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# Evaluation of Stability of Unit Loads for Tilt and Shock Events During Distribution

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**ABSTRACT**

*Initiatives to lightweight and reduce packaging materials to achieve sustainability goals have created unit load stability challenges in the transportation and handling of palletized packaged goods. Consequently, an increased focus is being placed on evaluating how current pre-shipment performance tests evaluate load stability. This study was undertaken to address the current need for establishing test methodologies towards observing a unit load's overall stability during transportation and handling related activities commonly experienced in the distribution environment. With this goal, this study developed two test methods as well as apparatus/measuring tool to observe a palletized load's overall stability. The experimentation involved unit loads of bottled water assembled using two commonly used stacking and stretch wrap patterns. Testing conditions for existing test procedures as well as personnel safety issues during testing were also considered and all tests were conducted in triplicate. The test methods developed included a "tilt test" which was designed to replicate the gravitational forces exerted on the unit load and an "incline impact test" designed to replicate the effect of short duration shocks experienced by unit loads. Collectively, the two test methods provide valuable test procedures and insight towards understanding a unit load's response to shocks and shifts commonly experienced during distribution related activities. The data collected from these tests should contribute to potential revisions for International Safe Transit Association's (ISTA) Procedures 3B and 3E testing requirements. Packaging engineers should be able to appropriately develop and/or validate unit loads of packaged goods utilizing the new test methods.*

**KEY WORDS**

*Unit load stability, tilt, shock, pallet, distribution, packaging*

## INTRODUCTION

Freight has been defined as “goods, cargo, or lading transported for pay, whether by water, land, or air” and provides the ordinary transference or means of transport of goods provided by common carriers [1]. Freight transportation, a key supply chain component, refers to the physical process involving transportation of raw materials and finished products [2]. With a daily moving average of approximately 49.5 million tons of freight valued at $52.7 billion in 2015, the freight tonnage and value rose by 6.5 and 8.2 percent, respectively, over 2012 levels, fully rebounding from declines during the December 2007–June 2009 economic recession [3]. The modes of transportation typically deployed to move cargo include ground (train & truck), water (ships and pipeline) and air (aircraft). With a 66% share of U.S. freight movement in 2015, trucks outweighed all other modes collectively. [4] Figure 1 shows the weight & value of shipments by truck as a percentage of total for 2012, 2015 and 2045 [4].

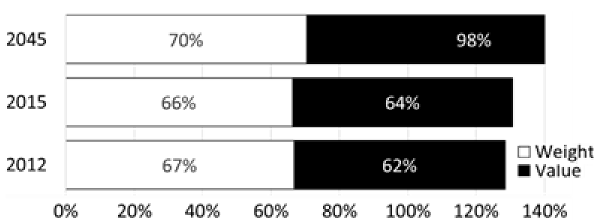


*Figure 1: Weight & Value of Shipments by Truck as a Percentage of Total: 2007, 2012, and 2040*

Freight in the truckload category is typically distributed on pallets in a unitized form to maintain stability and provide product protection during transit. Unitization of a load can also increase packaging and handling efficiency during distribution [5]. There are multiple ways of unitizing a load including stretch wrap, stretch hood, stretch net, and strapping or banding [6]. A few recent studies have investigated the specifications for the stretch wrapping operation as related to load stability [7-12]. As related to stretch wrapping and its effect on a unit load’s stability, it is critical to undertand how packaging, pallets and handling equipment interact. The interface between the pallet and unit load handling equipment during shipping and handling operations include vibration interactions, transfer of shocks and impact forces, compressive forces and load shifting [13].

Stretch wrap is applied to a unitized load to increase load containment and hence establish unit load stability. Load containment allows a load to be securely held in place so it can arrive undamaged at its desired destination. Proper stretch film application increases load containment [7]. Stretch film is properly applied when the film is stretched, applied under tension, and elastic recovery conforms the film to the load [14]. Additional wraps, heavier gauge film, and increased post-stretch can increase load containment. To obtain the maximum load containment, three factors must be considered. These factors are the unitized load type, wrapping configuration, and distribution environment [7].

The type of unitized load primarily refers to the items that are being shipped. The type of product and the orientation in which the product is unitized affect the ability of the load to be contained. Unitized loads that are uniform in shape and have no protrusions or puncture hazards are considered “A-Profile Loads”; loads with puncture hazards lesser than 7.62 cm (3 in) are considered “B-Profile Loads” and loads with puncture hazards over 7.62 cm (3 in) are considered “C-Profile Loads” [15].

There are many variables which affect the ability of stretch wrap to contain the load and they can be altered when stretch wrapping a pallet load. These variables include: wrap patterns which refers to the location that the stretch film is applied; film force to load which is the tension created due to the stretch film’s attempt to return to its original state after having been stretched; number of layers; turntable and carriage speed; pre-stretch which is the process of stretching film before it is applied to the load; and the film type [7].

The distribution environment refers to the dynamic and static stresses that a unit load endures during the typical shipping and handling events. These events frequently cause unit load failure and are a critical factor when selecting the load type and wrapping configuration. Unitized loads in less than truckload (LTL) shipments are subjected to a harsher environment than truckload shipments (TL) [16]. While TL carriers move full containers or trailers of typically one product from one customer, LTL carriers consolidate multiple customers' orders on the same trailer [17]. TL shipments commonly have one destination while LTL shipments experience multiple exchanges and handling which potentially result in higher abuse and hence increased load failures.

Initiatives to lightweight and reduce packaging materials to achieve sustainability goals have created unit load stability challenges in the transportation and handling of palletized packaged goods. Alternatives to standard rectangular corrugated fiberboard shippers, such as shrink wrapped bundles, retail ready display cases, blister packs and clam shells, perform distinctively when exposed to typical distribution hazard elements such as horizontal impacts [18]. Such impacts may occur during distribution related transport and handling events such as railcar coupling, pallet marshalling and transport vehicle motions. Consequently, an increased focus is being placed on evaluating how current pre-shipment performance tests evaluate load stability. Numerous load stability evaluation test methods already exist and include rotary vibration, rotational drop testing, horizontal or inclined impact testing, fork lift handling courses, tilt testing, road courses, and programmable acceleration/deceleration sled testing [18].

The International Safe Transit Association (ISTA) is an organization focused on the specific issues of transport packaging. ISTA is the leading industry developer of testing protocols and design standards that define how packages should perform to ensure protection of their contents during the ever-changing hazards of the global distribution environment [19]. ISTA's mandate is to enhance the effectiveness of package design and testing. In this regard, ISTA's Load Stability Testing Workgroup supported this study towards determining whether any of the load stability evaluation test methods mentioned above should be implemented in ISTA Procedures 3B and/or 3E. Procedure 3B (Packaged-Products for Less-Than-Truckload (LTL) Shipment) is a general simulation test for packaged-products shipped through LTL carriers' delivery system where different types of packaged-products, often from different shippers and intended for different ultimate destinations, are mixed in the same load [20]. Procedure 3E (Unitized Loads of Same Product) is a general simulation test for unitized loads of the same retail or institutional packaged products [21].

The two real world distribution hazards which are represented through ISTA 3B and 3E Procedures are unit load shocks from fork lift handling and unit load shift inside trailers during surface transport. ISTA's Testing Council was interested in exploring relatively low level, short duration shocks using the modified inclined-impact tester as detailed in ISO 10531-Section 7.2.2.1 (Packaging -- Complete, filled transport packages -- Stability testing of unit loads) [22]. It was also recommended that the impacts should be of less than 0.89 m/s (2 mph) to reduce the rotational forces that can be created by the incline. The intent was to mimic the short duration shocks that are experienced during pallet marshaling when fork lifts impact a pallet thereby potentially causing a shift in the unit load. It has been suggested that this on average occurs at an impact speed of 0.31 m/s (0.7 mph) [23].

With regards to tilt testing, it was established that determining how well a unit load would stay contained (stable) when experiencing the gravitational forces created by truck acceleration, truck braking and truck turning, was of importance. While tilt testing does not replicate the dynamic elements of unit load shocks from fork lift handling and unit load shift inside trailers, it was deemed to be of essence towards correlating load shift to real world containment capability. Figure 2 identifies

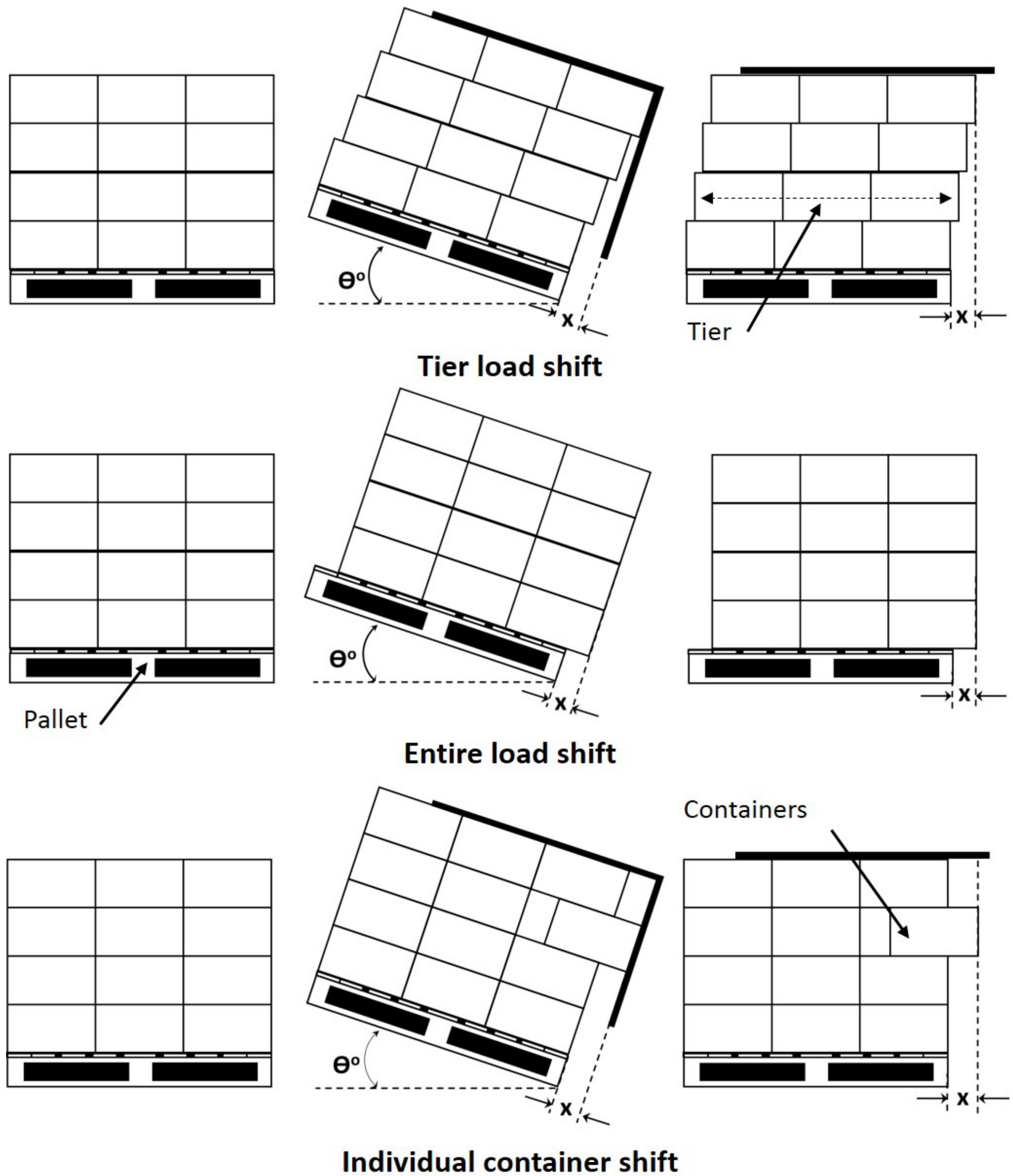


*Figure 2: Potential Load Shift Mechanisms during Tilt Testing*

three potential load shift mechanisms during tilt testing – by tiers, entire load above the pallet and individual containers. The tilt angle is identified as "ϴ" and the load shift with reference to the pallet edge as "x".

To assess the resilience of unit loads during distribution related events, this study established two test methods to observe a palletized load's overall stability.

- Tilt test: designed to replicate the gravitational forces exerted on the unit load during specific conditions such as truck acceleration, stopping and turning.
- Incline impact test: designed to demonstrate the short duration shocks experienced during pallet marshaling which could potentially cause a shift in the unit load. This test also replicates some of the short duration shocks that may occur to the unit load during its distribution.

The specific objectives of this study were:

- Design apparatus for and establish tilt test and incline impact test procedures.
- Observe and record the amount of offset of the unit load to evaluate the stability of the unit load per the tilt test and incline impact test procedures
- Test two different pallet patterns as a mean for comparison of unit load stability

## MATERIALS AND METHODS

### Load specifications

Following are the details for the packaging components and unit load employed in this study. The best practice stack and pallet pattern specifications are based on the input from Niagara Bottling, LLC.

- Primary packaging: Twenty-four 0.5L PET water bottles (Niagara Bottling, LLC, Ontario, California, USA)
- Secondary packaging: Polyethylene shrink film
- Pallet: CHEP timber block pallet, 121.92 cm x 101.60 cm x 14.22 cm
- Stretch wrap: 50.80 cm, 0.7 mil, multi-layer cast film - Model MP2 (Berry Plastics Corp., Evansville, Indiana, USA)
- Unit load: 125.73 cm x 105.41 cm x 132.08 cm, 1082 kg
- Wrap pattern: 11 total revolutions, 2 additional top wraps, 76-102 mm layer-by-layer film overlap, 13-51 mm top overwrap and 76-102 mm bottom overwrap. Applied (measured) stretch level: 180-210%. Containment force per ASTM D 4649 Testing: 5.89 ± 0.91 kgf [24]. For stretch wrapping unit loads, the Synergy 4 Automatic Stretch Wrapper (Highlight Industries Inc., Grand Rapids, MI, USA) was used. Towards obtaining the targeted containment force, the portable film force system used for this project consisted of a primary load cell and two secondary load cells each attached to 152.40 mm diameter force plates (Portable Film Force System, Highlight Industries Inc., Grand Rapids, MI, USA) [7]. Figure 3 shows this system as placed on the unitized load. After being stretch-wrapped, all unit loads were allowed to relax for one hour.
- Stacking pattern: Layer patterns "A" and "B" were used to construct six-tier stacking patterns of "AABBAA" and "AAAABB" for the two types of unit loads used in this study (Figure 4). The product cases were maintained upright, evenly centered on the pallet to within 5.08 cm and within 2.54 cm alignment between repeat layers.

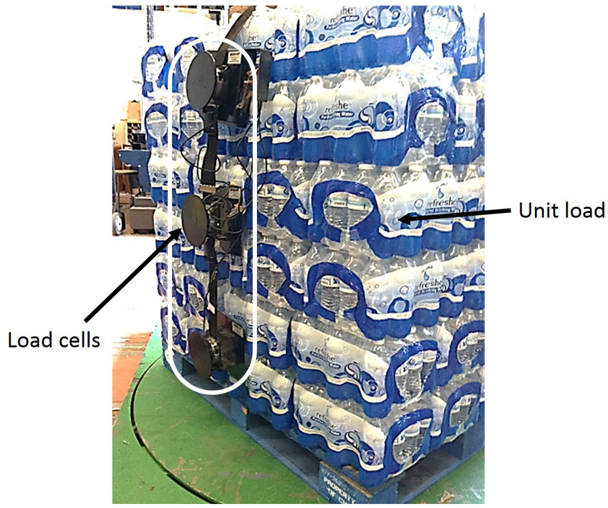


*Figure 3: Load Cell Assembly to Measure Containment Force*

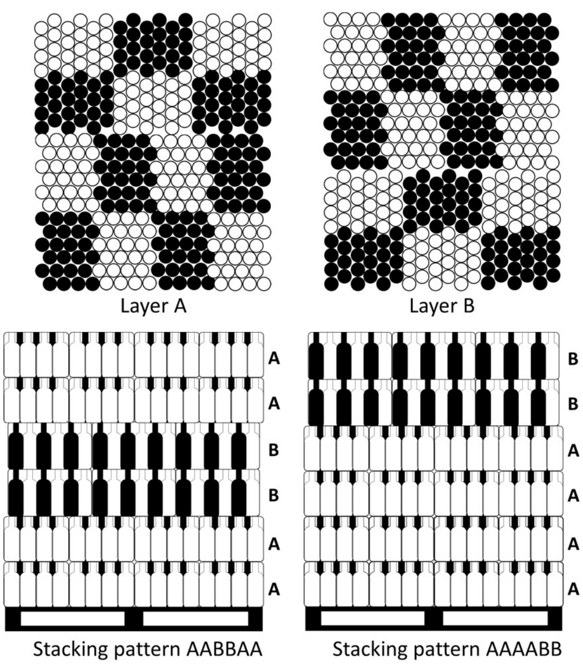


*Figure 4: Layer (top) and Stacking (bottom) Patterns Used for Unit Loads*

**Tilt Test**

The tilt test was designed to replicate the gravitational forces exerted on the palletized load during specific conditions such as truck acceleration, stopping and turning. This test was established to study the responses of a unit load under tilt stresses towards simulating load shifts during transportation activities. Tilt angles of $5^0$, $10^0$, $15^0$, $20^0$, $22.5^0$ and $25^0$ were considered for the experimentation. Testing conditions for ISTA Procedures 3B and 3E, as related to personnel safety, was also considered.

**Apparatus**

The tilt test apparatus was designed to withstand the static and dynamic forces exerted during various tilt angles for the unit load of product. The tilt test apparatus was constructed with wood as shown in Figure 5 below. Figure 6 shows the recommended method to perform tilt tests using the apparatus.

A vertical measuring tool was also designed to determine the amount of offset of the cases on the unit load. The laser measuring tool, Bosch model DLR130K (Palo Alto, California, USA), was utilized to record the measurements. The vertical measuring tool was constructed utilizing square steel telescope tubing for the main structure. The laser measuring tool fixture was built with a square steel telescope tubing, a strip aluminum sheet and a device holder/cradle. Figure 7 on the next page provides details of the construction and assembly. After visually identifying the most protruding cases of packaged product for each layer, the precise location of maximum protrusion for each case should be confirmed, marked and measured using the vertical measuring tool. To quantify the stability of the unit loads, offset measurements were taken between the water cases in relation to the pallet edge.

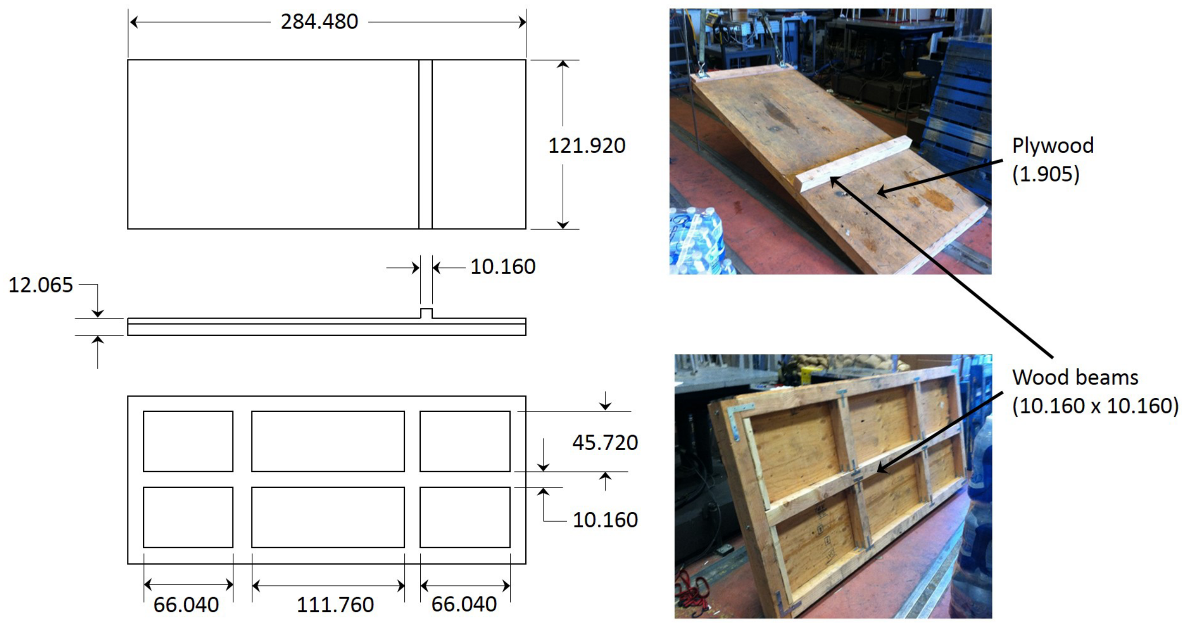


*Figure 5: Tilt Test Apparatus Design  (Dimensions shown in centimeters)*

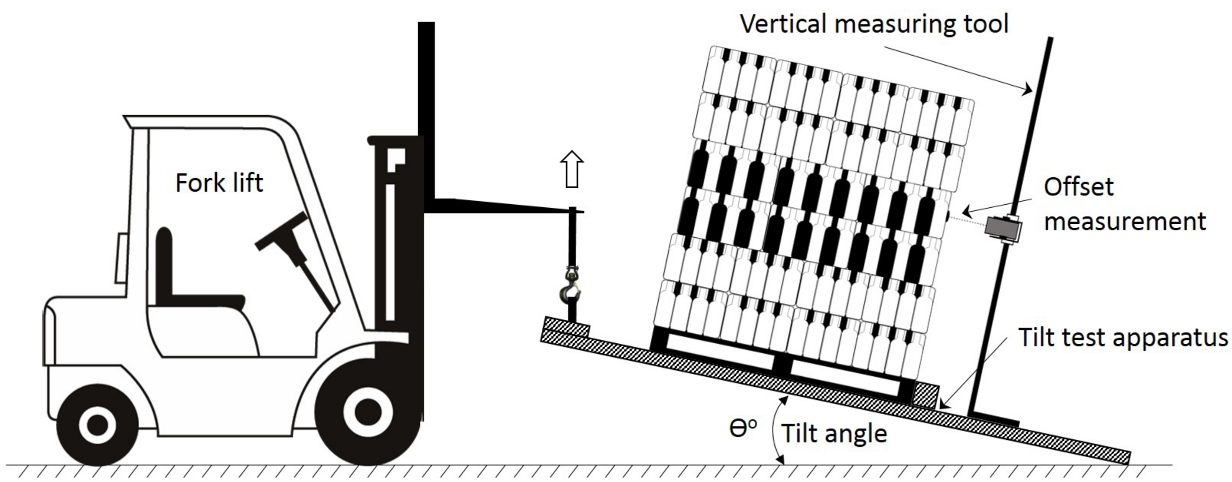


*Figure 6: Tilt Test Experimental Setup*

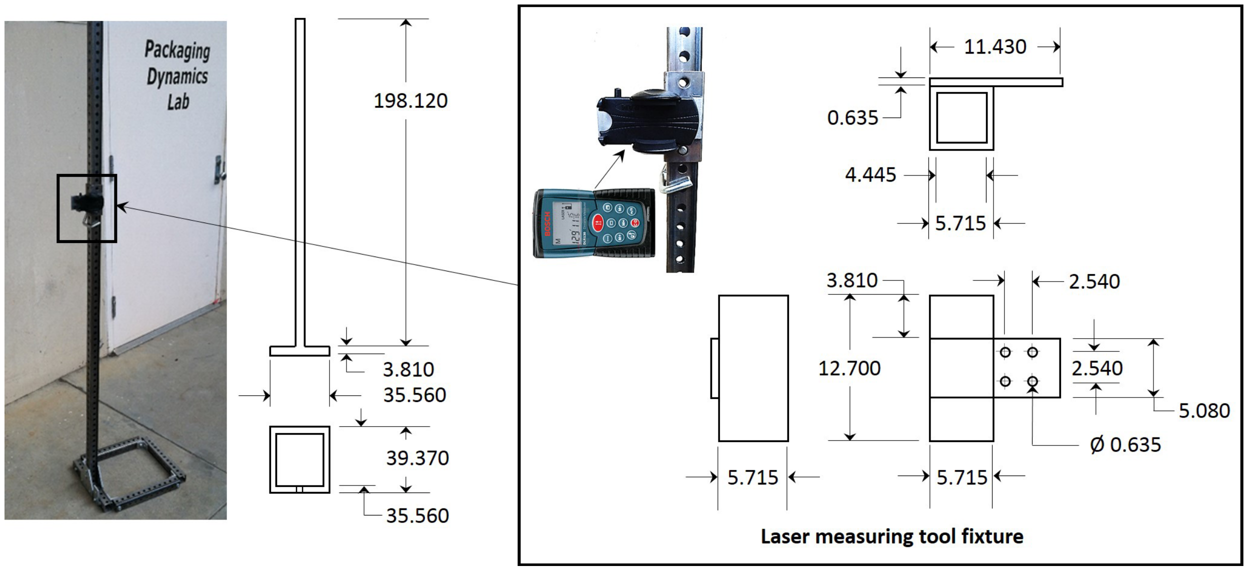


*Figure 7: Vertical Measuring Tool Design (Dimensions shown in centimeters)*

**Test Methodology**

Prior to beginning any testing, the faces for the unit load were identified as shown in Figure 8 [21]. For the six-tier unit load, "layers" were designated as follows:

1. Top layer: top two tiers of packaged-product
2. Middle layer: middle two tiers of packaged-product
3. Bottom layer: bottom two tiers of packaged-product

The testing procedure for the tilt test is detailed in Table 1. Due to the potential limitations and safety issues related to the mid-test measurement setup, it may not be possible to measure the offsets for each layer and for each Face. In this situation, it is recommended that only one offset value be measured for each tilt angle. A single marked case with the highest measured pre-test offset value regardless of the Layer and Face is to be used for the mid-test offset value measurement.

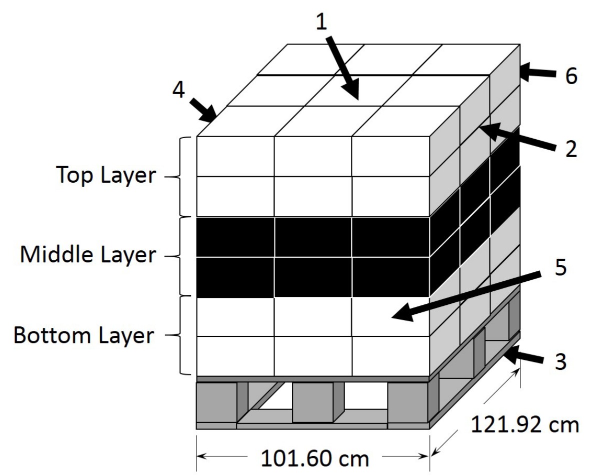


*Figure 8: Identification of Faces of Unit Load*

*Table 1: Tilt Test Procedure*

<table>
<tr><th>Step</th><th colspan="2">Action</th></tr>
<tr><td>1</td><td colspan="2">Prepare three unit loads each replicate test of packaged product for each stack-pattern ("Load specifications" Section) and tilt-angle ("Tilt Test" Section). Identify the Faces and Layers of the unit load as shown in Figure 8</td></tr>
<tr><td>2</td><td colspan="2">Apply the stretch wrap per specifications provided in "Load specifications" Section. Allow 1 hour of relaxation time for all stretch wrapped unit loads prior to testing.</td></tr>
<tr><td colspan="3">Pre-test offset measurement (Figure 9)</td></tr>
<tr><td>3</td><td colspan="2">Measure the pre-test offset for each layer of Face 2 and Face 4 of the unit load as stated in "Tilt Test - Apparatus" Section and record in the values in Table 1.</td></tr>
<tr><td colspan="3">Mid-test offset measurement (Figure 9)</td></tr>
<tr><td>4</td><td colspan="2">For each layer and tilt angle of the two stack-patterns, identify the Face with the largest individual offset (Table 1) and tilt the packaged-product along the selected Face. If the offset is the same for both faces, selest either Face 2 or Face 4.</td></tr>
<tr><td>5</td><td colspan="2">Using tilt test apparatus, slowly tilt each unit load along the pallet Face identified in Step 4 from its horizontal position to the first tilt level angle of $5^0$. Measure the mid-test offset for each location identified in Step 4 while the tilt angle is maintained after 1 and 10 minutes (Table 2).</td></tr>
<tr><td rowspan="4"></td><td>If...</td><td>Then...</td></tr>
<tr><td>At any point testing becomes unsafe and/or</td><td rowspan="3">Slowly return the unit load to the horizontal position</td></tr>
<tr><td>the unit load is no longer contained and/or</td></tr>
<tr><td>Load shift exceeds $25^0$ and/or</td></tr>
<tr><td colspan="3">Post-test offset measurement (Figure 9)</td></tr>
<tr><td>6</td><td colspan="2">Slowly return the unit load to the horizontal position and record the post-test offest measurements for each location identified in Step 4 in Table 3.</td></tr>
<tr><td>7</td><td colspan="2">Repeat steps 3-6 for the next tilt angles of $10^0$, $15^0$, $20^0$, $22.5^0$, and $25^0$</td></tr>
</table>

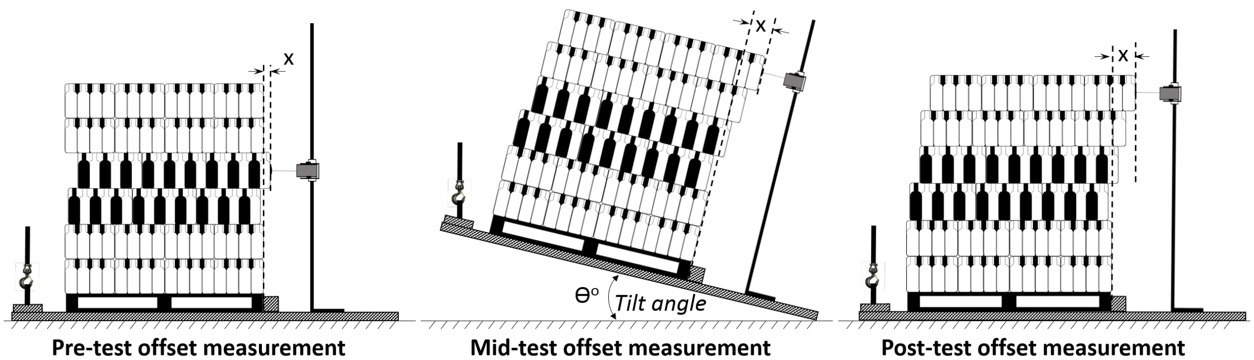


*Figure 9: Pre-, Mid- and Post-Tilt Test Measurement Setup*

Figure 9 illustrates the pre-test, mid-test and post-test offset measurement setup.

**Incline Impact Test**

The incline impact test was designed to replicate the short duration shocks that are experienced during distribution activities such as pallet marshaling when fork lifts impact a pallet and potentially causing a shift in the unit load. Testing conditions for ISTA Procedures 3B and 3E, as related to personnel safety, was also considered.

**Apparatus**

The incline impact apparatus was designed to withstand the weight of the unit load, as well as set an angle that would allow for the unit load to impact the wall parallel to the floor. The modified incline impact tester, as detailed in ISO 10531-Section 7.2.2.1, was developed to simulate relatively low level and short duration shocks [22]. Figure 10 shows the modified incline impact sled design that was constructed with wood as well as the mechanism for its usage in incline impact tests for unit loads. It was designed to allow for the unit load to be horizontally impacted at a velocity of 0.7 m/sec.

The vertical measuring tool, as illustrated and described in "Tilt Test - Apparatus" Section was engaged to measure the offset for the unit loads.

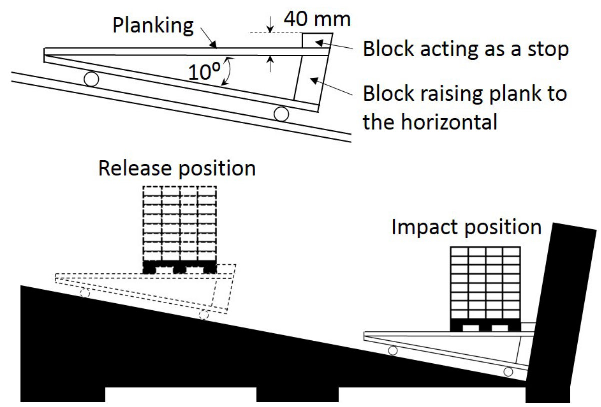


*Figure 10: Incline Impact Test Apparatus Design (top) and Methodology (Bottom)*

**Test Methodology**

The identification of faces and layers for the unit load was identical to that described in "Tilt Test - Test Methodology" Section. The testing procedure for the incline impact test is detailed in Table 2 below.

*Table 2: Incline Impact Test Procedure*

| Step | Action |
|---|---|
| 1 | Prepare one unit load for each replicate test of packaged product for each stack-pattern as stated in "Load specifications" Section. Identify the Faces and Layers as shown in Figure 6. |
| 2 | Apply the stretch wrap per specification identified in "Load specifications" Section. Allow 1 hour of relaxation time for all stretch wrapped unit loads prior to testing. |
| Pre-test offset measurement | |
| 3 | Measure the pre-test offset for each layer of Faces 2, 4, 5 & 6 of the unit load as stated in "Tilt Test - Apparatus" Section and record in the values in Table 5. Identify the faces with the largest offset between Faces 5 * 6 (along the length of the pallet) and Faces 2 & 4 (along the width of the pallet). The two faces identified with the larger pre-test offset will be impacted in step 4. |
| Mid-test offset measurement | |
| 4 | Use a modified inclined impact tester as described in "Incline Impact Test - Apparatus" Section. Center the unit load in the proper orientation on the carriage, with the edge of its pallet in contact with the levling appartus stop bloack (Figure 9). |
| 5 | Impact the selected face between Face 5 & 6 per Step 3. The required impact velocity for the inclined-impact test is approximately 0.74 m/s |
| 6 | Allow the carriage to roll back to the starting position |
| 7 | Reposition the unit load on the carriage and impact the selected face between Face 2 & 4 per Step 3. The required impact velocity for the inclined-impact test is approximately 0.74 m/s |
| 8 | Record mid-test offset as stated in "Tilt Test - Apparatus" Section and record the values in Table 5 |
| Post-test offset measurement | |
| 9 | Repeat Steps 4-8.* |
| 10 | Record post-test offset measurements in Table 55 |

* Each of the two Faces selected from pre-test offset measurements receives one impact each during the mid-test and post-test.

## RESULTS AND DISCUSSION

The observations for pre-, mid- and post-tests are placed in Tables 3-5 for both stacking patterns (AABBAA and AAAABB) for tilt tests, and in Tables 7 for incline impact tests.

### Tilt Test Results & Observations

The results for the unit loads tested per the procedure identified in "Tilt Test - Test Methodology" Section are reported in Tables 3-5 below.

The tilt angles identified in Table 3 are simply identifiers for subsequent testing. The third replicates for $15^0$ tilt pre-test for AABBAA stack pattern were not undertaken due to failures observed in the subsequent mid-tilt tests towards ensuring the safety of the equipment and operators. Consequently, all tests for $20^0$, $22.5^0$ and $25^0$ were omitted. The third replicates for $10^0$ tilt test for AAAABB stack pattern were not undertaken due to failures observed in the subsequent mid-tilt tests towards ensuring the safety of the equipment and operators. Consequently, all tests for $15^0$, $20^0$, $22.5^0$ and $25^0$ were also omitted

Due to the potential limitations and safety issues related to the mid-test measurement setup, it was not possible to measure the offsets for each layer and for each Face. Consequently, only one offset value

*Table 3: Pre-Test Offset Measurements (cm)*

| Tilt Angle | Layer | Face 1 | | | Face 2 | | |
|---|---|---|---|---|---|---|---|
| | | Replicate 1 | Replicate 2 | Replicate 3 | Replicate 1 | Replicate 2 | Replicate 3 |
| Stacking Pattern AABBAA | | | | | | | |
| $5^0$ | Top | 5.72 | 6.09 | 5.72 | 3.18 | 2.54 | 6.35 |
| | Middle | 7.62 | 5.08 | 5.72 | 3.81 | 3.18 | 5.72 |
| | Bottom | 4.45 | 3.18 | 6.99 | 3.18 | 5.08 | 3.81 |
| $10^0$ | Top | 3.81 | 5.72 | 3.18 | 6.35 | 5.08 | 3.18 |
| | Middle | 3.18 | 7.62 | 1.91 | 5.72 | 2.54 | 6.35 |
| | Bottom | 3.81 | 3.18 | 2.54 | 3.81 | 2.54 | 5.72 |
| $15^0$ | Top | 3.81 | 4.45 | - | 3.18 | 0.64 | - |
| | Middle | 3.81 | 5.72 | - | 3.18 | 6.18 | - |
| | Bottom | 3.18 | 5.72 | - | 2.54 | 4.45 | - |
| Stacking Pattern AAAABB | | | | | | | |
| $5^0$ | Top | 1.27 | 1.27 | 5.08 | 6.35 | 3.81 | 1.91 |
| | Middle | 4.45 | 3.81 | 5.08 | 4.45 | 5.08 | 2.54 |
| | Bottom | 1.91 | 4.45 | 5.08 | 4.45 | 4.45 | 5.08 |
| $10^0$ | Top | 4.45 | 3.18 | - | 3.81 | 3.18 | - |
| | Middle | 4.45 | 3.81 | - | 3.81 | 4.45 | - |
| | Bottom | 4.45 | 3.18 | - | 2.54 | 5.08 | - |

*Table 4: Mid-Tilt Test Offset Measurements (cm)*

| Tilt Angle | Replicate 1 | | Replicate 2 | | Replicate 3 | |
|---|---|---|---|---|---|---|
| | 1 minute | 10 minute | 1 minute | 10 minute | 1 minute | 10 minute |
| Stacking Pattern AABBAA | | | | | | |
| $5^0$ | 6.99 | 6.35 | 7.62 | 7.62 | 7.62 | 7.62 |
| $10^0$ | 12.07 | 13.97 | 13.34 | 15.24 | 12.7 | 13.97 |
| $15^0$ | Failed | Failed | Failed | Failed | Did not attempt due to prior failures | |
| Stacking Pattern AAAABB | | | | | | |
| $5^0$ | 2.54 | 2.54 | 5.72 | 8.89 | 8.26 | 8.26 |
| $10^0$ | Failed | Failed | Failed | Failed | Did not attempt due to prior failures | |

was measured for each tilt angle. A single marked case with the highest measured pre-test offset value regardless of the Layer and Face was used for the mid-test offset value measurement.

*Table 5: Post-Test Offset Measurements (cm)*

| Tilt Angle | Layer | Tilted Face (Face 2 or Face 4) | | |
|---|---|---|---|---|
| | | Replicate 1 | Replicate 2 | Replicate 3 |
| Stacking Pattern AABBAA | | | | |
| $5^0$ | Top | 5.08 | 5.72 | 7.62 |
| | Middle | 6.35 | 3.81 | 6.99 |
| | Bottom | 3.18 | 3.18 | 6.35 |
| $10^0$ | Top | 11.43 | 10.80 | 7.62 |
| | Middle | 10.80 | 10.80 | 9.53 |
| | Bottom | 5.72 | 4.45 | 8.89 |
| $15^0$ | Top | Failed | Failed | Did not attempt due to prior failures |
| | Middle | | | |
| | Bottom | | | |
| Stacking Pattern AAAABB | | | | |
| $5^0$ | Top | 9.53 | 5.08 | 9.53 |
| | Middle | 6.35 | 5.72 | 6.99 |
| | Bottom | 6.99 | 4.45 | 6.99 |
| $10^0$ | Top | Failed | Failed | Did not attempt due to prior failures |
| | Middle | | | |
| | Bottom | | | |

*Table 6: Observations from Tilt Tests*

| Tilt Angle | Observations/Notes |
|---|---|
| Stacking Pattern AABBAA | |
| $5^0$ | During the tilt at $5^0$ the unit load displayed little stress and no noticeable offset was observed or recorded. No damage to the bottles was observed. |
| $10^0$ | In bringing up the apparatus up to $10^0$ tilt angle, the unit load started to experience significant strain resulting in an almost immediate 5.08 cm shift in offset. No damage of the bottles was observed. |
| $15^0$ | It was observed the unit load failed in both trials conducted at approximately $12.5^0$ degrees. There was significant damage observed to the unit load such as cracked/ fatigued bottles and deformed bottle necks. The unt loads collapsed upon reaching the tilt angle of $15^0$ (Figure 11). To ensure the safety of the equipment and operators, the third trial was not conducted. |
| Stacking Pattern AAAABB | |
| $5^0$ | No noticeable shift during test. Unit load maintained integrity throughout test. |
| $10^0$ | Unit load failed prior to reaching the $10^0$ tilt angle. Compared to the AABBAA configuration, there were significant stability issues in attempting to reach this tilt angle. Most of the observed instability was concentrated at the AAAA column stack (Figure 12). |

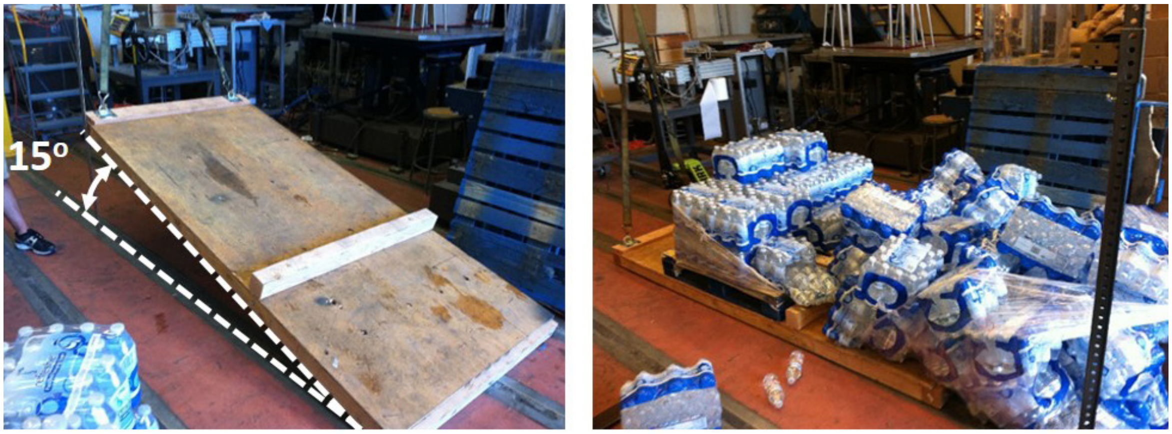


*Figure 11: Mid-Tilt Test Failure at $15^0$ for Stack Pattern AABBAA Unit Loads*

*Figure 12: Mid-Tilt Test Failure at $10^0$ for Stack Pattern AAAABB Unit Loads*

The observations from the testing above are summarized in Table 6 and illustrated in Figures 11 and 12.

**Incline Impact Test Results & Observations**

The results for the unit loads tested per the procedure identified in "Incline Impact Test - Test Methodology" Section are reported in Table 7. The average impact velocities for stacking patterns AABBAA and AAAABB were observed to be 0.73 m/s and 0.70 m/s respectively.

As the first two AAAABB stack pattern unit loads failed during the mid-test impact testing, subsequent replicates were not undertaken to ensure the safety of the equipment and operators.

*Table 7: Incline Impact Test Offset Measurement Results (cm)*

| Stacking Pattern AABBAA | | | | | | |
|---|---|---|---|---|---|---|
| Replicate | Test | Face 5 | Face 6 | Face 4 | Face 2 | Layer |
| 1 | Pre-Test | 2.54 | 1.91 | 4.45 | 3.81 | Top |
| | | 3.18 | 1.27 | 3.18 | 4.45 | Middle |
| | | 1.91 | 2.54 | 1.91 | 5.08 | Bottom |
| | Mid-Test | 12.07 | Face 5 selected for mid- and post-tests | Face 2 selected for mid- and post-tests | 7.62 | Top |
| | | 10.16 | | | 8.26 | Middle |
| | | 6.99 | | | 7.62 | Bottom |
| | Post-Test | 16.51 | | | 14.61 | Top |
| | | 15.24 | | | 13.97 | Middle |
| | | 10.80 | | | 7.62 | Bottom |
| | Total Offset | 13.97 | | | 10.80 | Top |
| | | 12.07 | | | 9.53 | Middle |
| | | 8.89 | | | 2.54 | Bottom |
| 2 | Pre-Test | 1.27 | 0.00 | 0.64 | 5.08 | Top |
| | | 1.91 | 1.91 | 0.00 | 6.35 | Middle |
| | | 0.00 | 1.27 | 2.54 | 4.45 | Bottom |
| | Mid-Test | 7.62 | Face 5 selected for mid- and post-tests | Face 2 selected for mid- and post-tests | 8.89 | Top |
| | | 3.81 | | | 10.16 | Middle |
| | | 0.64 | | | 3.81 | Bottom |
| | Post-Test | 10.80 | | | 15.24 | Top |
| | | 6.99 | | | 15.24 | Middle |
| | | 2.54 | | | 9.53 | Bottom |
| | Total Offset | 9.53 | | | 10.16 | Top |
| | | 5.08 | | | 8.89 | Middle |
| | | 2.54 | | | 5.08 | Bottom |
| 3 | Pre-Test | 4.45 | 0.00 | 4.45 | 4.45 | Top |
| | | 5.08 | 0.00 | 0.00 | 5.08 | Middle |
| | | 1.91 | 0.64 | 2.54 | 2.54 | Bottom |
| | Mid-Test | 12.07 | Face 5 selected for mid- and post-tests | Face 2 selected for mid- and post-tests | 13.34 | Top |
| | | 10.16 | | | 12.07 | Middle |
| | | 5.08 | | | 8.26 | Bottom |
| | Post-Test | 19.05 | | | 23.50 | Top |
| | | 15.88 | | | 19.05 | Middle |
| | | 9.53 | | | 11.43 | Bottom |
| | Total Offset | 14.61 | | | 19.05 | Top |
| | | 12.07 | | | 13.97 | Middle |
| | | 7.62 | | | 8.89 | Bottom |

| Stacking Pattern AABBAA | | | | | | |
|---|---|---|---|---|---|---|
| Replicate | Test | Face 5 | Face 6 | Face 4 | Face 2 | Layer |
| 4 | Pre-Test | 4.45 | 2.54 | 1.91 | 6.35 | Top |
| | | 5.72 | 0.00 | 0.00 | 6.35 | Middle |
| | | 2.54 | 0.00 | 2.54 | 6.99 | Bottom |
| | Mid-Test | 15.24 | Face 5 selected for mid- and post-tests | Face 2 selected for mid- and post-tests | 12.07 | Top |
| | | 13.34 | | | 12.07 | Middle |
| | | 7.62 | | | 6.35 | Bottom |
| | Post-Test | 22.23 | | | 19.05 | Top |
| | | 18.42 | | | 17.15 | Middle |
| | | 11.43 | | | 10.16 | Bottom |
| | Total Offset | 17.15 | | | 12.70 | Top |
| | | 7.62 | | | 10.16 | Middle |
| | | 3.81 | | | 5.08 | Bottom |
| 5 | Pre-Test | 4.45 | 2.54 | 1.91 | 6.35 | Top |
| | | 5.72 | 0.00 | 0.00 | 6.35 | Middle |
| | | 2.54 | 0.00 | 2.54 | 6.99 | Bottom |
| | Mid-Test | 13.34 | Face 5 selected for mid- and post-tests | Face 2 selected for mid- and post-tests | 23.50 | Top |
| | | 8.26 | | | 17.15 | Middle |
| | | 10.16 | | | 11.43 | Bottom |
| | Post-Test | 17.15 | | | 40.64 | Top |
| | | 15.88 | | | 29.85 | Middle |
| | | 11.43 | | | 16.51 | Bottom |
| | Total Offset | 12.70 | | | 34.29 | Top |
| | | 10.16 | | | 23.50 | Middle |
| | | 8.89 | | | 9.53 | Bottom |
| Stacking Pattern AAAABB | | | | | | |
| Replicate | Test | Face 5 | Face 6 | Face 4 | Face 2 | Layer |
| 1 | Pre-Test | 5.72 | 0.00 | 6.99 | 0.64 | Top |
| | | 5.72 | 0.00 | 6.99 | 1.91 | Middle |
| | | 6.99 | 0.64 | 0.64 | 3.81 | Bottom |
| 2 | Pre-Test | 0.00 | 5.08 | 3.81 | 6.35 | Top |
| | | 1.27 | 3.81 | 1.27 | 5.72 | Middle |
| | | 1.27 | 3.18 | 4.45 | 2.54 | Bottom |

## OBSERVATIONS

### AABBAA Stacking Pattern

After the first two impacts during the mid-test, the unit loads experienced slight deformation to both impacted faces. The top cases on the unit load had the greatest amount of offset due to the shock loading from impact. The last two impacts across the replicates rendered significantly greater offsets than the first two. Figure 13 shows the average offset measurements for the five replicates by Layer as well as average across all Layers. It was observed that the offsets became larger from the bottom to the top Layers and were observed to be significantly higher for the faces along the pallet length in comparison to faces along the pallet width.

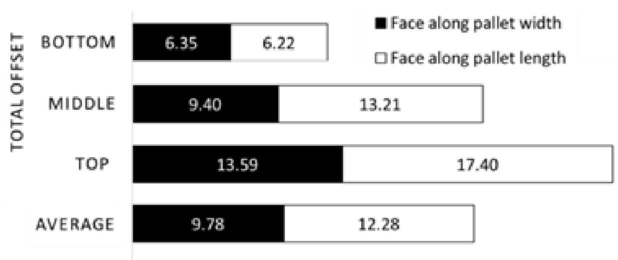


*Figure 13: Incline Impact Total Offset Results for Stacking Pattern AABBAA (cm)*

### AAAABB Stacking Pattern

After completing the second impact during the mid-test, all unit loads experienced extensive offsets rendering them unsafe to proceed with to the next stage of the testing (Figure 14). Subsequently, further testing was discontinued and the trials were recorded as having failed.

*Figure 14: Mid-Test Failure After Second Impact for Stack Pattern AAAABB Unit Loads*

## CONCLUSIONS

This study was undertaken to address the present need for establishing test methodologies towards observing a unit load's overall stability during transportation and handling related activities commonly experienced in the distribution environment. ISTA's Load Stability Testing Workgroup supported this study towards exploring relatively low level, short duration shocks using the modified inclined-impact tester as well as determining how well a unit load would stay contained (stable) when experiencing the gravitational forces created by truck acceleration, truck braking and truck turning. Towards addressing this, test methodologies as well as apparatus/measuring tool for tilt and incline impact tests were also developed. Collectively, these provide valuable insight and test procedures towards understanding a unit load's response to shocks and shifts commonly experienced during distribution related activities.

With regards to the tilt test, the unit load with the AAAABB stack pattern demonstrated significantly lower stability as compared to the AABBAA configuration. The AAAABB stack pattern also exhibited handling related safety issues due to excessive offsets during the experimentation related activities such as fork lift handling, stretch wrapping, and measurements. Altering the unit load to four or five tiers, stack pattern to ABABAB as well as the stretch wrap material and/or pattern may potentially increase the overall stability of the unit loads. Testing with smaller increments of tilt angles up to $15^0$ is also recommended.

As related to the incline impact testing, the unit load with the AABBAA stack pattern demonstrated significant stability and containment of the cases through all five replicate tests. For the AAAABB stack pattern, the four consecutive layers of column stacked cases appeared to be a key factor in the failure of the unit loads. Based on the observations and results of this study, the AAAABB configuration would not be safe to use in a distribution environment where the unit load was likely to experience shocks such as those demonstrated in this research. Testing at various speeds such as 0.40, 0.50, 0.60 and 0.70 mps, towards evaluating the unit load stability, is recommended for future work.

The findings of these tests should contribute to potential new methods for International Safe Transit Association's (ISTA) Procedures 3B and 3E testing requirements. Packaging engineers should be able to appropriately develop and/or validate unit loads of packaged goods utilizing the new test methods.

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