SHOCK, DROP, and IMPACT TESTING EQUIVALENCE

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ABSTRACT

ISTA, ASTM, and other test procedures often permit alternative ways of performing shock and impact tests. The various methods include free-fall drop, rotational drop, shock test machine, inclined-impact, and horizontal impact. This paper will examine the similarities and differences between these approaches, and the conditions under which they are and are not equivalent.

MECHANICAL SHOCK AND HOW TO PRODUCE IT IN THE LAB

The Shock and Vibration Handbook\(^1\) defines Mechanical Shock as “nonperiodic excitation (e.g., a motion… or an applied force) of a mechanical system that is characterized by suddenness and severity, and usually causes significant relative displacement in the system.” It defines Shock Pulse as “a substantial disturbance characterized by a rise of acceleration from a constant value and decay of acceleration to the constant value in a short period of time. Shock pulses are normally displayed graphically as curves of acceleration (vs.) time.” Shock is produced when two bodies collide, or when a moving body or surface strikes a stationary one. Shock, drop, and impact testing is performed in packaging and environmental test laboratories to assess the ability of products and packages to withstand these types of transient dynamic events.

Free-Fall Drop Tests

Uncontrolled free-fall drops happen in the transportation, handling, and use of products. In a testing laboratory, these events are simulated with controlled free-fall drops. The idea is to eliminate as many of the extraneous variables as possible, so that the tests can be documented and correctly reproduced. Generally some apparatus is employed to accurately control the height of drop and the orientation at impact. For smaller items, a “Drop Tester” is commonly used (Figure 1). Here the test specimen is placed on the surface of a moveable arm which quickly travels down and then back, out of the way, to initiate a drop. The impact surface is hard (steel,
stone, or concrete) and massive (at least 50 times the mass of the test specimen). The typical testing specification requires impact accuracies of $\pm 2$ degrees for flat impacts and $\pm 5$ degrees for angle impacts\textsuperscript{2}. Further, edge and corner drop orientations require that the specimen be at or near (within 5 degrees) its “balance point” at impact. In other words, the center of gravity is to be closely above the edge or corner being impacted.

For items which are too big or heavy for a testing machine, the “sling and quick-release” method may be used (Figure 2). A single-point suspension ensures that the test item’s center of gravity is directly below it (so that no rotation is imparted, and so that the desired impact angles are achieved), and careful measurements to the impact surface define the orientation. To initiate a drop, the suspension rope, cord, or cable is cut, or a quick-release mechanism is used.

The same requirements for impact accuracies and massive foundation apply regardless of the apparatus used – machine, slings, suspension devices, etc. This can become an issue when testing very large and heavy items.

**Rotational Drops**

During the handling of unitized (pallet) loads, large cases and crates, etc. by lift trucks or other mechanical means, impacts can occur following “rotational” motion. One edge or corner of the item may be dropped, or it may be lowered to the floor unevenly. These events are simulated in a testing laboratory by rotational flat, edge, and corner drops\textsuperscript{3}. The first word (“rotational”) describes how the item *falls*, and the second word describes how the item *impacts*. A rotational flat drop starts with one edge of the item resting directly on the floor, and the other edge raised to the desired drop height. Upon release, the item *rotates* as it falls, then impacts *flat* on the floor. A rotational edge drop starts with one edge of the item blocked up, and the opposite edge raised to the desired drop height. Upon release, the item *rotates* as it falls, then impacts on an *edge*. 
See Figure 3. A rotational corner drop starts with one corner blocked up, and the opposite corner raised and dropped. The item rotates to impact on a corner.

**Shock Test Machine**

Testing with a shock machine (Figure 4) involves mounting the item to be tested onto the table of the machine, raising the table, then allowing it to fall and strike shock pulse programmers underneath. The amplitude, duration, and waveshape of the resultant pulse is controlled by the drop height and the characteristics of the programmers. These tests are not generally intended to simulate shocks that occur in the actual distribution environment, but to excite precisely controlled responses in the test items. Shock machine tests are used to quantify the shock fragility of products, and if performed properly, can produce the same effects as drop or impact tests but with a higher degree of control and repeatability.

**Inclined-Impacts**

Goods in transit receive horizontal impacts from pallet marshalling, rail car coupling, and other sources. The sway of ships and railcars, combined with load looseness, creates lateral shock (the motion is too low in frequency to cause vibration damage per se). Over 50 years ago, the inclined-impact machine was developed to produce “horizontal” shocks in the laboratory (the ASTM governing method, D880, was first adopted in 1946). The machine reflected the simplicity of its time, required no instrumentation, but did not produce truly horizontal impacts since it used gravity as the prime mover. Now recognized as NOT in any way simulating the rail car coupling environment (see below), the inclined-impact test has nonetheless proven itself useful in evaluating the ability of products and packages to withstand various types of shock inputs.

The test machine (Figure 5) consists of a wheeled carriage, guided by steel rails, upon which the test item is placed. The rails are inclined at 10 degrees (a persistent typo in D880 says 10 percent), and there is an impact “backstop” at the low end, with its surface perpendicular to the carriage’s direction of travel. The test item is positioned to overhang the front of the carriage by 2 inches. When the carriage is pulled up the rails and released, it freely rolls down the track and the specimen impacts the backstop. It is now required that the impact velocity be of certain values, as measured with suitable instrumentation.
Horizontal Shocks

True horizontal shocks are now recognized as the best way to simulate rail switching and, to some extent, pallet marshalling impacts. The inclined-impacter cannot recreate the looseness and backload conditions necessary for adequate rail car coupling simulation, and is difficult to configure for the range of impact velocities reasonably required. A typical horizontal impact test system, meeting the requirements of ASTM D4003\textsuperscript{7}, is shown in Figure 6. The specimen-mounting carriage, which is guided to move horizontally and to resist overturning moments, incorporates a vertical bulkhead to simulate the end of a railcar. It is accelerated by a pneumatic or hydraulic cylinder, and impacts shock programming devices attached to a reaction mass. Shock pulses simulating those of both standard and cushioned draft gear rail cars can typically be produced, the carriage is generally large enough to hold the specimen and a sufficient backload, and the velocity capability allows very severe events to be simulated.

![Figure 6: Horizontal Impact Test System](image)

WHAT IS EQUIVALENCE?

The dictionary definition of equivalence is “equality of quantity, value, force, meaning, etc.” In testing, equivalence is taken to mean producing the same results, performance, damage or malfunction. But when testing a packaged product, are we looking for equivalent effects on the outer package, the inner packaging (cushion, etc.), the product, components of the product, or what? It would be nice if it could be all of these, all of the time. But if that’s the requirement, then we could never hope to achieve total “equivalence”; one could always imagine a configuration of product, package, or test variable that would produce different results. As a ridiculous example, consider that a horizontal impact test could never be equivalent to a side drop test if the product were a cup of coffee!

It’s interesting to note that the ISTA 1- and 2-Series (Integrity and Integrity Plus tests) call out “alternative” ways of performing shock and impact tests, without calling them “equivalent”. The ISTA “Guidelines for Selecting and Using ISTA (Tests)” state that the purpose of Integrity Testing is only to “challenge the strength and robustness of the product and package combination”, it is “not designed to simulate environmental occurrences”.\textsuperscript{8} Therefore the “challenge"
produced by alternative tests can be somewhat different without defeating the basic purpose. Series 3 procedures, on the other hand, which are intended to be general simulations of the damage-producing conditions of transport, contain very few alternative shock tests. This implies that alternatives are not necessarily equivalent, don’t simulate the same conditions. And in the general case that is true. In order to achieve “equivalence”, we usually need to narrow our scope and definitions of results. This certainly applies in the case of programmed shock tests vs. free-fall drop tests.

**PROGRAMMED SHOCKS VS. FREE-FALL DROPS**

ASTM D5487, which is referenced in most of the ISTA 1- and 2-Series tests, is entitled “Simulated Drop of Loaded Containers by Shock Machines”. It “covers the general procedures of using shock machines to replicate the effects of vertical drops of loaded shipping containers”. Two very important conditions are specified: (1) “The frequency of the shock pulse (must be) at least three times that of the package system’s natural frequency”, and (2) “The shock test machine (must) produce a… velocity change (impact + rebound) of the shock machine table… (equal) to the impact velocity for the chosen free-fall drop height”. There are actually more requirements that are important, beyond just these two, as we shall see. Why these conditions and requirements, and do they ensure “equivalence”?

**Frequency Relationship**

The frequency condition is required because of unavoidable differences between the shock machine’s programmed pulse (usually a half sine or haversine shape), and the indefinable acceleration-time signature of a package striking a hard surface. The *Shock and Vibration Handbook* (chapter 8) states that “if… the pulse duration divided by the system natural period is less than 1/4, the pulse shape is of little consequence… and the system response can be determined… by the use of simple impulse theory”. This means that if the input pulse duration is short enough compared to the system natural period, only its velocity content – not its peak acceleration or waveshape – will determine the response. So the system response to a sufficiently short-duration shock machine pulse can be the same as to the short “pulse” caused by a rigid or semi-rigid package striking the floor, even though the waveshapes are completely different. And if we define “equivalence” as “same system response”, then the two tests may indeed be equivalent.

The “system response” referred to here is the response of a corresponding *spring-mass* system. The strong implication, although not directly expressed in D5487, is that the test item is a *cushioned package*, where the cushion is the *spring* and the product is the *mass*. So this becomes another requirement, or at least an extension of the frequency condition; if the test item cannot in some way be represented by a spring-mass model, then in all likelihood the approach loses its validity.
Putting the *Shock and Vibration Handbook*’s requirement into D5487 terms:

The *Handbook* requires that \( \frac{D_s}{T} < \frac{1}{4} \), where \( D_s \) = the pulse duration and \( T \) = the system natural period.

But period is the inverse of frequency, \( T = \frac{1}{F_p} \), where \( F_p \) = package system frequency, so the *Handbook* requires that \( D_s \times F_p < \frac{1}{4} \), or \( D_s < \frac{1}{4 \times F_p} \).

(1)

The duration of the shock pulse represents one-half of a full-cycle waveform. Therefore the full *period* of that wave would be \( 2 \times D_s \), and the *frequency* of that wave, \( F_s \), would be \( \frac{1}{2 \times D_s} \). \( D_s \) expressed in terms of frequency is then \( \frac{1}{2 \times F_s} \).

Substituting into (1) above gives \( \frac{1}{2 \times F_s} < \frac{1}{4 \times F_p} \), or -

\[ Fs > 2 \times F_p \]

D5487 actually requires \( F_s > 3 \times F_p \) (a factor of 3 rather than a factor of 2), in order to be more conservative and to make the equivalence more assured. D5487 gives two examples: if the shock machine pulse is 2 milliseconds (a typically-used value), then the package must have a natural frequency of not greater than 83 Hz. \( (1 \times 0.004 = 250, 250 \div 3 = 83) \); if a 3 msec. pulse is used, the package natural frequency cannot exceed 56 Hz. \( (1 \div 0.006 = 167, 167 \div 3 = 56) \).

Package natural frequency can be determined by a vibration test or other means.

**Velocity Relationship**

D5487 requires that the *velocity change* (impact + rebound velocities) of the shock table be set to the *impact velocity* resulting from the free-fall drop. This means that the machine drop height is typically much less than the free-fall drop height. Why the inequality – why not the same impact velocity, or the same total velocity change, or the same drop height?

Imagine a test item consisting of an outer package, resilient cushioning material, and rigid product with measuring accelerometer attached, as shown in Figure 7a. Assume that the package and cushion is massless, or at least very lightweight compared to the product. When this item is dropped from some height, it strikes the floor with a certain impact velocity. As the package strikes, its velocity quickly decreases to zero. The product inside, however, continues downward and starts compressing the cushion. This is the beginning of the “system response”, the product shock pulse (as measured by the accelerometer). It creates a downward force (force = mass x acceleration, \( F = MA \), Newton’s second law) on the cushion and therefore the package. Since the package is massless, this force holds it down to the floor and prevents it from rebounding (Figure 7b). The product continues to move down, compressing the cushion, and causing the shock pulse acceleration to rise, all the while holding the package to the floor (Figure 7c). The product compresses the cushion to some maximum value and then begins to rebound. The acceleration begins to decrease, but it’s still in the same direction, still creating a downward force on the cushion, still holding the package to the floor (Figure 7d). Not until the acceleration returns to zero does the downward force become zero (Figure 7e). At this point the shock pulse of interest (as measured on the *product*) is over; the product may rebound into the upper cushion...
and lift the package off the floor, but that motion is of no importance in terms of damage potential and has no bearing on the shock pulse of interest. So in fact, the shock pulse of interest, the pulse applied to the product, was caused entirely by the impact velocity, without rebound, of the outer package. Another way to think about this is to consider that the package is “overpowered” by the heavy product and prevented from rebounding during the product response pulse.

Figure 7: Free-Fall Drop of Heavy Product in Lightweight Package – Package Does Not Rebound During Product Response Pulse, Product Response is Caused Entirely by Package Impact Velocity.
Now consider the shock machine test. Here, the package is fixtured to the (heavy) table of the machine, and the table is lifted and dropped. It impacts on and rebounds from the shock pulse programmers, thereby producing the required short-duration pulse. The package obviously doesn’t prevent rebound of the table because the table is much heavier, so the impact + rebound velocity from the shock test becomes the input pulse to the package. This pulse then causes a response in the test item (Figure 8).

![Figure 8: Shock Machine Input Pulse (Impact + Rebound), Product Response](image)

In the case of the free-fall test, the “velocity content” of the input was just the impact velocity from the fall, because the product “overpowered” the package and prevented it from rebounding during the response pulse. In the case of the shock machine test, the “velocity content” of the input is the impact + rebound of the table, because the table “overpowers” the packaged product. But it doesn’t matter to the product response; if the input-duration-to-package-frequency condition is met, the input will be essentially finished before the product pulse begins, and the product will respond the same in either case.

**Shock/Drop Equivalence**

So a shock machine test can be the equivalent of a free-fall drop test in terms of product response if the following conditions are met:

1. The packaged product can be reasonably represented as a spring-mass system, where the inner packaging (cushion) is the spring, and the product is the mass.
2. The natural frequency of that spring-mass system is less than 1/3 the frequency of the shock machine’s input pulse.
3. The velocity change of the shock machine test is set to the impact velocity which would result from the free-fall.
4. The package is very light in weight compared to the product. If this condition is not met, then the velocity change of the shock machine test should not be set to the impact
velocity of the free-fall test. In the extreme example of a lightweight product packaged in a cushion-filled 55 gallon steel drum, the velocity change of the shock machine test must be set to the (difficult to determine) velocity change of the drum in a free-fall test.

With all these conditions and complexities, why would anyone want to use a D5487 shock test instead of a simple free-fall drop test? The answer is, to achieve improved controllability and repeatability. As described earlier, drop test impact angles are only required to be within 2 to 5 degrees; in addition, typical packages are not precision structures in terms of their surfaces, angles, weight distributions, etc. The result is that the impacts caused by drop tests have a certain inherent variability which cannot readily be overcome. And it has been shown\(^9\) that even small non-perpendicularities of impact can result in disproportionately lower accelerations transmitted to the cushioned product.

Shock testing is much more precise. The table is guided to move only vertically, the input shock pulses are carefully measured and can be controlled to be repeatable, and the test item is accurately fixtured to the table. If a “flat” drop equivalence is desired, it can be absolutely assured – because the package is placed \textit{flat} on the “impact surface” (the table’s mounting surface) and stays in contact with it during the entire test!

So when control and repeatability are of paramount importance, the additional effort involved in shock testing instead of drop testing can be worthwhile. A leading supplier of packaging materials exclusively uses D5487-type testing (rather than “standard” D1596 cushion tests or drop tests) to produce their dynamic cushion curves\(^10\).

**Can Unpackaged Product Shock Tests Be Made Equivalent to Free-Falls?**

This question has sometimes been asked, particularly with regard to small electronic products like cell phones, pagers, and the like. The desired survivable drop heights are quite large, there is the potential problem of controlling impact orientation during drops, there are difficulties in attaching instrumentation, etc. – and shock machine testing using the principles of D5487 appears to be an attractive alternative. But in practice, equivalence is likely to be difficult, if not impossible, to achieve. Consider if the conditions stated in the previous section can be met:

1. Can the test item be represented as a spring-mass system? In D5487 terms, the structure of the product could be considered the “package”, and a fragile component inside could be considered the “product”, flexibly mounted on a “spring”. But whereas the “spring” and “mass” in a “loaded container” (D5487) are rather clearly defined, they might be extremely difficult to identify in an unpackaged product.

2. What is the natural frequency of the critical spring-mass system(s)? This information is required to determine the appropriate shock pulse duration. But again, these frequencies may be very difficult to identify – and they might change with product orientation.

3. The “package” (the structure of the bare product) would certainly not be lighter than the “product” (the fragile component). So a determination of the rebound velocity of the
product during free-fall impacts would have to be made for each desired orientation. Then this impact + rebound velocity would need to be set on the shock machine.

4. The damage potential to “non-resonant” portions of the product (the case, very stiff internal structures and components, etc.) would likely be different for the two types of tests, either because the frequency relationship was not satisfied and therefore the responses follow the different input waveshapes, or because the structures simply do not behave like spring-mass systems at all.

The most rational approach to shock testing unpackaged products for free-fall impact performance might be to use the shortest practical shock pulse duration (down to 0.05 msec. is possible for some small, high-performance machines), and a velocity change approaching 2 times the free-fall impact velocity (as a worst-case scenario). In most instances this should produce a correlation between the severity of the shock pulse and the likelihood of surviving higher free-fall drops. This could be very useful in comparing a proposed product modification to a design with known field performance. But to attempt to make a direct equivalence – i.e., stating that a certain shock test is “equivalent” to impacts from a specific drop height – would seem to be overly risky.

HORIZONTAL SHOCK EQUIVALENCE

The ISTA “Guidelines” state “when conducting a horizontal shock test, the parameter to monitor and control is velocity change”. Further, “short-duration… pulses… (of) around 10 milli-seconds are desirable if practical”. Although not explicitly stated, this appears to be a horizontal shock implementation of D5487 methodology. This could certainly be a valid approach in certain situations, but again bear in mind the required conditions:

1. The packaged product must be capable of being reasonably represented as a spring-mass system. This may be an issue for products packaged in large cases, crates, and unitized loads, where the horizontal shock test is most likely to be employed.
2. The natural frequency of the package must be less than 1/3 the shock pulse frequency. For a nominal 10 millisecond shock pulse, that would be a very low package frequency of 17 Hz. (1 ÷ .020 = 50, 50 ÷ 3 = 17).
3. The package must be very light in weight compared to the product. This could certainly not be the situation for large cases and crates.

It is not difficult to imagine situations where either a significant over-test or a significant under-test would result from attempting to do the “alternate” to a drop or impact test using the ISTA Horizontal Shock procedures. A better technique might be to use a “gap”, as in ISTA Procedure 3H. Here, the horizontal shock test is set up with a particular velocity change, but the test specimen is positioned back from the vertical bulkhead by some distance. Upon program-
ming of the primary shock pulse into the machine’s carriage, the specimen slides forward and impacts the bulkhead. This creates a package-to-hard-surface impact similar to a drop onto a hard floor, with a relative velocity equal to the impact velocity. Package weight in relation to carriage weight might be an issue, however; an unfavorable ratio would interfere with the velocity-change-to-impact-velocity equality. Additional research would certainly be required to determine if this is a reasonable approach, but it seems to offer promise in comparison with the current one.

Horizontal shock testing is the best way, perhaps the only viable way, of simulating rail switching in the laboratory. But its equivalence to drop or impact testing, or even its use as an alternative to these, is questionable.

DROP AND IMPACT TEST EQUIVALENCE

The other alternatives to be considered (free-fall and rotational drop, inclined-impact) all involve the striking of the actual package against a hard surface, so there are no requirements regarding pulse durations, frequency relationships, and so on. For an inclined test, the impact velocity is set to be the same as that from the corresponding free-fall drop, according to the formula $V_i = \sqrt{2gH}$ where $V_i$ is the impact velocity, $g$ is the acceleration due to gravity (386.1 inches/second$^2$, or 9.8 meters/second$^2$), and $H$ is the drop height.

But of course, even with equal impact velocities, there are differences between these various tests. A rotational drop will likely produce different results from those of a free-fall drop, not only because of the difference between rotational and linear motion, but because in a rotational drop a portion of the package (the supported edge or corner) is not even involved in the impact. An inclined-impact could produce different results from those of a free-fall due to any or all of the following factors: (1) the test item is oriented differently with respect to gravity, causing a different “pre-impact” configuration, (2) there are undoubtedly structural differences between the machine’s backstop and a hard floor, (3) the effect of the carriage sliding underneath the package on impact, (4) support of one face of the package while impacting another portion, which isn’t the case during a free-fall drop. In the general case, these tests could not be deemed “equivalent”.

CONCLUSIONS

Whether or not one way of producing a shock or impact is “equivalent” to some other way is often a matter of definition. The results in terms of performance and/or damage are probably as much dependent on the test item as on the particular test. In other words, results are likely to be “product-specific”. This is certainly the case with the D5487 equivalence of shock to drop, where “equivalence” is defined as “same system response”, and a number of conditions must be satisfied to make the equivalence valid. The test engineer or operator must constantly keep in mind the objectives of the tests, must be certain that the right tests are being performed, and
must interpret results in terms of reasonable engineering expectations and adequate package and product knowledge.

Is it even reasonable to expect the same results from different test approaches? While “alternatives” are permitted in the ISTA Integrity Test Procedures, “equivalence” is never claimed and is probably not achieved in most cases. It could be theoretically possible, with a marginally-performing package, that the selection of different “alternatives” would change the outcome from pass to fail or vice-versa. If such discrepancies were to arise, they should be analyzed with respect to the product, the package, and the anticipated distribution environment. Choosing a particular alternative just to pass the test would be to ignore the basic objective of assuring safe and economical transport.

This paper has only discussed the equivalence (or lack) between various laboratory testing procedures. The greater question of lab test equivalence to actual field shock and impact conditions involves not only examination of the tests, but analysis of in-field performance. It is not possible to determine the effectiveness or appropriateness of laboratory testing without studying its correlation to actual field performance. The Shock and Vibration Handbook describes the situation in these words: “A principal characteristic of shocks encountered in the field is their variety. These field shocks cannot be defined exactly. Therefore shock simulation can never exactly duplicate shock conditions that occur in the field. Assurance that... (correlation) exists requires a comparison of ... test results and field experience extending over long periods of time.”

REFERENCES