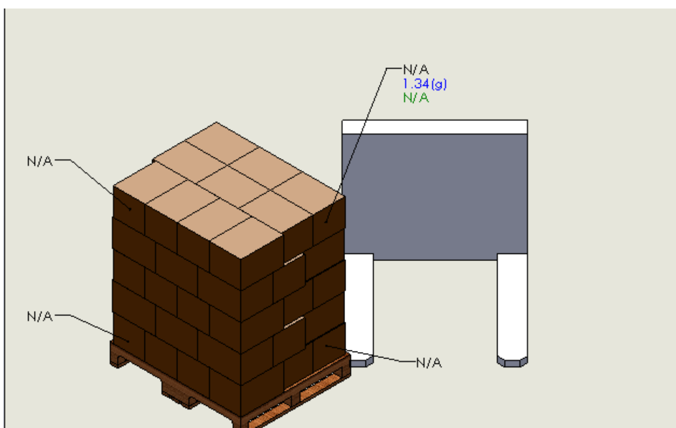




Half Sized Configuration Edge Impact

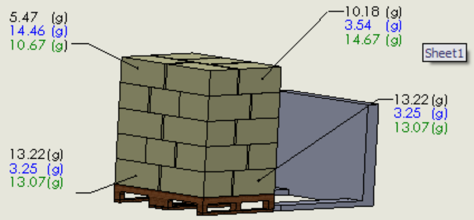


Half Sized Horizontal Impact

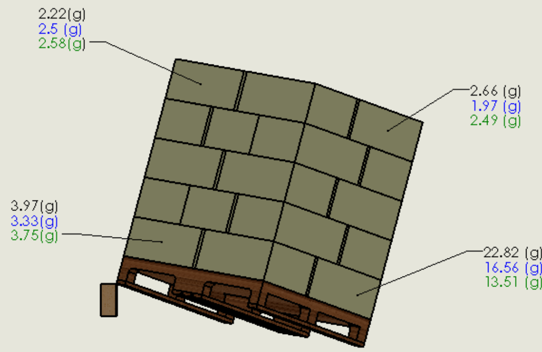


Half Sized Left Tine / Right Corner Impact

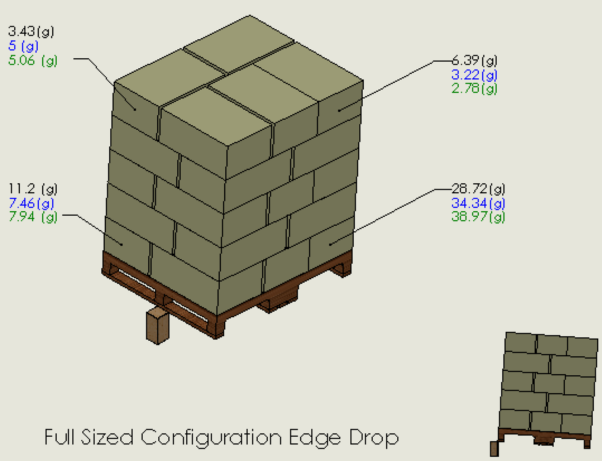
David Guadagnini Tyler Blumer



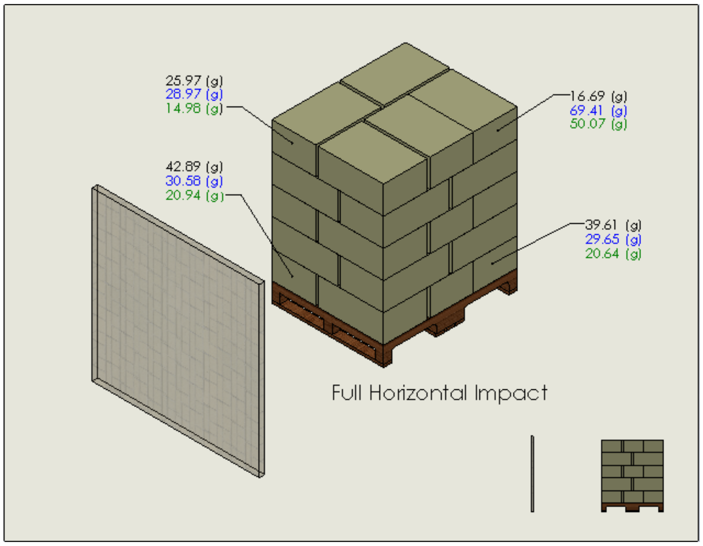
Full Configuration Back Rest Impact

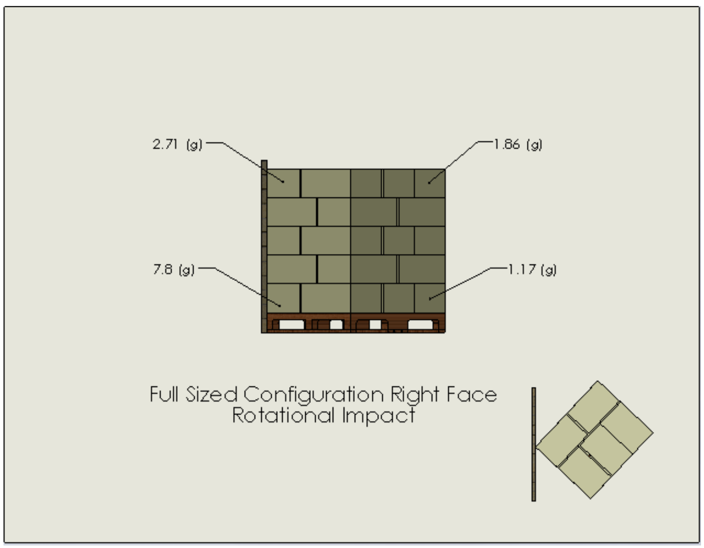


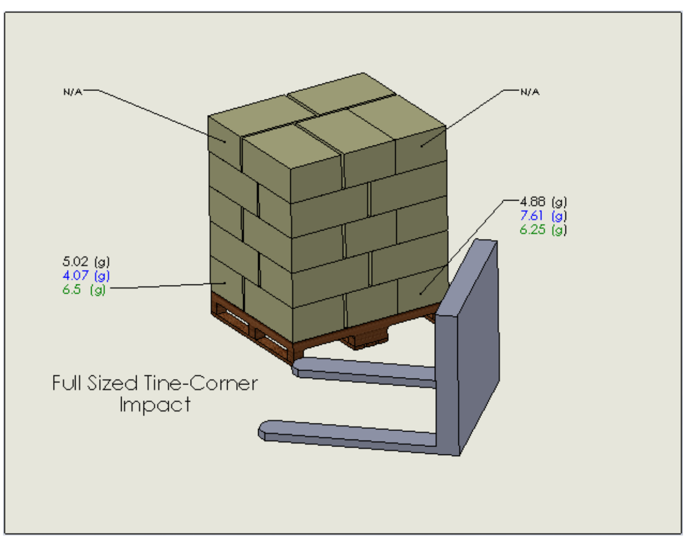
Full Sized Configuration Corner Drop



Full Sized Configuration Edge Drop


25.97 (g)
28.97 (g)
14.98 (g)
16.69 (g)
69.41 (g)
50.07 (g)
42.89 (g)
30.58 (g)
20.94 (g)
39.61 (g)
29.65 (g)
20.64 (g)
Full Horizontal Impact


2.71 (g)
1.86 (g)
7.8 (g)
1.17 (g)
Full Sized Configuration Right Face Rotational Impact


N/A
N/A
4.88 (g)
7.61 (g)
6.25 (g)
5.02 (g)
4.07 (g)
6.5 (g)
Full Sized Tine-Corner Impact