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STUDY OF LATERAL SHOCKS OBSERVED DURING FORK TRUCK
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STUDY OF LATERAL SHOCKS OBSERVED DURING FORK TRUCK AND PALLET JACK OPERATIONS FOR THE HANDLING OF PALLETIZED LOADS

By

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ABSTRACT

STUDY OF LATERAL SHOCKS OBSERVED DURING FORK TRUCK OPERATIONS FOR THE HANDLING OF PALLETIZED LOADS

By

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This study measured the lateral impact levels that occur when fork trucks are used to handle palletized loads. The existing ASTM-D4003 standard on pallet marshalling recommends a 40 G, 10 ms shock or a 10 G, 50 ms shock to simulate impacts on pallet loads due to fork truck equipment. This study investigated the validity of these levels since no previous studies documenting these levels is provided in the ASTM standards. A set of ten impacts were conducted in the following scenarios using boxes, bins, and drums:

- Pallet load on a fork truck impacts a similar stationary pallet load.
- Fork truck impacts pallet load.

Results are presented for each category of impacts performed in terms of average and maximum levels measured. The average peak acceleration for all the data collected was 35.84 G and the average duration of impact was 4.3 ms. An analysis describing the limiting conditions for the shock acceleration G and the duration T as a function of the fork truck weight, impact speed, pallet weight and impact condition was determined. This showed that the impacts should have the product of maximum shock in G and duration T lie between 37.2 and 368 G-s for half-sine shocks.

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1.0 INTRODUCTION

Throughout the distribution system packages are handled and shipped in various ways to deliver products from manufacturers to consumers. The concept of using pallets developed concurrently with the introduction of the forklift trucks in the 1940's. This was mainly to efficiently transport large volumes of packaged products to support the Allied forces during World War II. A pallet in general is a fabricated platform used as a base for assembling, storing, handling, and transporting materials and products in a load. Today pallets form the basis of all rational materials handling in the United States (Bakker, 1986). There is a very small use of slip sheets for handling and moving very light products like breakfast cereals and snack crackers in cartons that when unitized weigh less than 500 lb.

In 1989 an estimated 505 million pallets were bought in the United States to transport various packaged products (Healy, 1990). Pallets come in many different designs and may be made from wood, plastic, corrugated or honeycomb, metal, or combinations of these materials. Over 90% of these pallets are made from wood. The most commonly used pallet in the United States is a 40 in. x 48 in. wood stringer pallet. However, in Europe the common type is a 800 mm x 1200 mm wood block pallet (Bakker, 1986).

There is also a series of new plastic pallets that have been developed in the last decade. Plastic containers and pallets have excellent performance characteristics. They are strong, lightweight, durable, corrosion-free, non absorbent, and weather resistant. International transport regulations allow plastic pallets and containers to carry a great number of hazardous materials. Plastic pallets are predominantly used for returnable/reusable packaging operations in the automotive industry, or as part of intra-plant clean room requirements in the food and pharmaceutical industry. The Grocery Manufacturers Association (GMA), which forms the largest percentage of pallet users is also evaluating various new plastic pallets as part of the international need to select a standardized size (40 in. x 48 in.) reusable pallet for the grocery industry.

1.1 Palletized Packaged Loads

The most common packaging systems that are combined and handled as palletized loads are described in this section.

1.1.1 Palletized Loads of Corrugated Boxes

The vast majority of products that are palletized are usually first packaged in corrugated boxes and these are stacked on a pallet. Depending upon the size of the corrugated box and the strength requirements, corrugated boxes can be stacked in various configurations. Some of the most common types used are column, interlock, and spiral. Some recent studies have investigated the effect of transport vibration and stack configuration on the dynamic compression in corrugated boxes (Eungjoo, 1993). Various load stabilization methods like stretch wrap, shrink wrap, strapping, etc., are used to maintain the load intact during transportation and handling.

1.1.2 Palletized Loads of Drums

Bulk liquid products are generally shipped in four 55 gallon drums which stand on end on a standard GMA pallet. The 55 gallon drums are usually made of metal, plastic, or fiber composite. Metal drums form the vast majority of all drums. The disadvantages of metal drums are: they may be subjected to permanent dents during impacts; they are heavy to manually handle when empty, and they are attacked by many chemicals. Plastic drums are often used for caustic chemicals. They are also used in the food-processing industry for the shipment and storage of products that include concentrated fruit juices, vegetable pulps, condiments, etc. (Bakker, 1986). Fiber composite drums are usually used for low density dry powdered products. There is also a small percentage of palletized liquid tanks used by the pesticide industry for agricultural applications.

1.1.3 Pallet Bins

A pallet container, or pallet bin, is defined as a pallet having a superstructure of at least two sides (fixed, removable, or collapsible), with or without a lid. Pallet bins may have any design of pallet as a base, and the bin may be constructed of plywood, lumber, wire, mesh, corrugated paper, plastic, or metal. The bin may be attached permanently to the pallet base or it may be removed and folded, or collapsed, to become a collapsible bin.

Wooden bin pallets have been widely used in the agricultural industry for the past several decades. They are used to transport fresh produce from the farm to regional processing facilities to be graded, sorted, cleaned, and packaged for shipment. The automotive industry also has been using metal and plastic bins to handle and transport heavy metal parts to assembly plants. Some recent plastic bins offer access gates for operators to retrieve the contents, are lighter and therefore preferred for ergonomical reasons.

1.2 Fork Lift Pallet Handling Equipment

This section discusses the various types of material handling equipment that is used to handle various types of palletized loads. Forklift Trucks (also called Fork Trucks) are either totally 'automated' (where they use computerized wire or optical guiding systems) to control the truck or 'semi-automated' (where a human operator controls the truck). The use of automated driverless trucks will increase in the future. Such a truck can pick a pallet automatically from a given level, transport it and deposit it at a different level. In this way, the truck becomes an alternative to a conveyor. Other, more specialized types of driverless trucks are called automatically guided vehicles (AGVS). Semi-automated forklift trucks are commonly used in most warehouse loading operations because they have no route restrictions and are suitable for application where flexibility is important.

The Swedish Standard SMS 2795 uses the following classifications to describe the most common types of forklift trucks used to handle palletized loads (Lindvist, 1985):

- Powered truck: A powered mechanical handling vehicle for load carrying or traction purposes.
- Hand pallet truck: A non-powered mechanical handling vehicle able to lift and carry loads.

The *counterbalanced* type of forklift truck is the most commonly used palletized load handling equipment. A counterbalanced truck is large and heavy when compared to other types of trucks with equal lifting capacity. Its weight and size may also make it slower and less maneuverable than other smaller truck types. Counterbalanced trucks carry their loads outside the stability polygon. The stability polygon is an area limited by assumed lines drawn between the truck's points of contact with the floor (Figure 1). The load's tendency to tip the truck forward is counteracted by the truck's weight. To increase the load capacity additional ballast is normally mounted at the rear of the truck and therefore referred to as 'counterbalanced truck'.

As counterbalanced trucks always carry their loads outside the chassis area they can accommodate large weights although the size need not be excessive. They are useful as general purpose machines and are employed in most branches of trade and industry. Counterbalanced trucks can

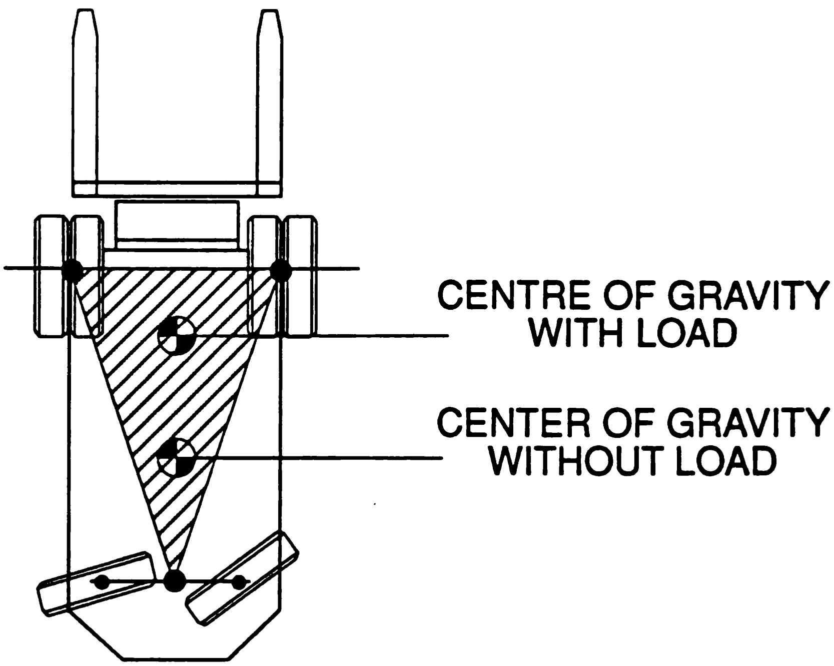


Figure 1: Stability Polygon of a 4 Wheel Truck

accommodate good sized cabs and comparatively large wheels and are also suitable for outdoor use on uneven ground.

Powered stackers are more compact than counterbalanced trucks and can operate in narrower aisles. Powered stackers carry their loads mainly inside the stability polygon to give good space utilization. Powered stackers come with different fork concepts: pallet base and straddle base. The straddle concept uses fixed wheels often solid or with solid tires that are mounted in the support arms of pallet base stackers, and the forks envelop the arms from above. Both arms and forks are inserted beneath the load. The support arms of the straddle base stacker are adjacent and parallel outside the forks. When fully lowered, the forks (and therefore the lower surface of the load) are below the upper surface of the support arms. The support arm wheels may be larger than those for the pallet base stacker and the forks thinner. Larger wheels are better able to cope with uneven surfaces. In general straddle stackers are more stable than pallet base stackers.

Powered stackers are used primarily where space is limited (transport in warehouses, workshops, rail wagons, containers, etc.). They are comparatively cheap and common.

Reach trucks combine the characteristics of counterbalanced trucks and powered stackers. When the load (often a pallet) is lowered between the support arms, the truck is stable and requires only a small area to manoeuvre. With the mast extended, it functions as a counterbalanced truck. Loads of various type can be handled outside the chassis area and it is not necessary for the support arms to enter the racking as it is with a pallet base stacker. Because of their versatility these trucks are common in palletized warehouses. They stack unloading operations from floor level. As a result they are able to replace several other truck types.

Reach trucks are designed primarily for pallet racking operations at greater heights than those suited to counterbalanced trucks. They require little space and are fast. Because they incorporate the advantages of counterbalanced trucks, they are also versatile. For instance, they can load and unload Semi-trailers and rail cars from ground level.

Pedestrian operated pallet trucks are the simplest and cheapest powered vehicles for handling pallets. They are design to transport materials over short distances (less than 50 m) on hard, smooth floors. Because they are controlled by pedestrian operators, their maximum speed is set at 1.67 m/s.

General driving visibility and close visibility are important for safe and efficient fork truck operations of all types. Fork tip visibility is an important aid to efficient handling and to prevent damage to materials. Fork heel visibility is vital for satisfactory handling precision. Stand-On and more especially Sit-On powered pallet trucks are better than pedestrian versions for moving materials over long distances. Driving speed is higher, normally 6-8 km/h (standing drivers) and 8-12 km/h (seated drivers).

1.3 Forklift Truck Impact on Pallet Loads

When palletized loads are handled using fork trucks, they are subjected to impacts. The task of moving palletized loads during loading, unloading and storage is referred as pallet marshalling. The impact conditions depend on a number of factors like forklift truck design, the impact speed, pallet type and load, etc. Such impacts occur every time palletized loads are moved around from manufacturing areas, for temporary storage in warehouses, and loading and unloading trucks and rail cars. These impacts result in mechanical shocks (Brandenburg and Lee, 1991). The acceleration versus time plot for most shocks is very complex, as shown in Figure 2. To understand and estimate the potential damage a shock may cause, we need to know both the magnitude of the acceleration and the duration of the shock. Packages and products typically receive mechanical shocks lasting somewhere between 1 and 50 ms in the distribution system due to various types of impacts (Brandenburg and Lee, 1991). The shock duration is related to the product weight and cushion characteristics. Every element of the distribution system has a unique, complex profile and very little is known about the shock levels encountered during the handling of palletized loads.

There are various studies that have specifically measured the vibration levels and impacts experienced by individual packages during small parcel shipments. However, virtually no recent information exists on the forklift handling environments of palletized loads.

The ASTM-D4003 test method titled "Standard methods of controlled

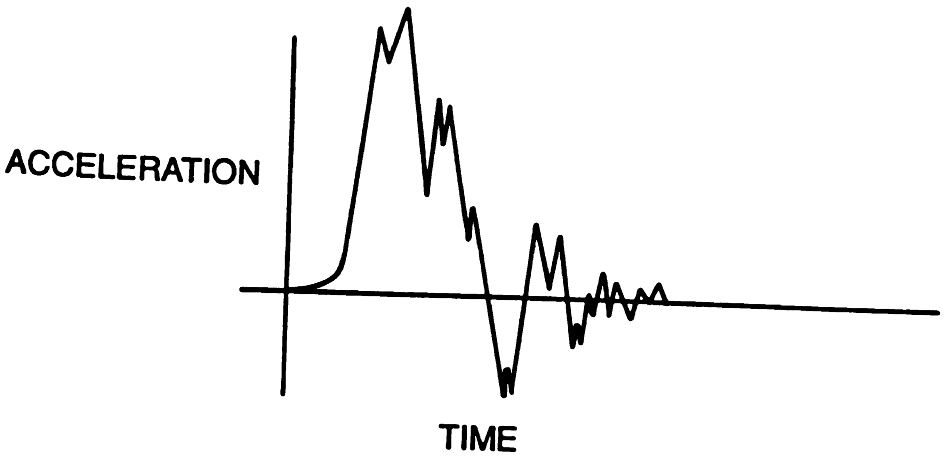


Figure 2: Acceleration Time History of a Mechanical Shock

horizontal impact test for shipping containers" is used by packaging engineers to determine the ability of a package or product to withstand laboratory simulated horizontal impact forces. The horizontal impacts used in this method are programmed shock inputs that represent the hazards as they occur in the shipping and handling environments. Specifically, the Test Method B (Pallet Marshalling Impact Tests) determines the ability of single containers and unit load quantities to withstand the forces encountered during pallet marshalling operations. These impacts may cause the containers thereon to become disoriented or crushed (ASTM, 1981). This current ASTM standard on pallet marshalling recommends a 40 G and 10 ms shock, or a 10 G and 50 ms shock, to represent a fork truck impact to a palletized load. However, there is no reference to any studies representing the source of these test levels.

In a previous study, done at the Sandia Laboratories, the dynamic environment of four industrial forklift trucks was studied (Gens, 1975). The purpose of this study was to determine the dynamic input to the cargo during transport on various types of forklift trucks. This study primarily focussed on the shock and vibration ride qualities for palletized cargo movement. Among the variations examined were: trucks with capacities of 2000, 3000, 4000, and 7000 lbs.; trucks with pneumatic and solid rubber tires and; trucks powered by either gasoline engines or electric motors.

The cargo used a simulated bomb shape mounted on a cradle-like rack which was used to transport and handle weapons. It was found that there was little steady-state continuous vertical excitation transmitted through the forks to the load. Many discrete excitations were present. Data reduction in the form of vertical shock response spectra showed responses up to 10 G in amplitude below 20 Hz and up to 40 G at 100 Hz. Of the variables investigated, the one that had the greatest influence with respect to producing a smooth ride was the ratio of vehicle lifting capacity to the weight of the load. The truck most heavily loaded had the smoothest ride. The type of tire had little, if any, effect on the dynamic environment. (Gens, 1975).

1.4 Study Objectives

No other study has documented any measurement of impacts during various pallet marshalling operations. This study primarily measured the various shock levels occurring to pallet loads of corrugated boxes, drums, and bulk bins during marshalling tasks. It also developed recommendations on selecting impact conditions to perform pallet marshalling tests using horizontal impact testers.

Specifically, this research had the following objectives:

1. Measure the shock levels during normal and severe impact conditions to pallet loads of corrugated boxes, drums, and bulk bins during pallet marshalling.

2. Develop criteria for determining impact conditions required to simulate horizontal impacts to pallet loads due to pallet marshalling.

3. Develop a recommended test protocol to simulate both average and severe pallet marshalling conditions in a laboratory.

2.0 EXPERIMENTAL DESIGN

This study investigated three types of unit load configurations. These were palletized loads of stacked corrugated boxes, bulk bins, and plastic drums. The stacked corrugated boxes contained individually cushioned product. The automotive bulk bin is a standard HDPE structural foam knock-down returnable container used by General Motors. The 55 gallon HDPE plastic drums contained water. The stacked corrugated boxes and the plastic drums were loaded on standard GMA wood stringer pallets. The automotive bulk bin had an integral plastic pallet built into the structure.

The different weights of the various palletized loads used in this study are:

- Stacked corrugated boxes: 500 lb and 1500 lb.
- Automotive plastic bulk bin: 600 lb and 1200 lb.
- 55 gallon plastic drums: 2000 lb.

The maximum driving speed of most widely used industrial fork trucks ranges from 2.5 to 5 MPH for standing drivers to 5 to 7.5 MPH for seated drivers. However impacts/collisions at these speeds can result in injury to the operators as well or severe product damage. These speeds were therefore not used as a basis to collect data for designing and testing packages.

The tests were conducted in the MSU stores warehouse using counterbalanced fork truck equipment in both normal and severe handling conditions. Normal conditions, in this study means the use of an experienced forklift operator instructed to drive as close to the average operating speed of the truck as he possibly can. This speed was approximately 0.7 MPH. The severe conditions, in this study means the use of an experienced forklift operator instructed to operate and impact the load as close to the maximum speed of the truck as he possibly can without resulting in a severe injury. The highest speed feasible under these conditions was approximately 4 MPH.

The weights of various commercial fork truck equipment varies from 4000 to 7000 lb. This study used a counterbalanced forklift truck weighing approximately 6700 lb.

The objective of this study was to measure the lateral impact levels that occur when fork trucks are used to handle various palletized loads described above. The impact levels were measured along the direction of impact both on the pallet and the pallet load. A minimum of ten impacts were performed in the following scenarios for both the average and severe conditions using the fork truck described above:

- Pallet load on the fork truck impacts a similar stationary load
- Fork truck impacts a stationary pallet load.

In addition, a series of ten impacts were performed with the pallet load on the fork truck impacting a rigid wall. Initially these types of impacts were to be performed for both normal and severe conditions for the three types of palletized loads. However, the first set of impacts resulted in hazard conditions for the operator so additional data was not collected for this category.

2.1 Instrumentation and Data Acquisition

The impact levels experienced by the pallet and the load were measured using accelerometers. The two accelerometers used in this study were PCB Piezotronics Model #302A02, Sensitivity 10.00 mV/G and Model #302A02, Serial #17809, Sensitivity 9.80 mV/G. The output from the accelerometers was each connected to Dytran Model 4102 piezoelectric couplers (Serial #1301 and #1302) using accelerometer cables. The output from the couplers was measured and recorded using the Test Partner Data Acquisition System (Lansmont Corporation). All the data was processed using the Test Partner Analysis Software.

2.2 Test Setup

The accelerometers were mounted on aluminum face plates which were rigidly connected to the pallet and the load. One of them was located on the pallet and the other on the load at the top section. Figure 3 describes the test setup to collect pallet impact data during pallet marshalling operations.

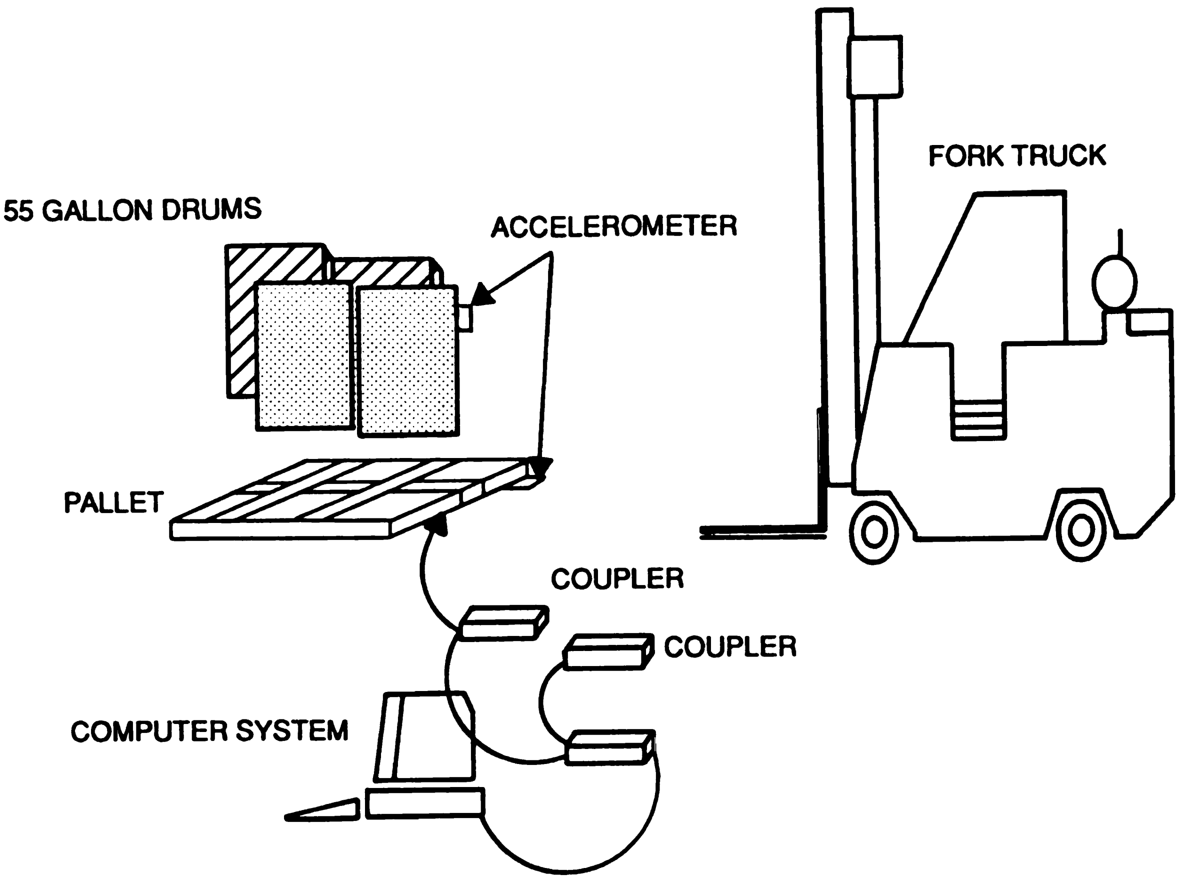


Figure 3: Test Setup to Measure Pallet Impacts

3.0 DATA ANALYSIS AND RESULTS

The entire data for each impact condition in this study on the pallet is listed in Appendix A in Tables A1 to A21. These tables list the peak acceleration (G) and time duration (ms) data for all impacts measured. Appendix B lists all the impact data measured to the load during the various impact conditions in Tables B1 to B21. All these impacts were measured in the direction of impact.

The summarized data is presented for each category of impacts performed in terms of the average and maximum levels measured. Table 1 provides the average and maximum impact levels measured in this study on the pallet as a function of impact condition and pallet weight for corrugated boxes. Similarly Tables 2 and 3 provides the average and maximum impact levels measured in this study on the pallet as a function of impact condition and pallet weight for bulk bins and drums, respectively.

Table 4 provides the average and maximum impact levels measured in this study on the load as a function of impact condition and pallet weight for corrugated boxes. Similarly, Tables 5 and 6 provide the average and maximum impact levels measured in this study on the load as a function of impact condition and pallet weight for bulk bins and drums, respectively.

The data for all impacts measured in this study had a average peak acceleration of 35.84 G's and a average duration of 4.33 ms.

TABLE 1: Shock Levels to the Hardwood Pallet in Palletized Handling of Corrugated Boxes

Impact Condition	Pallet Weight (lb)	Impact Surface	Average Levels		Maximum Levels		
			Shock (G)	T (ms)	Shock (G)	T (ms)	Product (G_p x T)
Average	500	Pallet	33.35	3.72	60.88	2.70	164.38
Average	500	Truck	23.73	9.00	35.37	8.12	287.20
Average	1500	Pallet	33.58	3.00	153.38	1.32	202.46
Average	1500	Truck	19.48	9.20	31.28	9.80	306.54
Severe	500	Pallet	107.15	1.79	222.02	0.63	139.87
Severe	500	Truck	39.86	11.60	46.03	12.15	559.26
Severe	1500	Pallet	88.47	2.07	174.55	1.67	291.50
Severe	1500	Truck	29.11	6.73	41.35	4.85	200.55
Average	500	Wall	59.34	3.20	188.80	1.09	205.79

TABLE 2: Shock Levels to the Pallet in Palletized Handling of Bulk Bins

Impact Condition	Weight (lb)	Impact Surface	Average Levels		Maximum Levels		
			Shock (G's)	Duration (ms)	Shock (G's)	Duration (ms)	Product (G_p x T)
Average	600	Pallet	27.48	3.10	76.35	0.94	71.77
Average	600	Truck	15.57	1.12	22.38	1.32	29.54
Average	1200	Pallet	14.95	1.70	32.47	2.18	70.78
Average	1200	Truck	25.19	1.95	54.04	4.24	229.13
Severe	600	Pallet	22.22	3.65	34.80	1.46	50.81
Severe	600	Truck	23.27	1.14	34.46	1.14	39.28
Severe	1200	Pallet	31.13	2.86	56.68	3.84	217.65
Severe	1200	Truck	26.25	2.55	35.69	9.46	337.63

TABLE 3: Shock Levels to the Pallet in Palletized Handling of Drums

Impact Condition	Weight (lb)	Impact Surface	Average Levels		Maximum Levels		
			Shock (G's)	Duration (ms)	Shock (G's)	Duration (ms)	Product (G_p x T)
Average	2000	Pallet	26.73	2.99	88.25	2.32	204.74
Average	2000	Truck	17.66	8.19	22.82	9.80	223.64
Severe	2000	Pallet	50.90	3.37	88.10	2.84	250.20
Severe	2000	Truck	37.21	8.03	48.49	0.42	20.37

TABLE 4: Shock Levels in Top Layer for Palletized Handling of Corrugated Boxes (Load Response)

Impact Condition	Weight (lb)	Impact Surface	Average Levels		Maximum Levels	
			Shock (G's)	Duration (ms)	Shock (G's)	Duration (ms)
Average	500	Pallet	4.04	25.15	8.41	22.25
Average	500	Truck	8.24	8.28	12.33	14.58
Average	1500	Pallet	4.73	6.06	14.35	1.32
Average	1500	Truck	13.00	5.46	29.63	3.42
Severe	500	Pallet	4.09	5.44	10.39	3.14
Severe	500	Truck	15.55	16.60	24.92	5.85
Severe	1500	Pallet	4.32	7.98	13.47	4.41
Severe	1500	Truck	13.53	11.25	24.23	7.85
Average	500	Wall	4.70	5.87	9.84	7.61

TABLE 5: Shock Levels at the Top Edge of the Bin for Palletized Handling of Bulk Bins (Load Response)

Impact Condition	Weight (lb)	Impact Surface	Average Levels		Maximum Levels	
			Shock (G's)	Duration (ms)	Shock (G's)	Duration (ms)
Average	600	Pallet	27.48	3.10	76.35	0.94
Average	600	Truck	15.57	1.12	22.38	1.32
Average	1200	Pallet	14.95	1.70	32.47	2.18
Average	1200	Truck	25.19	1.95	54.04	4.24
Severe	600	Pallet	22.22	3.65	34.80	1.46
Severe	600	Truck	23.27	1.14	34.46	1.14
Severe	1200	Pallet	31.13	2.86	56.68	3.84
Severe	1200	Truck	26.25	2.55	35.69	9.46

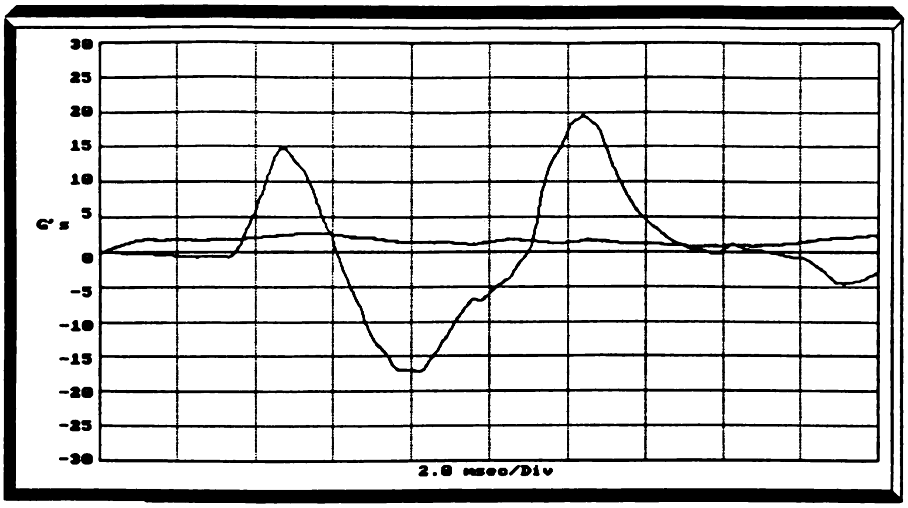
TABLE 6: Shock Levels at the Top Edge of 55 Gallon Drums for Palletized Handling of Drums (Load Response)

Impact Condition	Weight (lb)	Impact Surface	Average Levels		Maximum Levels	
			Shock (G's)	Duration (ms)	Shock (G's)	Duration (ms)
Average	2000	Pallet	6.45	17.48	14.03	49.50
Average	2000	Truck	13.04	11.06	23.10	19.42
Severe	2000	Pallet	4.64	6.61	14.96	19.54
Severe	2000	Truck	5.37	11.88	17.52	19.46

The data collected was analyzed using "Test Partner" analysis software (Lansmont Corporation). The acceleration-time waveforms for pallet impacts are very complex and need careful interpretation and analysis. The reason for this is the variation that exists in obtaining perfectly similar impact conditions. Specifically, the choice of filtering frequencies where digital filtering was used depends on the shape of the shock pulse and is critical since it reflects the final acceleration and duration reported.

Figures 4 and 5 represent some specific shock pulses where the choice of filter frequencies are critical to correctly interpret the impact levels. The "Test Partner" usually uses a default filter frequency which is a function of the duration of the entire impact. However, for these specific cases this could result in providing misleading information.

Figure 4 is an example of a double impact measured in this study. These occur when the fork truck makes contact with one end of the pallet before the other end resulting in successive impacts monitored by the accelerometer. The top pulse shows this impact without any filtering. The bottom pulse shows the results using the default filter, which overfiltered this pulse and combined the two impacts resulting in a longer duration shock. It was therefore important to analyze individual impacts in this case manually. Figure 5 is an example of multiple shocks. These are likely to occur when a loaded fork truck impacts the stationary load as indicated by the top pulse. Similar shocks could also occur due to the truck continuing to impact the pallet



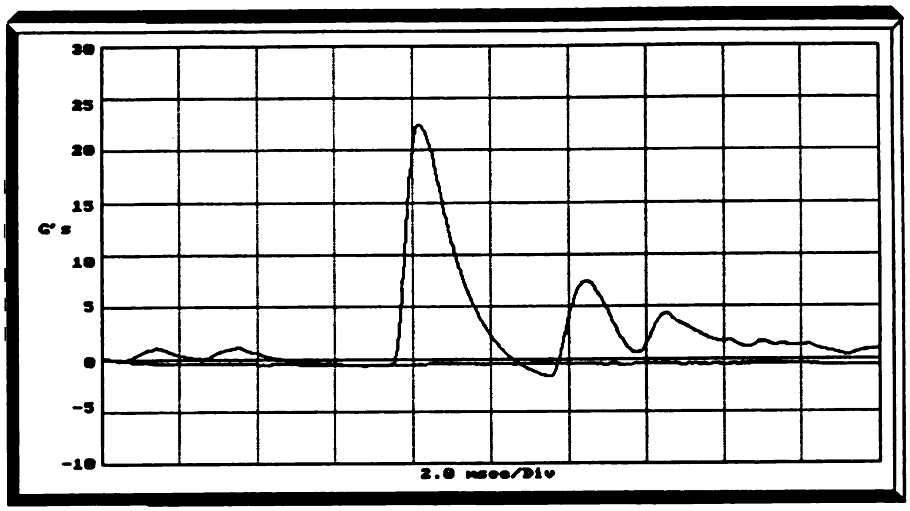
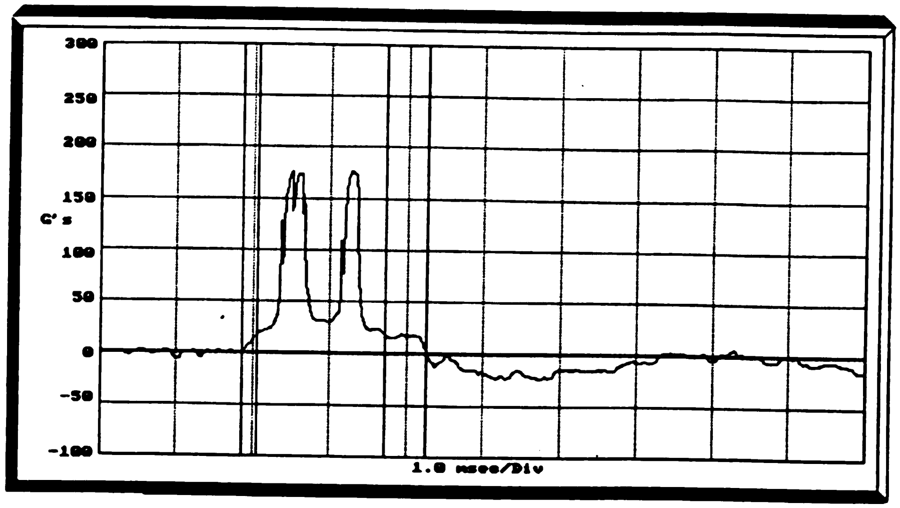


Figure 4: Shock Pulses for Multiple Impacts



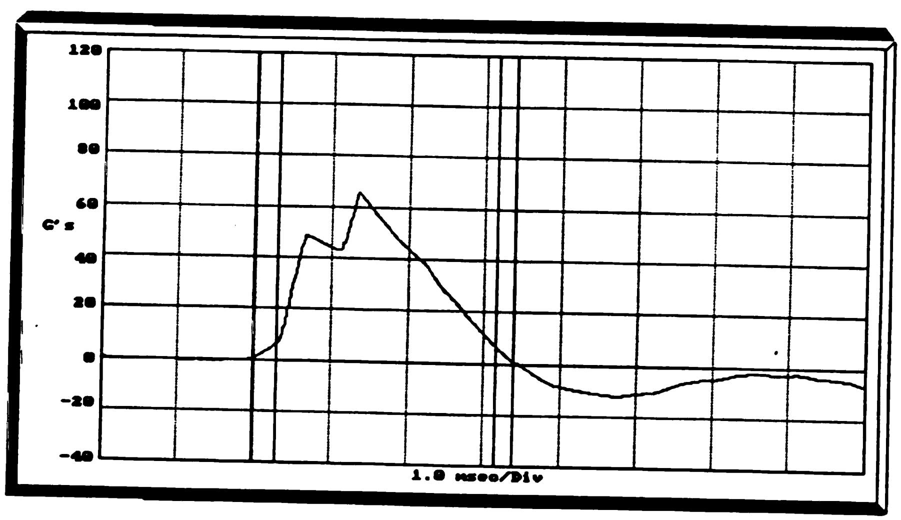


Figure 5: Shock Pulses for Double Impacts

and the contents (e.g., drums) repeatedly as shown by the bottom pulse. Figure 6 represents some examples of good shock pulses that were measured for the various impact conditions in the palletized loads.

This section discusses the analysis of a fork truck impacting a stationary pallet load. This will be used to discuss the data later on in this Chapter. Let us consider a fork truck impacting a pallet load as shown in Figure 7. Using momentum balance at impact,

$$W_t V_t + W_p V_p = W_t V_t^1 + W_p V_p^1 \tag{3-1}$$

where

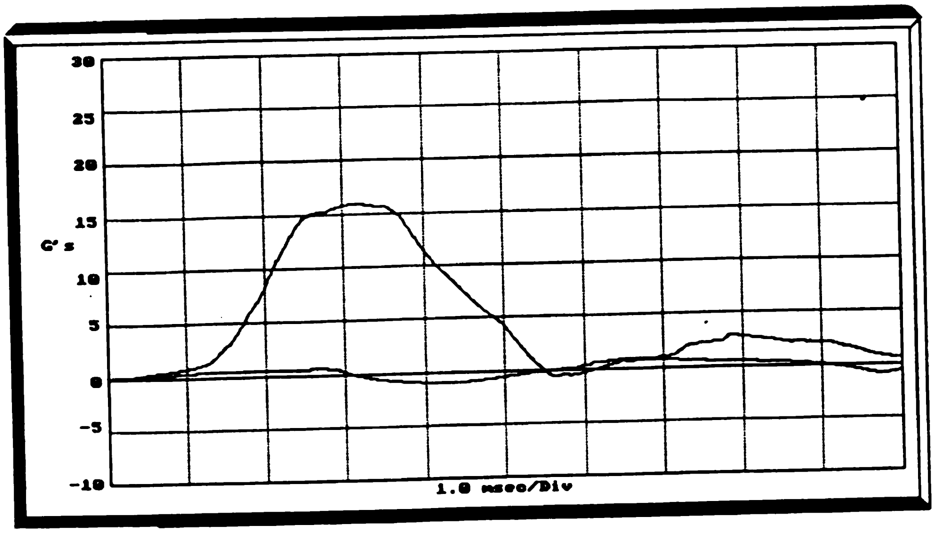
W_t	=	weight of truck
W_p	=	weight of pallet
V_t	=	velocity of truck before impact
V_p	=	velocity of pallet before impact = 0
V_t^1	=	velocity of truck after impact
V_p^1	=	velocity of pallet after impact

The coefficient of restitution 'e' at impact will be:

$$e = \frac{V_p^1 - V_t^1}{V_t - V_p} \tag{3-2}$$

The final velocities of the truck and pallet after impact, can be determined by simultaneously solving equations (3-1) and (3-2). These are represented as:

$$V_t^1 = \left(\frac{W_t - eW_p}{W_t + W_p}\right) V_t \tag{3-3}$$



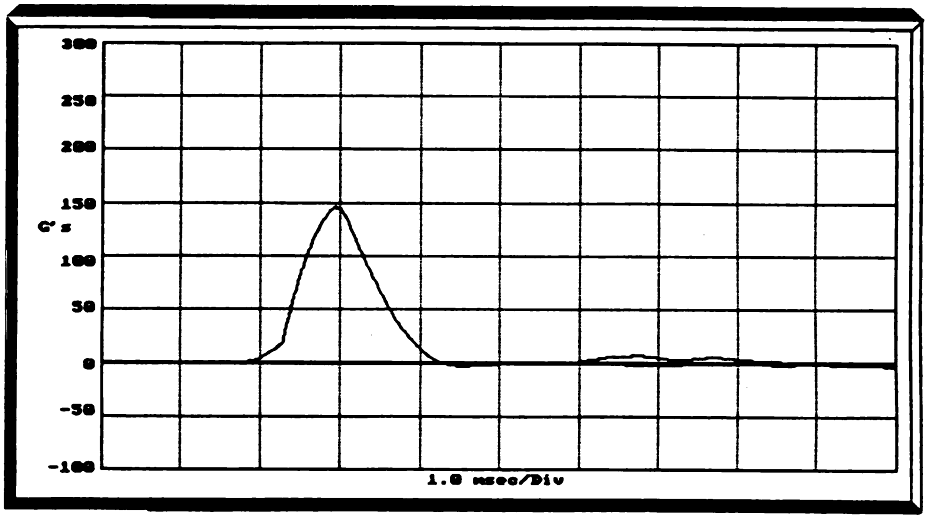


Figure 6: Shock Pulses for Good Impacts

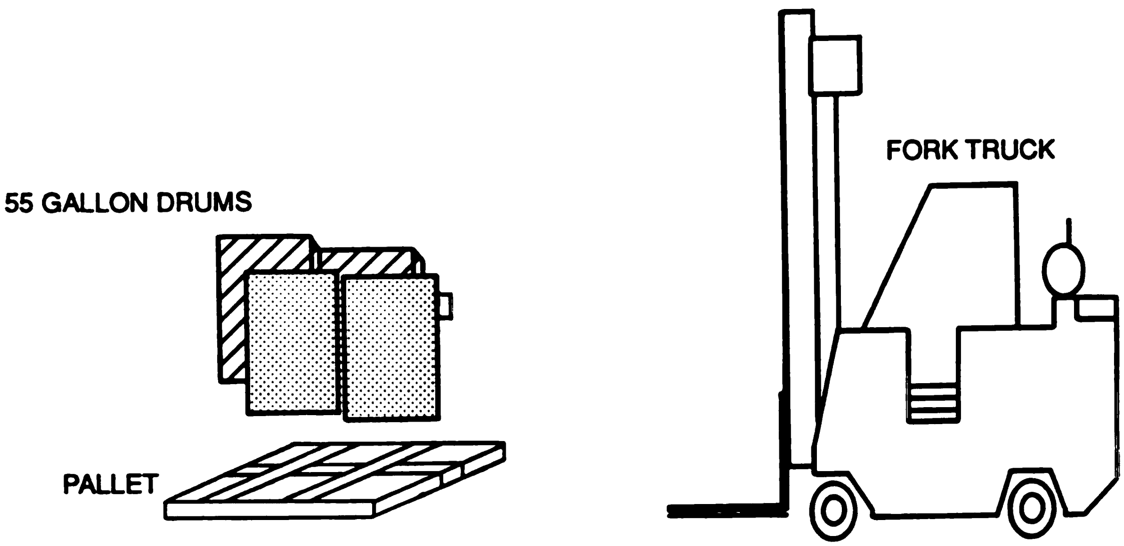


Figure 7: Fork Truck Impacts on Stationary Load

and $$V_p^1 = \left(\frac{(1+e)\,W_t}{W_t + W_p}\right) V_t \qquad (3\text{-}4)$$

The velocity change for the pallet at impact is:

$$\Delta V_p = V_p^1 - V_p = \frac{(1+e)\,W_t}{W_t + W_p} \cdot V_t \qquad (3\text{-}5)$$

Based on an acceleration-time plot of a shock representing a pallet impact as shown in Figure 8, let the average acceleration during impact be $\overline{G_p}$. This can be mathematically represented as:

$$\overline{G_p} = \frac{1}{g}\left(\frac{\Delta V_p}{T}\right) = \frac{(1+e)\,W_t}{W_t + W_p} \cdot \frac{V_t}{gT} \qquad (3\text{-}6)$$

where T = duration of impact
g = Acceleration due to gravity

Let us represent the weight ratio as: $$R = \frac{W_p}{W_t} \qquad (3\text{-}7)$$

Substituting (3-7) in (3-6) the average acceleration of the pallet is

$$\overline{G_p} = \left(\frac{1+e}{1+R}\right) \frac{V_t}{gT} \qquad (3\text{-}8)$$

The acceleration-time history of most pallet impacts is complex, and therefore the average acceleration term was determined in (3-8). However, to simulate

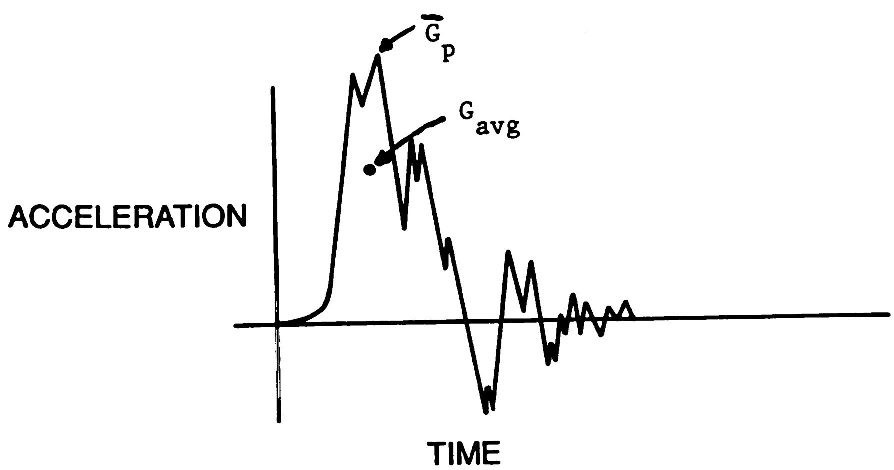


Figure 8: Acceleration Time Plot Representing Pallet Marshalling Impacts

these impact conditions in a laboratory test setup the equipment uses programmers that produce half-sine shape shock pulses. Therefore, the average acceleration term determined in (3-8) can be further represented as the peak acceleration of the pallet using the relation between the peak and average values of a sine wave as:

$$G_{peak} = \left(\frac{\Pi}{2}\right) G_{avg} \qquad (3\text{-}9)$$

Using conventional units used in packaging of $g = 386.4$ in./s^2, and V_t in ft/s, and T in ms, the equation (3-8) can be written as:

$$\overline{G_p} = \frac{(1+e)}{1+R} \frac{V_t \times 12}{386.4 \times \frac{T}{1000}} \qquad (3\text{-}10)$$

or

$$\overline{G_p} = 31 \left(\frac{1+e}{1+R}\right) \frac{V_t}{T} \qquad (3\text{-}11)$$

where $\overline{G_p}$, e, R = dimensionless

V_t = ft/s

T = ms

Any test standard which recommends the use of a certain average G and corresponding duration T to simulate pallet jacking/marshalling operations must choose these values to coincide with known limits on e, R, V_t via the above equation.

Specifically, the product of $\overline{G_p}$ and T must satisfy

$$\overline{G_p} \times T - 31 \left(\frac{1 + e}{1 + R}\right) V_t \tag{3-12}$$

The above equation describes the limiting conditions for the average shock acceleration and the duration as a function of the fork truck weight, impact speed, pallet weight, and impact conditions. As the weight ratio 'R' increases, the product of the average shock acceleration ' $\overline{G_p}$ ' and the duration 'T' will decrease. The product of ' $\overline{G_p}$ ' and 'T' is directly proportional to both the impact velocity 'V_t' and (1+e). The coefficient of restitution depends on the stiffness of impacting surfaces. Metal and wood pallets will generally result in higher 'e' values on impact as compared to plastic and corrugated or honeycomb pallets. The coefficient of restitution lies between 0.0 and 1.0. However, for test purposes it is recommended to select an "e" close to 1.0 representing the most severe impact condition. The impact velocity of the fork truck can be determined using different velocity measuring equipment like a video camera and a timer or a radar gun.

The impact conditions ($\overline{G_p}$ x T) to simulate pallet marshalling testing for specific cases can be determined knowing the truck weight, pallet weight, and selecting the most severe impact velocity and impact condition. Knowing these levels, the desired shock pulse can be programmed in the Impact Testing Machine.

In this study the following conditions applied to all the data collected. The impact velocity V_t ranged from 1 ft/s for average impact conditions to 4 ft/s for severe conditions. The weight of the truck W_t ranged from 6500 to 8500 lb. and the weight of the pallet W_p ranged from 500 to 2000 lb. We also know that 'e' is between 0.0 and 1.0. Therefore, substituting e, R, and V_t in (3-12) and establishing the limits so as to make $\overline{G_p}T$ as large and as small as possible gives:

$$31\left(\frac{1+0}{1+.31}\right)1 < \overline{G_p}T < 31\left(\frac{1+1}{1+.059}\right)4 \qquad (3\text{-}13)$$

or

$$23.66 < \overline{G_p}T < 234.18 \qquad (3\text{-}14)$$

If half-sine shocks are used to simulate pallet marshalling tests, the peak conditions for (3-14) will be obtained from (3-9) by multiplying by $\frac{\Pi}{2} \rightarrow$.

These are:

$$37.2 < (\text{peak } G_{pallet}) \times (\text{ms duration}) < 368 \qquad (3\text{-}15)$$

Reviewing the data that was collected for pallet marshalling in this study (Tables 1, 2, and 3), almost all of it falls within the limits for both the "average acceleration levels" and "maximum acceleration levels" established by equations (3-12) and (3-15). Those data which do not lie between these limits are either not a half-sine shock, or not the result of a 1 to 4 ft/s impact.

The above limits, and in general, the result:

$$(\textit{peak } G \times ms) = \frac{\Pi}{2} \times 31 \left(\frac{1 + e}{1 + R}\right) V_t = 48.7 \left(\frac{1 + e}{1 + R}\right) V_t \qquad (3\text{-}16)$$

makes sure that the requirements of peak acceleration and duration are realistic. However, it is clear that test conditions recommended in the ASTM D 4003 are significantly more severe than those recommended by equation (3-16), especially for simulating fork truck impacts to single stationary pallet loads.

Based on the data measured in Tables 1, 2, and 3, it is also evident that most of the pallet impacts are significantly short duration shocks (average duration of 4.3 ms), as compared to ASTM D 4003 where impact durations of

10 ms and 50 ms are recommended. This study recommends using a shorter duration shock of 5 ms or below to simulate pallet marshalling tests and determine a recommended shock level using expected values of e, R, and V_t in equation (3-14).

4.0 CONCLUSIONS

Based on the data collected in this study, the following conclusions were made:

1. The existing levels of shocks recommended by ASTM D 4003 are excessively severe and do not truly represent pallet marshalling conditions based on actual data collected.

2. This study shows that short duration impacts (approximately 5 ms) should be used to simulate pallet marshalling operations.

3. This study recommends using the following equation to determine impact levels to simulate pallet marshalling, using a duration 'T', fork truck impact velocity 'V_t', pallet weight W_p, fork truck weight W_t, and coefficient of restitution 'e':

$$\overline{G_p} \times T - 31 \left(\frac{1 + e}{1 + R}\right) V_t \qquad (4\text{-}1)$$

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APPENDIX A

TABLE A.1: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	38.21	2.80
2	37.23	2.65
3	24.07	3.90
4	60.88	2.70
5	60.41	2.65
6	7.00	7.25
7	18.46	2.50
8	13.26	3.70
9	13.81	6.40
10	60.19	2.60

TABLE A.2: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	14.85	3.50
2	18.27	4.54
3	35.37	8.12
4	23.22	11.86
5	21.97	10.50
6	23.42	11.34
7	28.36	8.94
8	17.39	8.88
9	23.70	11.26
10	30.70	11.10

TABLE A.3: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	4.43	0.56
2	22.58	2.18
3	20.56	2.25
4	36.47	4.11
5	13.51	4.55
6	17.82	2.39
7	18.32	2.00
8	31.43	6.49
9	153.38	1.32
10	17.30	4.14

TABLE A.4: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	20.68	8.00
2	20.05	8.44
3	19.52	8.26
4	16.94	12.38
5	21.80	9.56
6	11.94	6.78
7	28.67	11.20
8	31.28	9.80
9	17.56	12.22
10	6.37	5.40

TABLE A.5: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	12.21	2.80
2	119.86	1.72
3	117.75	1.68
4	118.12	1.69
5	73.46	1.68
6	222.02	0.63
7	85.67	1.41
8	101.80	2.53
9	120.49	2.29
10	100.16	1.46

TABLE A.6: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	35.61	12.25
2	45.13	10.15
3	30.27	11.25
4	38.58	12.20
5	38.54	12.20
6	45.21	12.65
7	46.03	12.15
8	35.62	11.10
9	42.27	10.25
10	41.33	11.80

TABLE A.7: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	19.47	3.50
2	44.96	2.60
3	147.88	1.42
4	146.80	1.76
5	152.28	1.43
6	174.55	1.67
7	127.26	1.17
8	23.85	2.68
9	17.98	2.00
10	29.64	2.42

TABLE A.8: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	18.61	4.58
2	34.62	7.65
3	16.16	3.89
4	41.35	4.85
5	40.87	4.88
6	21.08	9.81
7	30.48	6.40
8	28.82	9.10
9	33.28	7.80
10	25.81	8.35

TABLE A.9: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Pallet Load Impacts a Rigid Wall.

Impact Number	Shock (Peak G's)	Duration (ms)
1	15.91	3.94
2	29.62	3.32
3	188.80	1.09
4	37.33	3.07
5	176.89	0.77
6	22.56	2.77
7	19.77	2.60
8	22.19	3.79
9	65.73	2.11
10	14.61	8.53

TABLE A.10: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	8.70	1.84
2	76.35	0.94
3	36.30	1.14
4	22.61	3.96
5	19.32	4.10
6	21.75	3.80
7	31.00	3.08
8	31.72	3.16
9	13.19	4.64
10	13.89	4.34

TABLE A.11: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	12.47	1.06
2	18.93	1.04
3	13.85	1.14
4	12.71	1.08
5	18.59	1.02
6	18.38	1.16
7	22.38	1.32
8	10.53	1.18
9	12.57	1.08
10	15.24	1.08

TABLE A.12: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	32.47	2.18
2	9.93	1.26
3	9.37	1.46
4	15.42	1.98
5	17.40	1.88
6	13.83	1.40
7	13.53	2.24
8	17.48	1.62
9	3.89	1.12
10	16.16	1.86

TABLE A.13: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	25.90	2.08
2	22.35	1.76
3	21.44	1.08
4	28.35	1.26
5	54.04	4.24
6	19.71	1.66
7	17.23	1.74
8	25.53	1.46
9	22.48	1.34
10	14.84	2.84

TABLE A.14: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	13.19	4.64
2	18.44	6.58
3	17.47	2.02
4	20.98	4.10
5	23.87	4.56
6	34.80	1.46
7	32.47	2.18
8	31.35	2.08
9	17.71	4.64
10	11.91	4.28

TABLE A.15: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	34.46	1.14
2	22.38	1.32
3	15.25	1.10
4	17.37	1.08
5	18.56	1.18
6	30.74	0.90
7	15.04	1.04
8	29.02	1.06
9	31.46	1.36
10	18.40	1.20

TABLE A.16: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	7.32	1.68
2	39.84	1.90
3	28.71	0.82
4	31.33	1.90
5	56.35	1.56
6	18.10	4.44
7	18.09	4.44
8	27.58	4.10
9	56.68	3.84
10	27.30	3.90

TABLE A.17: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	33.44	2.96
2	35.69	9.46
3	4.91	1.10
4	31.65	1.74
5	19.18	1.90
6	25.70	1.82
7	24.33	1.74
8	32.22	1.74
9	26.67	1.44
10	28.67	1.58

TABLE A.18: Shock Levels in Palletized Handling of Drums at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	25.02	3.25
2	22.65	2.55
3	32.29	3.10
4	26.67	2.55
5	22.41	3.35
6	12.65	1.54
7	88.25	2.32
8	11.78	4.12
9	12.18	4.06
10	13.43	3.08

TABLE A.19: Shock Levels in Palletized Handling of Drums at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	0.63	19.78
2	22.64	13.34
3	20.66	0.66
4	15.20	11.80
5	20.66	0.66
6	20.36	9.00
7	22.82	9.80
8	19.53	8.94
9	19.15	0.50
10	14.98	7.44

TABLE A.20: Shock Levels in Palletized Handling of Drums at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	69.07	2.62
2	41.69	4.06
3	23.25	8.34
4	88.10	2.84
5	66.57	2.80
6	61.58	2.42
7	54.46	3.34
8	49.45	0.24
9	18.58	1.36
10	36.20	5.72

TABLE A.21: Shock Levels in Palletized Handling of Drums at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	48.49	0.42
2	28.00	9.74
3	42.68	7.58
4	41.82	7.48
5	34.37	8.34
6	43.39	8.32
7	30.48	9.06
8	33.60	10.32
9	39.76	8.60
10	29.47	10.44

APPENDIX B

TABLE B.1: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.64	49.60
2	2.47	49.50
3	4.30	9.05
4	2.61	10.85
5	3.04	13.65
6	2.60	24.55
7	3.45	47.80
8	8.41	22.25
9	6.69	7.80
10	4.23	16.45

TABLE B.2: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	5.64	2.70
2	3.57	1.00
3	8.83	5.30
4	10.88	10.62
5	12.33	14.58
6	8.80	11.16
7	9.40	3.30
8	4.55	10.40
9	9.45	11.12
10	8.90	12.64

TABLE B.3: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	0.49	8.74
2	2.62	3.75
3	6.40	2.63
4	14.35	3.80
5	3.92	9.29
6	2.00	4.62
7	4.24	3.97
8	2.62	4.18
9	7.87	9.68
10	2.82	9.89

TABLE B.4: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	6.39	1.90
2	10.33	2.58
3	9.94	2.40
4	23.98	3.70
5	5.56	9.28
6	5.53	2.76
7	6.23	3.86
8	12.04	19.64
9	29.63	3.42
10	20.32	5.08

TABLE B.5: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.51	7.51
2	3.85	1.07
3	2.67	1.40
4	2.26	1.14
5	6.09	1.68
6	10.39	3.14
7	0.57	9.90
8	2.03	9.19
9	2.79	9.61
10	7.69	9.73

TABLE B.6: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	12.95	35.05
2	14.51	15.85
3	13.22	1.60
4	14.11	28.60
5	13.90	35.10
6	15.30	9.35
7	14.08	9.35
8	16.41	16.10
9	16.07	9.10
10	24.92	5.85

TABLE B.7: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.70	19.80
2	13.47	4.41
3	1.56	8.77
4	1.58	3.99
5	1.52	9.91
6	2.54	9.46
7	1.85	8.45
8	4.36	3.53
9	5.66	3.99
10	7.94	7.45

TABLE B.8: Shock Levels in Palletized Handling of Corrugated Boxes at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.94	9.82
2	19.42	11.45
3	15.20	9.72
4	12.59	1.46
5	11.88	1.47
6	6.69	7.82
7	3.89	2.10
8	24.23	7.85
9	17.95	11.50
10	20.50	49.35

TABLE B.9: Shock Levels in Palletized Handling of Corrugated Boxes at Average Speed and Low Weight. A Pallet Load Impacts a Rigid Wall.

Impact Number	Shock (Peak G's)	Duration (ms)
1	1.01	2.45
2	5.23	4.80
3	4.18	2.99
4	5.61	4.57
5	9.84	7.61
6	2.99	9.88
7	2.76	9.85
8	9.29	7.16
9	3.09	0.02
10	2.98	9.38

TABLE B.10: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	8.70	1.84
2	76.35	0.94
3	36.30	1.14
4	22.61	3.96
5	19.32	4.10
6	21.75	3.80
7	31.00	3.08
8	31.72	3.16
9	13.19	4.64
10	13.89	4.34

TABLE B.11: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	12.47	1.06
2	18.93	1.04
3	13.85	1.14
4	12.71	1.08
5	18.59	1.02
6	18.38	1.16
7	22.38	1.32
8	10.53	1.18
9	12.57	1.08
10	15.24	1.08

TABLE B.12: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	32.47	2.18
2	9.93	1.26
3	9.37	1.46
4	15.42	1.98
5	17.40	1.88
6	13.83	1.40
7	13.53	2.24
8	17.48	1.62
9	3.89	1.12
10	16.16	1.86

TABLE B.13: Shock Levels in Palletized Handling of Bulk Bins at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	25.90	2.08
2	22.35	1.76
3	21.44	1.08
4	28.35	1.26
5	54.04	4.24
6	19.71	1.66
7	17.23	1.74
8	25.53	1.46
9	22.48	1.34
10	14.84	2.84

TABLE B.14: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and Low Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	13.19	4.64
2	18.44	6.58
3	17.47	2.02
4	20.98	4.10
5	23.87	4.56
6	34.80	1.46
7	32.47	2.18
8	31.35	2.08
9	17.71	4.64
10	11.91	4.28

TABLE B.15: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and Low Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	34.46	1.14
2	22.38	1.32
3	15.25	1.10
4	17.37	1.08
5	18.56	1.18
6	30.74	0.90
7	15.04	1.04
8	29.02	1.06
9	31.46	1.36
0	18.40	1.20

TABLE B.16: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	7.32	1.68
2	39.84	1.90
3	28.71	0.82
4	31.33	1.90
5	56.35	1.56
6	18.10	4.44
7	18.09	4.44
8	27.58	4.10
9	56.68	3.84
0	27.30	3.90

TABLE B.17: Shock Levels in Palletized Handling of Bulk Bins at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	33.44	2.96
2	35.69	9.46
3	4.91	1.10
4	31.65	1.74
5	19.18	1.90
6	25.70	1.82
7	24.33	1.74
8	32.22	1.74
9	26.67	1.44
10	28.67	1.58

TABLE B.18: Shock Levels in Palletized Handling of Drums at Average Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.94	11.85
2	6.94	10.50
3	6.92	6.80
4	14.03	49.50
5	9.82	45.70
6	8.40	19.40
7	3.00	4.12
8	4.12	2.58
9	5.18	4.52
10	3.13	19.78

TABLE B.19: Shock Levels in Palletized Handling of Drums at Average Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	22.53	2.38
2	10.13	7.94
3	4.06	19.72
4	11.81	6.52
5	4.06	19.72
6	16.37	5.86
7	12.25	15.62
8	15.37	6.98
9	10.68	6.42
10	23.10	19.42

TABLE B.20: Shock Levels in Palletized Handling of Drums at Severe Speed and High Weight. A Pallet Load Impacts a Stationary Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	3.21	6.16
2	3.07	7.32
3	4.14	4.88
4	14.96	19.54
5	3.15	4.22
6	2.18	5.40
7	4.12	2.58
8	1.25	6.36
9	1.32	4.28
10	9.00	5.40

TABLE B.21: Shock Levels in Palletized Handling of Drums at Severe Speed and High Weight. A Fork Truck Impacts Pallet Load.

Impact Number	Shock (Peak G's)	Duration (ms)
1	2.13	19.20
2	15.83	4.44
3	17.52	19.46
4	2.81	3.46
5	2.96	19.14
6	5.24	14.04
7	1.84	13.82
8	1.01	1.84
9	2.27	4.18
10	2.13	19.20