



PRODUCT FRAGILITY ANALYSIS MADE EASY

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Abstract

The Damage Boundary method of product fragility analysis has been around since the late 1960s and has proven itself to be an outstanding tool for reliability analysis, protective package design, and product fragility analysis. Yet it is not widely used in any of the areas where it can create a positive input. There are many possible reasons identified for this in the text. Possible different approaches and recommendations for procedure modifications are given in order to improve the effectiveness of product shock and vibration fragility assessment.

Background and Introduction

The Concept of Damage

In reality, fragility is another product characteristic unique to each product, just as size, weight, and color are unique product characteristics. Size and weight are determined by using a scale and/or ruler. In a similar way, product fragility is determined by using calibrated inputs and measuring a product's response to those inputs.

It is important to remember that product fragility (the reciprocal of ruggedness) is another unique product characteristic and it can be changed both as a function of the initial design and as product modifications, specifically for the purpose of increasing its ruggedness.

The term damage is unique to each particular product situation. In some cases, damage may be as minor as a misalignment of a chassis or slight bend in a cover. In other cases, it may be considered total non- functionality of a mechanical product. In still other cases, it may be a latent damage which doesn't show up initially but results in a reduced life expectancy for a product.

Quality Delivered

One of the most workable definitions of product ruggedness (lack of damage) is a quality delivered product. The concept here is that quality built into the product should remain there until the product is in the hands of the final customer. A quality product is not only one which meets the specifications for which it was designed and built, but one that satisfies the needs for which it was built in the most economical and optimum way possible. In short, a quality product is one that works like it's supposed to and keeps on working like it's supposed to.

Plug 'n Play

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The concept of “*plug 'n play*” was developed at Apple Inc. in response to a product introduction disaster. This concept has been widely accepted by other firms since that time and is basically this: When a product is taken out of the box, everything necessary for its proper operation is there in an easy-to-find and easy-to-use format. When assembled, it works as the customer expected it would. In other words, it meets all of the customer's expectations right out of the box.

The percentages of successful *plug 'n play* vary from product to product and company to company. Obviously it would be physically and economically impossible to guarantee 100% successful *plug 'n play*. The distribution environment is known to be hostile and, in some cases, abusive. Packaging for abuse is not economically justifiable or considered a viable engineering option.

The best that one can strive for is a high percentage of *plug 'n play* products. Many companies use the 3 Sigma statistical level as their target. In practical terms, this means that 99.4% of the products, on average, will arrive in good condition and in a *plug 'n play* configuration.

Stress Limits

Products break or fail oftentimes because stresses exceed the limits of the materials or systems used to build the product. For example, a given plastic material is known to have a compression yield strength of 100,000 psi. This material is used in a design situation where .01 sq. in. of the material is used to support a 10-lb mass which is subjected to a 100 G acceleration pulse and fails. This failure could have been predicted by an analysis of the stress limits of the actual material.

However, the straightforward application of stress limits involving engineering quantities of materials to actual design situations is vague at best. The effect of shape, dynamics, aging, and a host of other factors will make this calculation only an indication of potential problems.

Fatigue and the Effect of Recurring Stress

Few products are actually treated to environmental conditions that cause high levels of instantaneous stress. Most products, however, are treated to conditions where a lower level of stress is applied on a more or less continuous basis for an extended period of time. The effect of this recurring stress below the design limit of the component under study is referred to as *fatigue*. The effects are almost always destructive and manifest themselves as a weakening of the overall structure, misalignment of components, out of calibration condition, or similar results.

Most products, such as consumer products and electronic products, are not designed with fatigue resistance in mind, and therefore, the effects of fatigue are often disastrous. However, it's absolutely essential to determine the sensitivity of a product to vibration effects and fatigue characteristics in order to determine if a potential problem exists. All products will be subjected to some level of distribution related vibration during their life cycle. This is a fact of life in a society where products are made in one location and used somewhere else, often half a world away. In order to get to where they're going, they must be transported, and the vehicles on which they travel will produce vibration. The effects of that vibration on the product must be known.

History of Fragility Assessment

Design Stress Limits

Prior to the establishment of any kind of fragility testing, this type of information was generated using "static" stress limit calculations. The yield strength of materials and components would be calculated using engineering data, and the information used in a particular design situation. From this, the maximum acceleration level could be estimated.

The operative word here is *estimated*. Most of the time these calculations were fraught with errors based on assumptions (normally conservative) or on the inability to determine exactly how the forces were applied or what the resultants would be. In most cases they were extremely conservative numbers, because engineers were unwilling to make broad estimations in anything other than a conservative way.

Early Test Routines

In an attempt to determine actual mechanical fragility levels, certain rough-handling tests were initiated. These included a bench handling test, a roll-over test, and similar test procedures. Typically, the product would be monitored with some sort of instrumentation in order to determine the effect of the test input. However, this was not always the case.

What was determined from these tests was that very little repeatability could be established. The test varied from one product to another and from one test operator to another. In addition, the results were not usable in any type of scientific design process. At best the process would simply identify what failed and how.

“Fragility Factors” were established on some products using calibrated drop inputs onto certain cushion materials such as carpets or foam materials. For example, early

telephone tests had a fragility factor based on a 30-inch freefall from a desk surface onto a tile floor. The product had to survive this test for 9 out of 10 impacts. The test procedure was chosen based on the height of the table surface and the fact that the telephone would probably be pulled off the surface by a user who stretched too far with the handset.

Scientific Approaches

In the mid-50's the military decided to standardize fragility test procedures and published MIL Standard 810 which was the first attempt to quantify the hazards of the shipping environment.

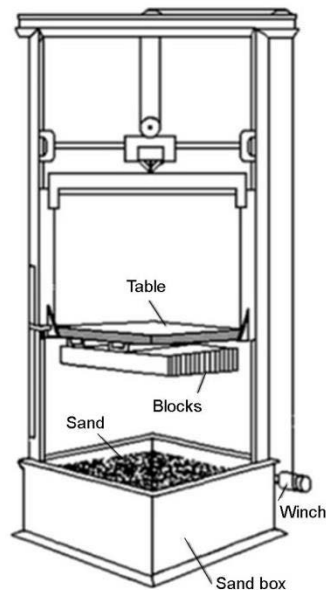


Figure 1 – Sand Dropper

Credit: Mechanical Vibration and Shock Analysis, Second Edition, Volume 2, Mechanical Shock, March 2013, by Christian Lalanne, John Wiley & Sons

For products that were too large for fragility analysis, an approach was borrowed from the architectural engineering field, referred to as Shock Response Spectrum (SRS) analysis. For this approach, the structure was monitored with transducers of the appropriate variety and was then excited by some low level input. The response of the structure to the input was monitored and in particular, the amplification and resonant frequency points were noted. With this information, it was possible to determine what level of input would cause the response of the structure to exceed its inherent strength, and therefore fail.

A simplification of the SRS analysis combined with availability of repeatable shock machines resulted in the Damage Boundary theory developed in the early 1970's and codified in ASTM D3332. The concept was a simple one. Instead of determining the response of a structure over a wide frequency band, use two shock pulses, one of which excited the velocity sensitivity of the product and one which excited the extreme level of the acceleration sensitivity.



Figure 2 – Mechanical Shock Testers
Credit: Lansmont Corporation, Dec 2014

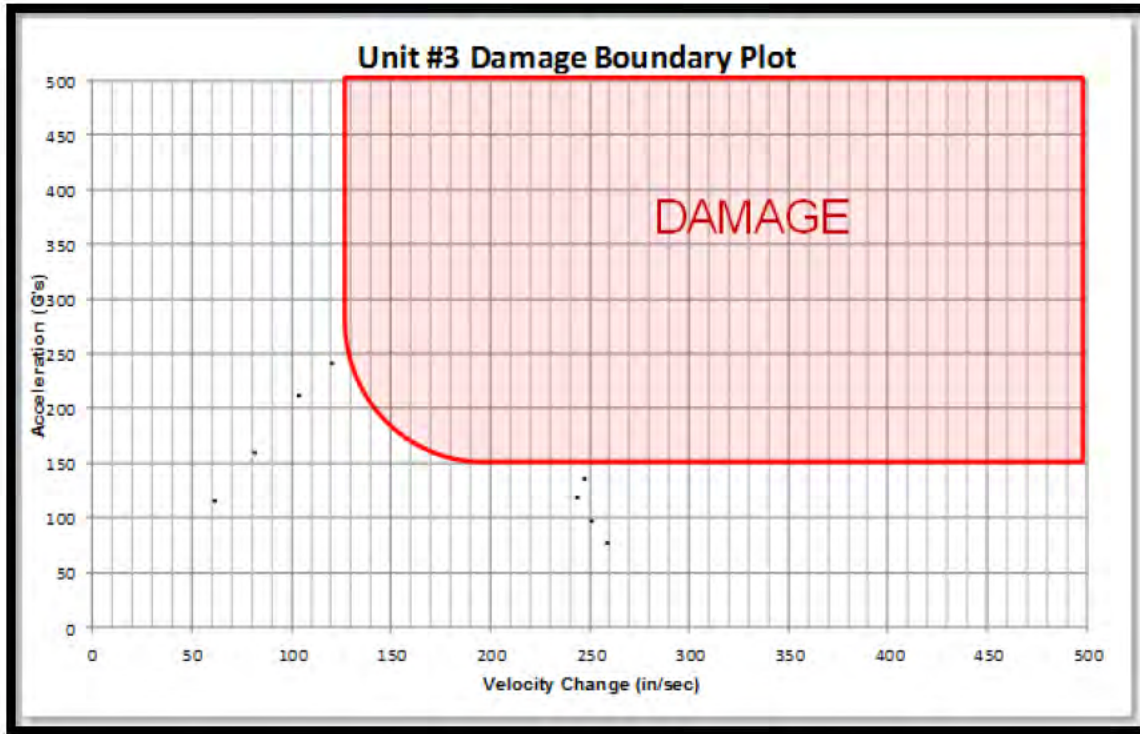


Figure 3 - Typical Damage Boundary Plot

Credit: WESTPAK, Inc.

A simpler version of this test procedure was also put forward as the ASTM D3331 shock fragility using cushion materials. The concept here was that the product would be excited by dropping it onto a stack of cushions, and the thickness of the cushions would be gradually reduced increasing their stiffness and therefore the acceleration level delivered to the product. The last non-failure input determined the product fragility. This approach was dropped in the late 1980s.

Vibration

The fatigue characteristics of products are determined by exciting them mechanically or acoustically in order to determine at what frequencies the response of the product components is greater than the input, that is, where the product resonated. The product or component fatigue is most likely to occur at resonance, and therefore the determination of this frequency is very important.

Sinusoidal vibration was often used for this testing because it is simple to produce and easy to understand. In concept, this procedure excites the product one frequency at a time while the instrumentation simply listens for the response of the monitored component to that frequency. The frequencies are changed slowly, and when the response of the product reaches a maximum, relative to the input, the operator knows

that a natural or resonant frequency has been determined. This information is normally plotted on a transmissibility plot showing the frequency as a function of the amplification ratio; that is, how much the component amplifies the vibration input.

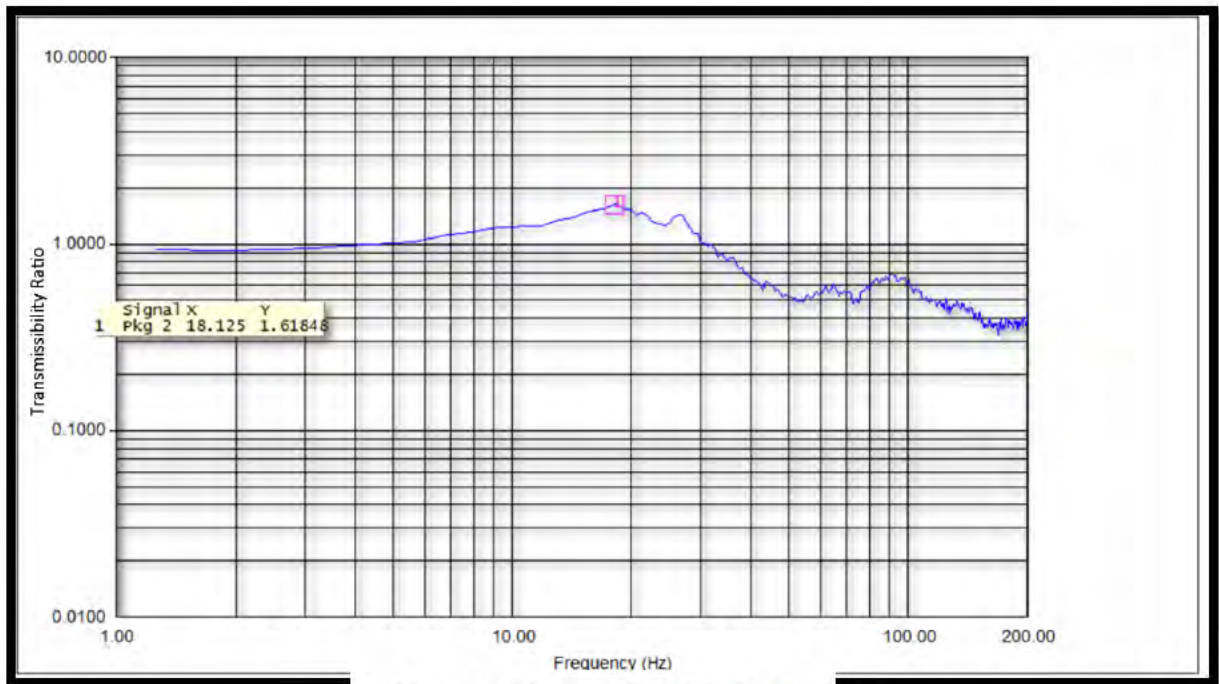


Figure 4 - Transmissibility Plot

Credit: WESTPAK, Inc.

This information is crucially important because all products will be exposed to vibration sometime during their product life cycle, certainly during transportation and delivery. It is also known that products can be very sensitive to the effects of natural or resonant frequency vibration, and those effects include fatigue, breakage, misalignment, out of calibration condition of components, and many others.

Drawbacks To The Current System

The Conservative Nature of Damage Boundary Testing

The Damage Boundary approach as described in ASTM D3332 is very conservative. This comes from a number of factors including the following:

1. Square Wave input used to determine the Critical Acceleration of products excites all natural frequencies within the product at their highest possible level. This level is never achieved in the life cycle except during a Damage Boundary test. Levels closer to that excited by a half sine are more typical and may be a better choice.
2. The effect of low cycle fatigue on a product subjected to a number of shock inputs is never seriously studied in the Damage Boundary procedure. It is known, however, that this fatigue will result in earlier failure of the product than would normally be the case. There is an ASTM standard that addresses this issue, but it is rarely used.
3. Damage Boundary testing is normally conducted on products in the prototype stage when the ruggedness of the product has yet to be maximized. Therefore the end result is a lower fragility estimate than would be the case for mature products.
4. The effect of fixturing a product to the table of a shock machine is largely unknown. The traditional approach has been to fixture the product to the table by any means possible, and the translation of the shock pulse through the product is largely a function of how it is fixtured to the shock table. This is an area that definitely needs close attention by the test engineer.
5. The numbers generated during a Damage Boundary test represent shock input numbers and not product responses. However, when a package system is designed for a breakable product, the results of the package drop test are determined by the response of the product to the cushioned impact. These numbers are always different from the input determined during the shock fragility test. What is needed is a fragility test procedure that determines both the input shock pulse and the response of a “referenced point” on or within the product.

The Misapplication of Damage Boundary

The Damage Boundary test procedure, as described in ASTM D3332, requires both a critical velocity and critical acceleration determination. Critical acceleration is determined using a trapezoidal shaped shock pulse, while critical velocity change uses a 2-3 msec half sine pulse.

It is noted that this use of the 2-3 msec half sine is not appropriate for products that have high natural frequencies. The whole purpose of this test is to excite products in a velocity shock manner which basically means that the shock pulse is over and done with before the product has a chance to respond to it. The response of the product in general and of the critical mass in particular is a response to the velocity change or energy content of the shock pulse rather than its acceleration and shape. This is an important concept which is often overlooked or misunderstood by those using this approach.

Vibration Data

The use of sinusoidal inputs to determine the natural or resonant frequency of products can be totally misleading, because it can ignore the constructive and destructive interference of components of the product in a vibration input. That is to say, when components have natural frequencies that are close to one another, they can amplify during a sinusoidal resonant frequency test and destructively interfere with each other during a random vibration excitation. Since random vibration is typically what will occur during the transportation of products, this type of input should be used during a vibration fragility test rather than sinusoidal input.

It is also known that sine vibration input is particularly abusive to products in that it will concentrate the vibratory effects at one frequency at a time. This is the most severe response mode of a product. More typical modes that will occur during its life cycle are random in nature and therefore far less stressful.

It is also known that components can interact and impact one another during a random vibration test where multiple resonances are excited simultaneously rather than in a sine test where only one resonance at a time is excited.

A Simpler Approach to Product Vibration Sensitivity - Vibration Testing

Random Vibration

The use of random vibration burst tests has gained wide popularity. The test basically involves securing a product to the table of a vibration test machine and fixturing it with a number of transducers in one axis. The product is then excited using a random vibration “burst”. The data is recorded and later analyzed. The entire test takes approximately 3 – 5 minutes of actual vibration testing.

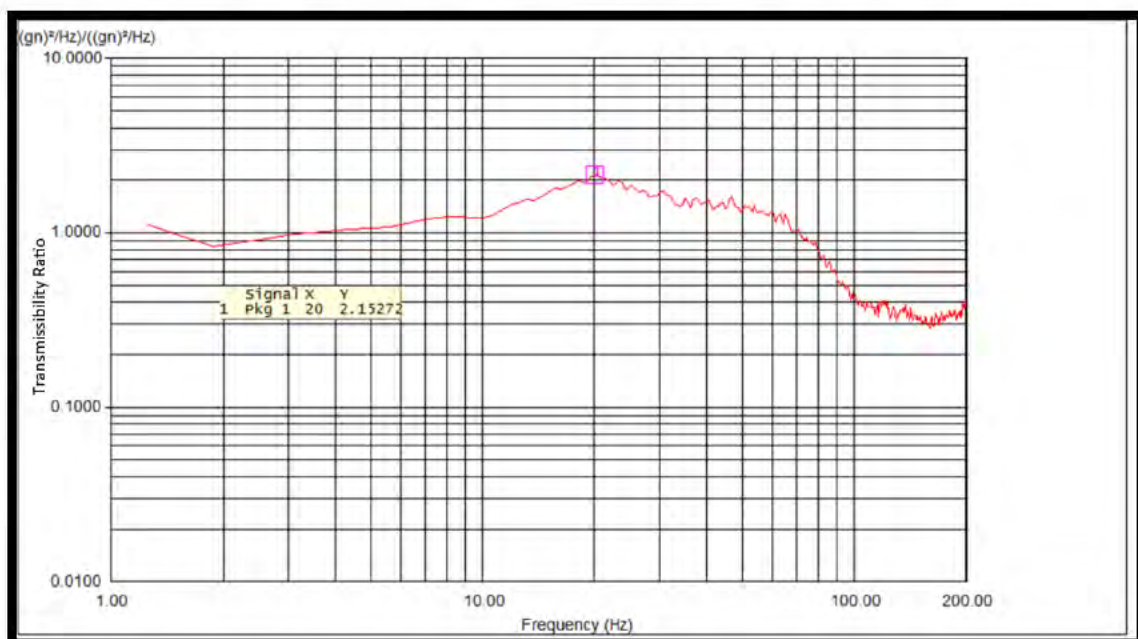


Figure 5 – Typical Transmissibility Plot

Credit: WESTPAK, Inc.

The analysis is done by the vibration controller that analyzes the response of the product and divides it by the input creating a random vibration transmissibility plot. This plot will show the natural or resonant frequencies of the product as a function of their amplification in a random vibration environment. This is considered to be much more realistic of how the product's components actually respond when exposed to the type of vibration that they will be expected to survive; namely, distribution on transit vehicles.

Shock Testing

The popularity of the Damage Boundary test is dwindling and in its place a step acceleration test is becoming more popular to determine the ruggedness or fragility of products. To conduct this test, a product is fixtured to the table of a shock test machine and subjected to a step acceleration test using a trapezoidal pulse recommended in the ASTM D3332, Method B. In addition, both the input shock pulse and the response of a referenced location on the product are monitored.

The test is conducted by stepping the acceleration up until failure occurs or until a safe limit is reached.

It is important that the monitored location be easily accessible to the outside of the product for the purposes of doing a package performance test. It is also important that all three axes be monitored in order to determine the cross axis translational motion of the product. This is something that is often ignored during Damage Boundary testing but can be very significant, especially with marginal fixtures.

It is also common to use a single product to determine the acceleration limit of a product in all axes. It is extremely rare to have the luxury to use one product to determine both velocity and acceleration limits in all axes of the product; a total of 12 potentially destructive tests.

To use a single product during this test, the product is subjected to a step acceleration test wherein the same acceleration level is applied to each axis of the product before the acceleration level is stepped up. The process is then repeated. Functional and aesthetic checking of the product is conducted between each shock input. The last non-failure input is used as the *critical acceleration* level for the product in all axes.

To use this information in the package design process, the shock input numbers are considered the fragility for a package design function. That is to say, if the product failed at a level of 50 G's but passed a 40 G shock input, this 40 G number is used in the package design process for selection and fabrication of a cushion material.

However, once the prototype package is assembled and the product placed in it and subjected to a drop test, the response product numbers on the fragility test are used to determine the passing criteria for the package drop test. This type of testing has been referred to as SIRM; that is, Simultaneous Input and Response Measurement.



Figure 6 - SIRM set-up
Credit: WESTPAK, Inc.

Conclusion

The value and limitations of Damage Boundary testing for product fragility analysis has been examined and recommendations have been made to eliminate the critical velocity change testing identified in that particular procedure. In its place, it is suggested that Step Acceleration Testing to failure be conducted with emphasis placed on measuring the acceleration response of the product to shock input at a referenced location. This max acceleration number should be considered the fragility of the product during subsequent package performance testing, in particular, package drop testing. This process should eliminate much of the overly conservative package design resulting from this method resulting in a much more optimum and cost-effective package system and even more significant savings from optimized supply chain logistics.

