Gauge Repeatability and Reproducibility Study for a Bulge Test Fixture for Corrugated Boxes

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ABSTRACT

This senior project evaluates the measurement variation within a corrugated container bulge tester by utilizing a gauge repeatability and reproducibility study. Bulge is a type of deformation containers experience when subject to compressive forces such as stacking or internal forces due to under- and over-packaging. Both compressive and internal forces can accelerate the failure of a container by causing panels to flex and flutes to buckle, compromising structural integrity. Additionally, variable environmental conditions such as temperature and humidity can magnify the effect bulge has on a container, speeding up the failure rate of a container.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Jay Singh for his guidance and idea for this project. I would also like to thank Dr. Soma Roy and Dr. Eric Olsen for statistical analysis guidance and experimental data collection methods. I appreciate all the help and I thank you greatly.

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INTRODUCTION

The purpose of this project is to create a standardized protocol for testing bulge in corrugated containers. Unlike other packaging test methods, there is no information about bulge related to corrugate packaging. Currently, patents issued and container designs that limit bulge in a container have not been adopted by the packaging industry, nor have standardized protocols for evaluating their effectiveness been created. With the addition of a bulge test fixture, package designers can use the data collected to improve product packaging and further understand container bulge.

Container bulge is due to a compressive force applied to the top of a container or an internal force on a container. As a force is applied to a container, the affected container faces will undergo a concave (positive, outward facing) or convex (negative, inward facing) deflection. Typically, the long faces of a rectangular container will undergo concave deflection while the short faces undergo convex deflection, resulting in an increased container footprint. Consequently, additional cargo or storage space is needed, the probability of product damage increases, and loads may destabilize during shipment.

In a distribution environment, compressive forces affect palletized or stacked containers and can be static (e.g., containers in a warehouse) or dynamic (e.g., containers in transport). Internal forces affecting a container vary greatly, but are typically caused by over- and under-packaging or product settling. In addition, the magnitudes of both compressive and internal forces can be amplified if the structure of a container is compromised due to fatigue, climate change, or damage. This force amplification can propagate throughout other containers and potentially cause container or product damage.

International and domestic organizations created testing methods covering compression, vibration, drop, fragility, and cushioning to evaluate the effectiveness of shipping containers within a distribution environment. Thus, it is important to know and understand the types of forces a container undergoes in order for package designers to avoid over- or under-packaging. Over-packaging can result in product damage during shipment and loss of sale and is environmentally unfriendly, while under-packaging costs product developers money because of unnecessary material use.

Needs

This section discusses the needs of different users, including ASTM International, package designers, researchers, and package testers. The needs associated with performing a measurement systems analysis are the creation of a standardized test method, becoming an ASTM International standard, improving upon past analyses, testing different sized containers, understanding bulge, ensuring proper calibration of the measurement system, and verifying repeatability and reproducibility of the measurement system. A score ranging between one and four ranks the needs below.

Table I – Recognition of Needs

Description of Needs	Importance
Create standardized method to measure bulge	4
Become ASTM Standard	4
Improve upon inconsistencies and/or failures in related or past projects	3
Investigate performance of different sized corrugated containers	2
Understand the significance of bulge	3
Ensure bulge test machine calibration	3
Ensure test data is repeatable and reproducible	4

Importance Scale: 4 = Highest Importance, 1 = Lowest Importance

The creation of a standardized method to measure bulge is important because all attempts at measuring bulge in past projects have been singular events, and not accurately repeated by others. If successful, ASTM International will receive the results of this analysis. A motion for the test method used in this study to become a subset of D642, Package Compression Testing will also be sent.

The success of this project will depend on looking at previous methods for measuring container bulge and improving on them. To accomplish this and give the analysis validity, different sized containers must be measured, which will also help researchers understand the significance of container bulge, figure out the calibration of the measurement system and ensure data reproducibility and repeatability.

Related Work

The first known bulge test fixture was created by James Skundberg in 1962. This fixture lacked application and utility, and a quote from the patent states "…the only common way of testing cartons for bulge is by observing the bulge in the cartons both before and after shipment (Skundberg, 1965)." This method only measures bulge caused by time and product settling, not bulge associated with compressive forces (Dundon, 2008).

Industrial Technology Master's candidate Jesse Dundon made the second fixture in 2008. Dundon's fixture did not have a resolution large enough to measure container bulge and introduced a large amount of bias and linearity by using independently controlled digital calipers. Also, the fixture was built beyond specifications, able to withstand compressive loads well in excess of a standard corrugate container before failing. According to Kutz (2009), the digital calipers used easily fell out of calibration, and accounted for the largest percentage of measurement system variation (p. 19).

The third fixture, created by Industrial Technology undergraduate Tyler Kutz in 2009 improved upon Dundon's design, incorporating modularity and accuracy. The frame of the fixture can accommodate containers as small as 8 in. x 12 in. to a full footprint (16.5 in. x 15.7 in.). In addition, a digital readout device replaced the digital calipers found on Dundon's fixture, eliminating issues with calibration (Kutz, 2009). This will be the fixture used in the study.

Potential Solution

Investigate the feasibility of a bulge test fixture becoming an ASTM International standard by accomplishing the following tasks:

1. Determine experiment guidelines
2. Test protocol creation
3. Data sampling
4. Testing and evaluation
5. Reproducibility of experiment
6. Statistical evaluation of data

Experiment guidelines will be determined by consulting with statistician Dr. Soma Roy. The number of testers and container samples required are crucial to ensuring a statistically valid test. A test protocol will be made, itemizing specific tasks that must be completed. Every aspect of this test must be recorded, from environmental variables during container construction to the amount of bulge each container undergoes. The test will be performed and data recorded, then the bulge test fixture will be sent to an independent testing company, to confirm repeatability. If the results are positive, a statistical analysis will be performed and the results will be sent to ASTM International for standards adoption.

Contribution

The results of this project will be instrumental in the process of standardizing bulge testing. With no official research effort surrounding bulge testing, this study will pave the way toward quantifying bulge and the implications it has on specific containers.

This project has the potential to benefit everyone, from container designers, distributors, retailers, and end-users. Product developers and package testers can add bulge testing as another package performance tool for use in identifying specific product packaging requirements. Warehouse workers can rest assured containers designed to reduce or eliminate bulge will fit on pallets and shelves, ensuring an efficient use of space. As a result, developers save money by having a properly packaged product; savings they can pass on to end-users.

Scope of Project

The purpose of this project is to evaluate the measurement variation within a corrugated container bulge tester. Bulge is a type of deformation containers experience when subject to compressive forces such as stacking or internal forces due to under- and over-packaging. Both compressive and internal forces can accelerate the failure of a container by causing panels to flex and flutes to buckle, compromising structural integrity. Additionally, variable environmental conditions such as temperature and humidity can magnify the effect bulge has on a container, speeding up the failure rate of a container. To evaluate the bulge tester, a gauge repeatability and reproducibility study will be performed. Testing will occur with two different sized corrugate containers. Correlations between the data, corrugate containers, temperature, relative humidity, testers, and container compression strength will be evaluated. Statisticians will aid in the creation of this study while following current standards set forth by ASTM International for compression strength testing and performing an interlaboratory study. The study is limited to the type of paper-based materials used and does not cover all paper-based materials in this evaluation.

SECTION II

REVIEW OF LITERATURE

The purpose of this project is to evaluate the measurement variation within a corrugated container bulge tester. Bulge is a type of deformation containers experience when subject to compressive forces such as stacking or internal forces due to under- and over-packaging. Both compressive and internal forces can accelerate the failure of a container by causing panels to flex and flutes to buckle, compromising structural integrity. Additionally, variable environmental conditions such as temperature and humidity can magnify the effect bulge has on a container, speeding up the failure rate of a container. To evaluate the bulge tester, a gauge repeatability and reproducibility study will be performed. Testing will occur with two different sized corrugate containers. Correlations between the data, corrugate containers, temperature, relative humidity, testers, and container compression strength will be evaluated. Statisticians will aid in the creation of this study while following current standards set forth by ASTM International for compression strength testing and performing an interlaboratory study. The study is limited to the type of paper-based materials used and does not cover all paper-based materials in this evaluation.

This literature review will cover three main topics, including container bulge, corrugated container construction and performance testing. First, the cause and characteristics of bulge will be discussed. Second, container construction will be a review in corrugated manufacturing, flute size and container styles and their applications. Lastly, five container evaluation methods and their effectiveness in reducing container failure will be discussed.

Cause and Characteristics of Bulge

Bulge is the deflection of the faces of a container that occurs when a compressive or internal load (container contents) is applied.

Compressive Forces: Mark, et. al. (2002) states that as a vertical load acts evenly upon the top of a container, the side panels will compress until a critical buckling load is applied. When the critical load is reached, the side faces of a container typically undergo a concave (outward) deflection, with maximum deflection occurring at the center of a face and minimum at the corners. At the same time, the majority of the load acting upon the bulging container will redistribute over the corners. Finally, the container will continue to undergo loading until failure occurs (p. 408).

Internal Forces: A container will typically bulge if filled with a liquid or flowable solid. As with compressive forces, these internal forces produced by container contents will compromise the flexural stiffness of the faces of a container. Combined with a small compressive force, a container will bulge and eventually fail (Dundon, 2008).

Other Considerations: Lee and Park (2004) suggest equivalent containers will always fail when under the same load at different times due to variations in the container construction process. The way a container is made will affect the flexural stiffness (resistance to bending) of the side panels, which affects the strength of the container (p. 275). Changes in ambient temperature, relative humidity, and fatigue also aid in the failure of containers. Corrugated fiberboard is a hygroscopic material that loses strength as relative humidity increases. The longer a container is exposed to a high humidity environment or liquid product seepage, the weaker the container gets and the more it will bulge, even if the compressive load does not change (Dundon, 2008). Also, when a container is stationary for an extended period, it can begin to deteriorate due to environmental fluctuations.

Container Functions

Corrugated containers are designed to serve several purposes, including containment, protection, convenience and communication. With corrugated containers becoming a global packaging medium, products can be measured uniformly, easily transported through large distribution networks, and serve as marketable symbols to consumers. The following section will provide a general overview of container functions.

Containment: Containment is the most basic tenet of container design, requiring products to be contained before being transported. The type of product and its characteristics size, shape, and amount dictate the container size and shape needed to contain a product (J. Singh, class presentation, January 12, 2010). Robertson (2006) states that without proper containment, products can break, become lost during handling or end up on the ground, contaminating the environment (p. 3).

Protection: Regarded as the primary function of a container, product protection is crucial. The container must protect its contents from damage during transportation and handling, such as temperature, humidity, compressive forces, shocks, vibrations, and drops. Designers take several product characteristics and the distribution environment into consideration when designing an adequate container (J. Singh, class presentation, September 28, 2009).

Convenience: Society has changed greatly over the years, precipitating the need for convenient packaging. Portioned into easy-to-use consumer sizes, it is now commonplace to utilize the primary container as a vessel for consumption (Robertson, 2006).

Communication: Communication is necessary for the survival of a container. A product must convey a message to a consumer to be sold. The message could be an attractive label, sleek container shape and design, or a combination of the two (J. Singh, class presentation, September 28, 2009). Also, containers must communicate information about their contents in the form of a Universal Product Code (UPC) to expedite movement through the distribution environment. In addition, labels can be added to a container, notifying handlers of a product with a specific fragility, required orientation or maximum stacking height (Robertson, 2006).

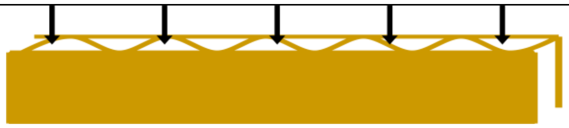
Container Construction

“Corrugated board is a composite structure in which a corrugated medium, the fluting, is bonded between two paperboard sheets, the linerboard, by means of an adhesive film” (Biancolini, 2003). Linerboard and fluting are typically composed of Fourdrinier Kraft material, which is the most popular paper used in corrugated packaging (Twede, et.al., 2005). A corrugator is needed to bind the linerboard with the medium. It flutes the medium, glues the medium to the linerboard, and then glues another layer of linerboard to the other side of the medium. The combined board is cut into sheets, typically die-cut into designs, slotted, scored, possibly printed upon, and then folded and glued. The most popular container style made today is called a Regular Slotted Container (RSC) (Fibre box association, 1999).

The corrugator machine is also capable of creating boards that increase the mechanical properties of containers, called double- and triple-wall boards. A double-walled board has two sheets of fluting glued between three linerboards, while triple-walled board has three sheets of fluting glued between four linerboards. Double- or triple-wall containers are used for accommodating products with high gross weight, strict compression strength or puncture-resistant requirements (Maltenfort, 1996).

Significance of Flutes: The corrugated medium used to create combined board is fluted into a series of arches, giving the combined board immense strength in two directions. Maltenfort (1996) describes these strengths, saying when oriented flat (flutes run parallel to a surface), the combined board has good flat crush resistance, as the flutes direct any distributed forces downward (see: Table 2-1). When oriented vertically (flutes run perpendicular to a surface), the flutes form columns, giving the combined board excellent compression strength (p. 14).

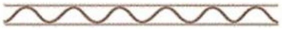
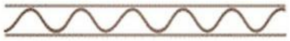
Table II – Flute Orientations

Flat	Vertical
	

Maltenfort, 1996.

Flutes come in a variety of sizes, each corresponding with a letter of the alphabet. Table 2-2 lists four common flute types: A-, B-, C- and E-flutes. A-flute was the first fluted medium created, C-flute is the most popular medium in the United States, B-flute is used mainly for its printability, while E-flute was designed to compete with folding cartons. Each size flute has specific characteristics that affect the mechanical properties of a container. For example, A-flute is large and thick compared to the other types, giving a container made from A-flute corrugate good flexural stiffness (resistance to twisting), top-to-bottom stacking (compression) strength and cushioning, but because it is so thick, package designers often skip using A-flute for C-flute. In another example, B-flute corrugate has more flutes per linear foot than A- and C-flute, giving it better flat crush resistance, yet a lower top-to-bottom stacking strength.

Table III – Common Flute Types

Flute Types		Flutes per linear foot	Approx Flute Height		Approx Take-up Factor
			(in.)	(mm)	
A		33 ± 3	3/16	4.76	1.58
B		47 ± 3	3/32	2.38	1.35-1.38
C		39 ± 3	9/64	3.57	1.43-1.45
E		90 ± 4	3/64	1.19	1.30

Fibre box association, 1999.

Take-up Factor: In addition to mechanical properties gained and lost due to flutes per linear foot and flute heights, there is a number relating flute types, called the take-up factor. Fluting corrugated medium requires more linear feet of that material than the linerboard used to make the combined board. For example, a 10 in. length of C-flute requires 14.3 to 14.5 in. of corrugated medium.

Common Container Styles

According to the Fibre Box Association, there exists a numerical identification system for corrugated containers called the International Fibreboard Case Code. Designed by the European Federation of Manufacturers of Corrugated Board (FEFCO) and the European Solid Fiberboard Case Manufacturer’s Association (ASSCO), there are hundreds of standardized container designs that can effectively contain and protect millions of products (Fibre Box Association, 1999). This section will cover three container styles commonly used in the agricultural industry, the Regular Slotted Container, Full Telescope Half Slotted Container (FTHS) and Bliss Style Container (J. Singh, personal interview, November 18, 2010).

Regular Slotted Container (RSC): An RSC is composed from one piece of corrugate board with flaps of identical length. The outer flaps are half the width of the container and join at the center when folded. This is the most common container design because of its amazing versatility and design (Fibre Box Association, 1999). During the manufacturing process, an RSC will produce less than one-percent scrap material (Maltenfort, 1996).

Full Telescope Half Slotted Container (FTHS): A telescoping container is a container comprised of two pieces, with one piece fitting over the other. The FTHS is made using two half slotted containers, which are the same as an RSC, minus one set of flaps (Fibre Box Association, 1999).

Bliss Style Container: A bliss style container has three pieces, including a folding body and two identical side panels. Six flaps on the body are used as glue folds for the side panels, giving it rigidity, impressive compression strength and the ability to contain products of high gross weight.

Testing Methods

Packaging performance testing is an invaluable tool for packaging designers. Due to corrugate material being the container medium of choice, testing methods were created to evaluate the performance of a container throughout the distribution environment. A common misconception is that a package is in the distribution environment only when it is being transported. From creation, through transportation and handling, to warehousing and retail, a package is in the distribution environment until it reaches the hands of a consumer (Maltenfort, p. 128).

Packaging must handle a multitude of stresses to ensure undamaged products, especially considering the variable nature of the distribution environment. Annually, $10 billion worth of products are damaged in the United States due to poor package design, under-packing, or over-packing (J. Singh, class presentation, September 24, 2010). Organizations such as ASTM International and the Technical Association of the Pulp and Paper Industry (TAPPI) have created test methods that evaluate the performance of a package in a laboratory setting under ideal conditions (Fibre Box Association, p. 88). These methods give package designers insight to what happens to packages and the knowledge to fix any flaws.

This section will contain an overview of five ASTM International test methods, including compression strength testing (ASTM D642), fragility testing (ASTM D5487), drop testing (ASTM D5276), vibration testing (ASTM D999), and dynamic shock cushioning testing (ASTM D1596).

Compression Strength Testing: Compression strength testing is a procedure used for measuring the ability of a container to resist compressive loads during distribution or storage. This test method will help package designers estimate a minimum amount of compressive load a package must resist while in the distribution environment as to not damage the product within.

ASTM International supports two types of compression machines to estimate the compression strength of a container, the fixed- and swivel-platen testing machines. A fixed-platen testing machine is equipped with two platens, one of which is stationary and the other is moveable vertically. A swivel-platen testing machine is also equipped with two platens, one of which is stationary and the other attached to a universal joint, allowing it to move vertically and tilt to lay flat on the container undergoing testing. Both types of machines are commonly found as one machine, with operators having the ability to lock the swivel-platen in place. Additionally, each test method is useful for specific types of compression tests; fixed-platen is great for testing the edges or diagonal corners of a container, while swivel-platen is used for face-to-face testing (ASTM D642, 2005).

The procedure for compression testing is quite simple. To conform to ASTM D642 standards, the number of test specimens required must represent the sample population, and test specimens tested in a top-to-bottom orientation. In addition, a pre-load (initial force) for single wall (50 lbf), double-wall (100 lbf), and triple-wall (500 lbf) containers are recommended. A pre-load ensures congruent test start points as well as making sure each container tested is in contact with the top platen. After the pre-load is applied, the test begins with either the fixed- or swivel-platen descending (0.5 in/min) onto the test specimen. The platen continues to apply a force to the container until it fails, typically after a ten-percent yield in force occurs (ASTM D642, 2005).

Due to the variable nature of corrugated fiberboard, equivalent containers tested will not share equivalent test results. Biancolini, et. al. (2003) suggests the quality of the raw materials, discrepancies in the manufacturing process, and environmental conditions all contribute to the failure of a container. Unfortunately, due to the nature of this test, the root cause of failure is difficult to identify because factors affecting the quality of the test specimen are acting upon it concurrently (p. 48).

Fragility (Shock) Testing: ASTM D5487, Standard Test Method for Simulated Drop of Loaded Containers by Shock Machines replicates the effects of vertical drops on a container. Package designers can test the amount of shock transmitted to a product at specific heights and on variable surfaces. Combined with knowledge of how a package moves through the distribution environment, fragility testing is an essential part of creating an adequate container. Data from this test will allow designers to figure out the optimal combination of container size and interior cushioning required, controlling the amount of shock transmitted to a product.

To perform a fragility test, a container is placed upon the test surface and a plastic or gas programmer is chosen. Plastic or gas programmers simulate specific drop scenarios. Plastic programmers mimic hard surfaces such as concrete, while gas programmers mimic softer surfaces such as carpet. Typically, containers dropped using plastic programmer scenarios experience high G-forces and an extremely short shock pulse, which is the time it takes for the container to suspend motion after hitting a surface. Containers dropped using gas programmer scenarios experience lower G-forces and a longer shock pulse. Comparatively, a product will not necessarily always fail a plastic impact and survive an elastic impact. A product will fail only due to G-forces experienced, which is a combination of shock duration and deceleration (ASTM D5487, 2002).

Drop Testing: This test method allows a package designer to evaluate the performance of a package after sustaining a free fall from specific drop heights. This is beneficial for containers manually handled in the distribution environment, as they are more likely to be subject to sudden falls. ASTM D5276, Standard Test Method of Drop Test of Loaded Containers by Free Fall recommends using this tester to compare designs or evaluate the progressive failure of a container through multiple drops.

To perform a drop test, a container is placed upon the drop tester at a certain height and orientation (face, edge, or corner), then dropped. There are multiple test cycles a package can undergo when drop testing. Each test cycle is very general and selected after package designers determine a point of failure. In this case, failure is up to the designer and can be a multitude of things, ranging from a scratch or dent on a package to a broken product. Preexisting knowledge of the distribution environment is helpful, as is the type and severity of drop required to cause actual product or package failure.

Vibration Testing: Vibration testing simulates the performance of a container during transport. Everything from a road surface, tires, engine or vehicle body can transmit longitudinal, lateral, or vertical vibrations to a product and damage it. ASTM D999, Standard Test Methods for Vibration Testing of Shipping Containers, states that containers of any form can be subject to four tests offered within this standard, the vertical motion repetitive shock, rotary motion repetitive shock, single container resonance, or palletized load test.

Within each of these tests, a container or palletized load is subject to vibration at random or set frequencies. A container is placed on (or secured) onto a platen and vibrated. Accelerometers attached to the platen measure G-forces observed by the product, allowing test operators to calculate the natural frequency of the product. The natural frequency of a product is where the most damage will occur, and is a valuable number for package designers to know, allowing them to design a container around this number (ASTM D999, 2001).

Dynamic Shock Cushioning Testing: The dynamic shock cushioning test is a method for determining the effectiveness of a cushion. Cushioning material helps to elongate the shock pulse of a falling container to lessen the chance of product damage.

This test only requires an eight by eight inch sample of cushioning material. A weighted platen is dropped from specific heights to simulate an equivalent free-fall in. Accelerometers attached to the platen record the shock transmitted to the test cushion (ASTM D1596, 1997).

Testers can compare performance of a cushion at different drop heights by generating a dynamic cushion curve from the test data. This is useful for package designers looking to reduce the amount of G-forces transmitted to a product without over-packaging a product (Maltenfort, 1996).

SECTION III

ALTERNATIVES

The purpose of this project is to evaluate the measurement variation within a corrugated container bulge tester. Bulge is a type of deformation containers experience when subject to compressive forces such as stacking or internal forces due to under- and over-packaging. Both compressive and internal forces can accelerate the failure of a container by causing panels to flex and flutes to buckle, compromising structural integrity. Additionally, variable environmental conditions such as temperature and humidity can magnify the effect bulge has on a container, speeding up the failure rate of a container. To evaluate the bulge tester, a gauge repeatability and reproducibility study will be performed. Testing will occur with two different sized corrugate containers. Correlations between the data, corrugate containers, temperature, relative humidity, testers, and container compression strength will be evaluated. Statisticians will aid in the creation of this study while following current standards set forth by ASTM International for compression strength testing and performing an interlaboratory study. The study is limited to the type of paper-based materials used and does not cover all paper-based materials in this evaluation.

This section will discuss the advantages and disadvantages of statistical methods used for a measurement system analysis. The experiment design, test procedure, variables of interest, hypotheses, and tools required for the analysis will be discussed.

Proposed Solutions

Three different statistical methods will be discussed in the following section. The first is a crossed Gauge R&R study. The second is a nested Gauge R&R study. The last is the general linear model analysis of variance method. All of the methods are used in measurement system analyses; the correct method depends on the scope of the study.

1. Crossed Gauge R&R
    A. Advantages
        i. Non-destructive testing
        ii. All parts are the same
        iii. Can measure variation due to measurement system, operator, and part
        iv. Can measure repeatability and reproducibility
    B. Disadvantages
        i. Cannot be used for destructive tests
        ii. Each operator must test every part multiple times
2. Nested Gauge R&R
    A. Advantages
        i. Destructive testing
        ii. Measure variation due to measurement system, operator, part, and operator-to-part.
        iii. Can measure repeatability and reproducibility
    B. Disadvantages
        i. All parts are assumed to be the same
        ii. All factors are random
        iii. Cannot be used for non-destructive tests
        iv. Each operator tests only their parts once
3. General Linear Model (GLM) ANOVA
    A. Advantages
        i. Can assess all components of variation in this study
        ii. Can analyze main effects interactions in-depth to establish most effective statistical model
    B. Disadvantages
        i. Cannot directly give repeatability and reproducibility readings
        ii. Cannot validate the effectiveness of the measurement system – only strengthen results from a GR&R

Statistical Testing

Variables

1. Independent
    - Operator
    - Material used
    - Cutting table
    - Compression tester
    - Bulge tester
2. Control
    - Percent yield
    - Container preload
    - Compression tester test speed
    - Ambient temperature
    - Percent relative humidity
    - Date
    - Time
3. Dependent
    - Bulge amount
    - Container compression strength
    - Container deflection

Hypothesis

Null hypothesis (H_0): there is no significant statistical difference between measurements of equivalent containers ($\sigma^2{}_1$) by the bulge test apparatus in equivalent environments by different operators ($\sigma^2{}_2$).

Alternative hypothesis (H_a): there is a significant statistical difference between measurements of equivalent containers ($\sigma^2{}_1$) by the bulge test apparatus in equivalent environments by different operators ($\sigma^2{}_2$).

The null hypothesis is assumed true unless statistically proven otherwise.

Experiment Design: The purpose of this experiment is to assess the performance of the bulge test apparatus and validate that there is no significant statistical difference between operators testing similar parts in an equivalent environment. To accomplish this, a Gauge Repeatability and Reproducibility (GR&R) study is used. A GR&R can divide the total variation in a process into several components, including equipment variation (repeatability), operator variation (reproducibility), and part-to-part variation. A Crossed GR&R study is the most widely used type of this study, with parts being tested multiple times by multiple operators.

This experiment requires a Nested GR&R study, which is quite different from the typical Crossed GR&R study. In a Nested GR&R, each part is destroyed after testing, meaning multiple operators cannot test the same part. Instead, each operator measures a different sample of parts that are assumed to be homogenous. The parts tested are nested within each operator, meaning each operator tests a different sample from the same batch.

In discussion with statistician Dr. Soma Roy, determinations for the number of operators (testers), batches (container types: full- or half-footprint), and parts (containers) were made. Two operators, two batches, and 50 parts per batch were the minimum parameters required. Since the bulge test apparatus is new, its calibration, linearity, and bias were uncertain. It was suggested that the calibration of the apparatus be tested using a type-1 gauge study. A type-1 gauge study helps assess the capability of a measurement system by evaluating its bias and linearity using measurements taken of a single part tested by a single operator.

A spring-loaded wooden container was created to assess the measurement system. The side faces of the container are hinged to allow it to bulge while under compression. Surgical tubing was used to keep the container from collapsing under its own weight while having a low enough spring constant that bulge measurements were not affected.

Once the calibration of the apparatus was confirmed, two operators were to test one-hundred containers (fifty full-footprint and fifty half-footprint) at random to assess the performance of the apparatus as a statistically valid measurement device. A molded foam block made from expanded polystyrene was cut to size and inserted into each container prior to testing. The purpose of the foam block is to simulate a loaded container while maintaining homogeneity and to disallow negative bulge (the tendency of the face of a container to flex inward).

Test Procedure

1. Receive pallet load of corrugated sheets
2. Select 50 corrugated sheets from pallet load at random
3. Label each corrugated sheet sequentially
4. Cut out 50 half-footprint containers; label 1-50
5. Cut out 50 full-footprint containers; label 51-100
6. Fold and glue each container; stack sequentially and store in room where testing will commence
7. Create data sheet to record required measurements; ensure containers are randomly distributed on data sheet
8. Open Lansmont TTC-3 Compression Tester software
    - Select ‘Constant Load Deflection Test’
9. Ensure the following compression tester settings are in compliance with ASTM Standard D642 for compression testing
    - Preload: 50 lb.
    - Test Speed: 0.5 in/min
    - Yield Percentage: 10%
    - Stop Force: 30,000 lb.
10. Take container; seal bottom of container; insert foam block; seal top of container
11. Load container onto bulge test apparatus
12. Align bulge test measurement plates adjacent to each container face; tare each measurement plate
13. Test container
14. Record measurements
15. Remove container from bulge test apparatus; remove foam block
16. Repeat steps 10 through 15 until testing is concluded
17. Perform Gauge R&R (expanded)
18. Interpret results

Samples: This study requires testing two types of containers created from (60 x 96 x 0.18) in. non-coated Kraft colored corrugated sheets. The first container type is a (23.5 x 15.7 x 12) in.

random slotted container (RSC), at which size is called a full-footprint container. The second container type is a half-footprint container. It is one-half the size of the full-footprint container, having the dimensions (15.7 x 11.7 x 12) in.

Each container evolved from a built-in RSC design (FEFCO #0201) in ArtiosCAD, a drafting program used for packaging design. It was then cut out on a Kongsberg computerized cutting table to ensure each container cut out is the same. The containers are then numbered, folded, glued, and stored in the room used for testing until needed.

Operators: Anthony Hall and Evan Cernorkus operated the bulge test apparatus for this experiment. Both candidates are Industrial Technology students with prior experience operating all equipment used in this experiment.

Data: A spreadsheet was created to aid in the recording of measurements by each operator. The following values were recorded for each container:

1. Operator (Persons doing the testing)
2. Batch (Container types: full- or half-footprint)
3. Sample (Container number)
4. Test (Used for data sorting)
5. X-bulge (Amount the long face of the container bulged)
6. Y-bulge (Amount the short face of the container bulged)
7. Z-bulge (Amount the bottom of the container bulged)
8. Temperature (Measured by compression tester)
9. Percent relative humidity (Measured by compression tester)
10. Peak force (Largest amount of force container withstood before failure)
11. Peak deflection (Largest amount container was compressed)
12. Preload (Amount of compressive load applied to each container before peak force and peak deflection begin recording)
13. Test speed (Speed at which compression tester platen moves)
14. Date
15. Time

Tools

I. Spring-loaded Wood Test Container Construction

A. Materials
  - Wood
  - Plastic
  - Surgical tubing
  - Hinges
  - Washers
  - Screws
  - Metal dowel

B. Hardware
  - Table saw (Used to cut wood and plastic)

C. Tester
  - Bulge Tester (Made by Tyler Kutz)
  - Lansmont TTC 152-30 Compression Tester

D. Software
  - Minitab (Statistical Analysis)
  - Microsoft Excel (Data organization)
  - Lansmont TTC3 Compression Tester Software

II. Container Construction

A. Materials
  - Corrugated C flute (Non-coated, Kraft colored)
  - Hot melt glue
  - Clear packing tape

B. Hardware

- Kongsberg Table (Cut out corrugated containers)
- Tape holder
- Box cutting knife (Used for cutting containers after testing)
- Glue gun
- Band saw (Used for cutting foam block)

C. Tester

- Bulge tester (Made by Tyler Kutz)
- Lansmont TTC 152-30 Compression Tester

D. Software

- Lansmont TTC3 Compression Tester Software
- Microsoft Excel (Data organization)
- ArtiosCAD (Container design)
- GcWin 2000 (ArtiosCAD to Kongsberg Table interface program)
- Minitab (Statistical analysis)

SECTION IV

RESULTS/DISCUSSION

The purpose of this project is to evaluate the measurement variation within a corrugated container bulge tester. Bulge is a type of deformation containers experience when subject to compressive forces such as stacking or internal forces due to under- and over-packaging. Both compressive and internal forces can accelerate the failure of a container by causing panels to flex and flutes to buckle, compromising structural integrity. Additionally, variable environmental conditions such as temperature and humidity can magnify the effect bulge has on a container, speeding up the failure rate of a container. To evaluate the bulge tester, a gauge repeatability and reproducibility study will be performed. Testing will occur with two different sized corrugate containers. Correlations between the data, corrugate containers, temperature, relative humidity, testers, and container compression strength will be evaluated. Statisticians will aid in the creation of this study while following current standards set forth by ASTM International for compression strength testing and performing an interlaboratory study. The study is limited to the type of paper-based materials used and does not cover all paper-based materials in this evaluation.

Crossed GR&R

Table IV – Advantages and Disadvantages of Crossed GR&R

Advantages	Disadvantages
Can be used in non-destructive tests	Cannot be used for destructive tests
All parts are the same	Each operator must test every part
Can measure multiple sources of variation	
Can measure repeatability and reproducibility	

Nested GR&R

Table V – Advantages and Disadvantages of Nested GR&R

Advantages	Disadvantages
Can be used in destructive tests	All parts assumed to be equivalent
Can measure multiple sources of variation	Each operator tests specific parts, not all parts
Can measure repeatability and reproducibility	

GLM ANOVA

Table VI – Advantages and Disadvantages of GLM ANOVA

Advantages	Disadvantages
Can measure multiple sources of variation	Cannot directly give R&R readings
Can analyze main effects interactions	Cannot validate measurement system

Comparison of Solutions

Table VII – Comparison of Proposed Solutions

Needs	Crossed	Nested	ANOVA
Create standardized method to measure bulge	1	5	4
Become ASTM Standard	4	4	4
Improve upon past projects	2	5	5
Investigate performance of different sized containers	5	5	5
Understand the significance of bulge	2	4	4
Ensure bulge test machine calibration	4	4	4
Ensure test data is repeatable and reproducible	4	5	5
Total	22	32	31

Importance Scale: 5 = Highest Importance, 1 = Lowest Importance

Table VII above shows that a Crossed GR&R is not the right choice for this experiment, as they are limited to non-destructive testing. Fortunately, a Nested GR&R is perfect for a non-destructive experiment. Unfortunately, it does not address all of the unknowns prevalent in this experiment, such as what influence the main effects variable interactions have on total study variation. As such, the best choice solution is a combination of a Nested GR&R along with utilizing GLM ANOVA. The Nested GR&R can divide the total variation in a process into several components, including equipment variation (repeatability), operator variation (reproducibility), and part-to-part variation. The GLM ANOVA can go one-step further, determining which variables have the most effect on total gauge variation and provide input on the most effective statistical model to use in this experiment analysis.

Results

The bulge test apparatus failed to pass the Nested GR&R analysis in all measurements. Study variation for X-, Y-, and Z-bulge are 98.07%, 59.51%, and 70.97%, respectively. These measurements cause a rejection of the null hypothesis H_0: $\sigma^2{}_1 = \sigma^2{}_2$ and acceptance of the alternative hypothesis H_a: $\sigma^2{}_1 \neq \sigma^2{}_2$, meaning there is a significant statistical difference between measurements of equivalent containers ($\sigma^2{}_1$) by the bulge test apparatus in equivalent environments by different operators ($\sigma^2{}_2$). For a measurement system to be considered acceptable, the total Gauge R&R variation should be less than 30%. Any variation beyond 30% is suspect and usually accompanied with a measurement system that needs improvement.

Three test runs (20, 26, and 39) were removed from final analysis because ANOVA tests concluded that their residuals were greater than three deviations from the mean. Appendix B lists the runs and shows the highlighted outliers. Subsequent tests show the data is highly variable, with several residuals reporting large deviations from the mean. To preserve the true study results, those test runs will not be removed. The tests performed produced non-normal data. Descriptive statistics show the X-, Y-, and Z-bulge data are skewed, with measurements of -1.26, 0.88, and 0.39, respectively. Fortunately, the sample size is quite large (n = 97) and the statistical methods used in this study can handle non-normalcy.

Though the study variation is well beyond acceptable limits, these results do not take the interaction of variables as additional factors into consideration. Temperature and relative humidity were variables of interest throughout this study, and it was concluded that they had no statistically significant effect on the test specimens; the test specimens were not conditioned per ASTM Standard D4322, which states that the standard conditioning atmosphere shall be 73.4 ±

1°F and 50 ± 2% relative humidity. Correlations between other main effects variables such as peak deflection, part, operator, and peak force and interaction terms were made, resulting in no statistically significant results. As such, a nested GR&R was performed in Minitab using only the part, operator, and X-, Y-, or Z-bulge variables.

Bias, linearity, and precision are critical factors that must be known when a GR&R is performed. Since the bulge tester is new, no justifiable statement can be made on the bias of the machine because a true value cannot be measured. When the bulge test was conducted to measure the bulge of a container, the observed precision is a combination of the precision of the test method (including the measurement system, operators, and compression tester) and the precision of the containers being tested. Experience has shown that precision is highly dependent on the particular container being tested. This is mainly due to the variable nature of the corrugate material used; the root cause of failure will be difficult to identify due to the number of variables simultaneously affecting the container.

X-Axis Bulge

The ANOVA table (Appendix A) p-value for Part nested within Operator (P = 0.144) suggests the average bulge measurement is not dependent upon the operator taking measurements at the α = 0.05 significance level, concluding the relationship between parts and operators is weak. The Total Gauge R&R accounts for 98.07% of the study variation. This means that statistically almost all of the variability in the bulge measurements is due to either the measurement system (repeatability) or the operators (reproducibility). Additionally, there is a non-zero result (11.65%) for reproducibility. As this study contained destructive testing, taking multiple measurements of the same container is not possible.

Table VIII – Gauge R&R (Nested) for X-Axis Bulge

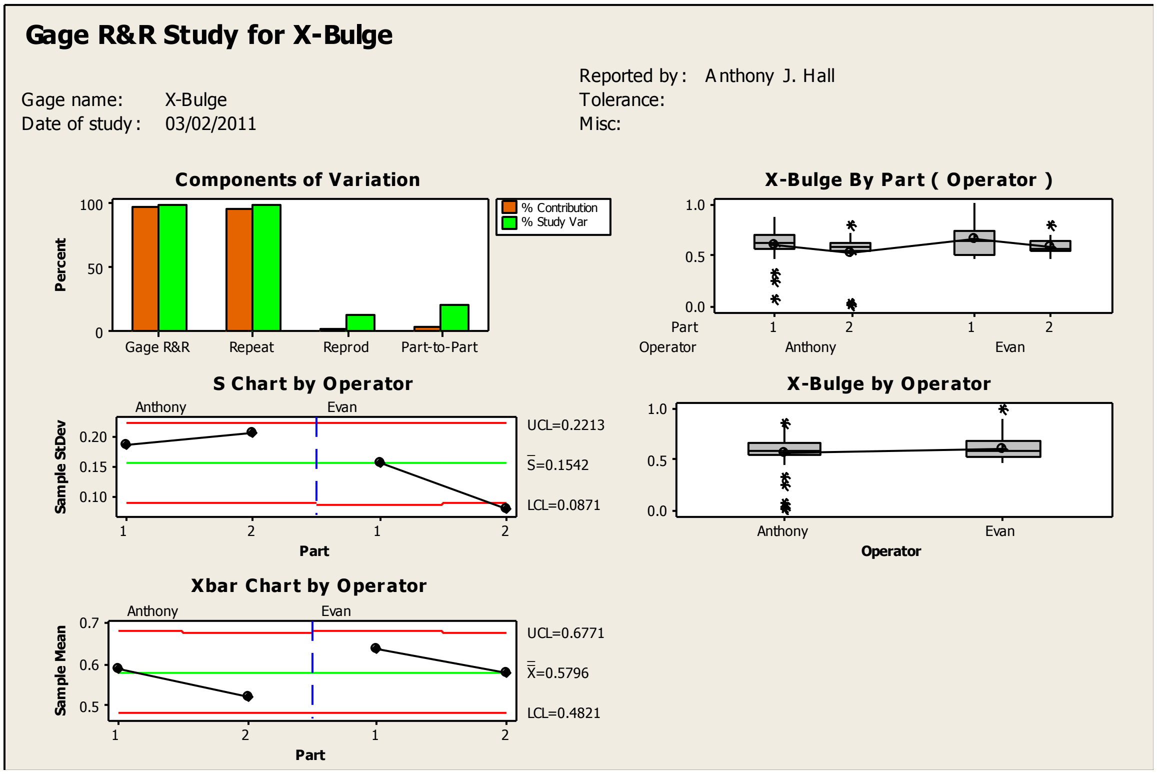
Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gauge R&R	0.163171	0.979028	98.07
Repeatability	0.162015	0.979090	97.37
Reproducibility	0.019391	0.116347	11.65
Operator	0.019391	0.116347	11.65

Table VIII – Gauge R&R (Nested) for X-Axis Bulge, continued

Part-To-Part	0.032539	0.195234	19.56
Part (Operator)	0.032539	0.195234	19.56
Total Variation	0.166384	0.998305	100.00

The xbar chart by operator in Figure 1 shows the measurements for both operators are in control, with points inside of the upper and lower control limits. This indicates the measurement system is inadequate. Further strengthening this fact is the number of distinct categories, which equals one (Appendix A). The conclusion is the analysis software cannot discern the variation between parts, resulting in variation being attributed to the measurement system. The bulge by operator boxplot show consistency in measurements, with a p-value for operator (P = 0.365).

Figure 1 – Gauge R&R (Nested) for X-Axis Bulge



Y-Axis Bulge

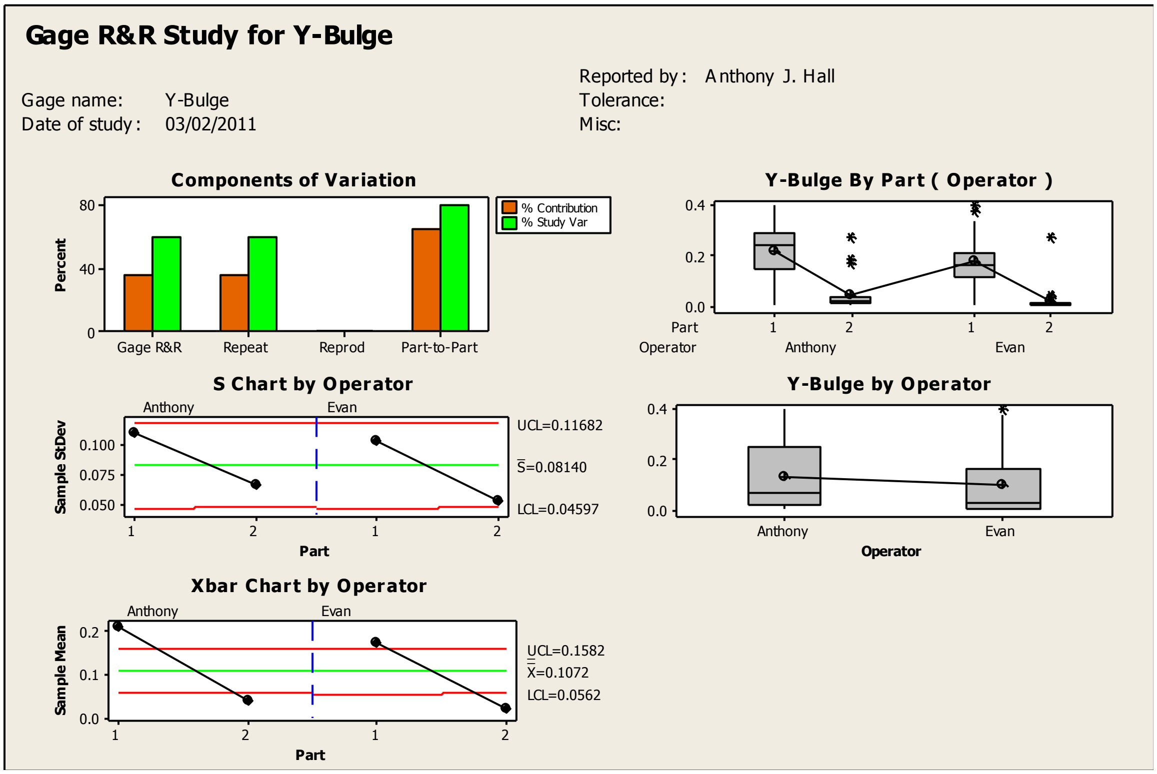
The ANOVA table p-value for Part nested within Operator (P = 0.000) suggests the average bulge measurement is dependent upon the operator taking measurements at the α = 0.05 significance level, concluding the relationship between parts and operators is strong. The Total Gauge R&R accounts for 59.51% of the study variation. Repeatability specifically (59.51%) accounts for all of the study variation, indicating the measurement system is not measuring parts consistently.

Table IX – Gauge R&R (Nested) for Y-Axis Bulge

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gauge R&R	0.084826	0.508954	59.51
Repeatability	0.084826	0.508954	59.51
Reproducibility	0.000000	0.000000	0.00
Operator	0.000000	0.000000	0.00
Part-To-Part	0.114549	0.687291	80.36
Part (Operator)	0.114549	0.687291	80.36
Total Variation	0.142537	0.855221	100.00

The xbar chart by operator in Figure 2 shows all measurements for both operators are beyond the control limits, indicating the parts used in this study represent the entire range of the sample population. Again, the number of distinct categories equals one, concluding the analysis software cannot discern the variation between parts. The bulge by operator boxplot show consistency in measurements, with a p-value for operator (P = 0.815).

Figure 2 – Gauge R&R (Nested) for Y-Axis Bulge



Z-Axis Bulge

The ANOVA table p-value for Part nested within Operator (P = 0.000) suggests the average bulge measurement is dependent upon the operator taking measurements at the α = 0.05 significance level, concluding the relationship between parts and operators is strong. The Total Gauge R&R accounts for 70.79% of the study variation. Repeatability specifically (70.79%) accounts for all of the study variation, indicating the measurement system is not measuring parts consistently.

Table X – Gauge R&R (Nested) for Z-Axis Bulge

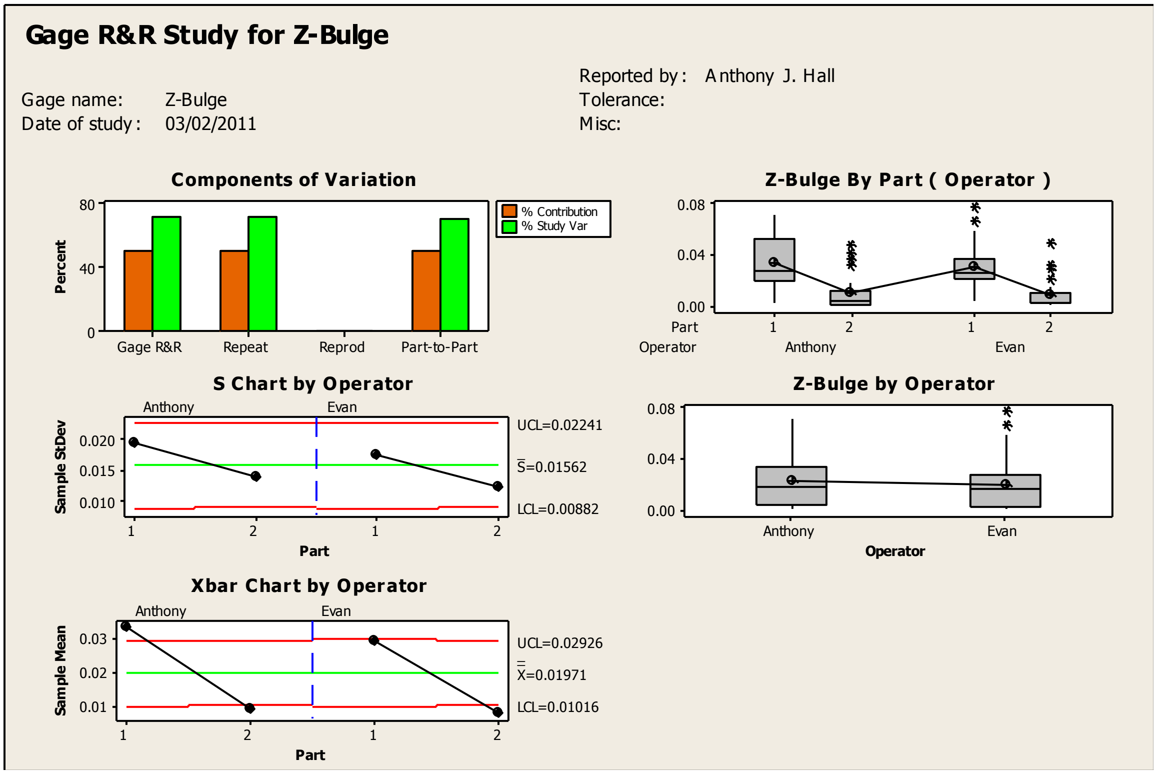
Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gauge R&R	0.0158762	0.095257	70.79
Repeatability	0.0158762	0.095257	70.79
Reproducibility	0.0000000	0.000000	0.00

Table X – Gauge R&R (Nested) for Z-Axis Bulge, continued

Operator	0.0000000	0.000000	0.00
Part-To-Part	0.0158400	0.095040	70.63
Part (Operator)	0.0158400	0.095040	70.63
Total Variation	0.0224268	0.134561	100.00

The xbar chart by operator in Figure 3 shows all measurements for both operators are beyond the control limits, indicating the parts used in this study represent the entire range of the sample population. Again, the number of distinct categories equals one, concluding the analysis software cannot discern the variation between parts. The bulge by operator boxplot show consistency in measurements, with a p-value for operator (P = 0.872).

Figure 3 – Gauge R&R (Nested) for Z-Axis Bulge



SECTION V

CONCLUSION/OBSERVATIONS

The following section covers the overall summation of the project, conclusions, learning objectives, open problems, and future works for the project. The section will also go over the facets of the implementation of the project.

Summary

For the project, the variation of the bulge test apparatus was questioned and tested by performing a Gauge R&R study. Help was provided by Dr. Jay Singh, Dr. Soma Roy, and Dr. Eric Olsen, with each providing guidance and technical support on the steps needed to accomplish this project.

The first step of the project was to find the problem, needs, and solutions. Once these areas were defined, a literature review was conducted. The review referenced several peer-reviewed articles related to the project, covering container construction, packaging distribution methods, and packaging test methods and instrumentation. Next, a study experiment was designed with help from Dr. Soma Roy.

The experiment was then performed, requiring the construction and testing of 100 test containers. The results were recorded and the variability due to the bulge test apparatus was determined through several statistical analysis methods.

Conclusions

Given the results found by utilizing a Nested Gauge R&R and GLM ANOVA analyses, it is obvious the experiment failed. There is, however, a possibility of the variation being attributed to the measurement system actually being variation within the corrugate material used to make the containers. The reason for this conclusion is multi-fold: the Gauge R&R and GLM ANOVA analyses run were not able to discern between factors not expressly measured and recorded, leading to the variability of the measurement system and variability of the corrugate material being grouped together. Lastly, the wooden test container used to ensure the bulge test apparatus gave repeatable results experienced extremely low variation. Due to time constraints, further inquiry into variation attribution was not possible.

Open Problems

There were several problems with the study, including machine design, sample construction, testing conditions, and machine calibrations. This section will discuss these problems.

Machine Design: The bulge test apparatus may need some improvements. After concluding testing, there is a definite possibility that the resolution (potential for measuring a change in variability) of the apparatus was not large enough. The digital readout kit attached to the apparatus is extremely accurate, so any variation within the apparatus is the fault of the measurements plates and the slides to which they are attached.

Sample Construction: The biggest assumption made when performing a Nested GR&R experiment is that the samples tested are homogenous. The corrugated sheets used were constructed with a tolerance of 0.125 in., which is as large as or larger than some of the observed bulge measurements. Furthermore, each container was to be assembled the same way. During container construction, inconsistent folding, taping, and gluing were observed. Each container did not sit flat on the bulge test apparatus, which may have introduced variability. In addition, there is a large amount of variation in the manufacture of corrugated fiberboard, making the identification of a specific cause of failure difficult.

Testing Conditions: When performing a GR&R study, it is a good idea to test over multiple periods, such as a batch in a day, then a batch over the course of a week. Every operator should experience a multitude of environmental conditions within those testing periods. The changing conditions provide a higher order of interaction to assess variation with, further validating the GR&R.

Supporting Machine(s) Calibration: Measurement systems tend to fall out of calibration over time and through use, making it necessary to ensure all equipment used in a Gauge R&R study is calibrated using proper equipment. If measurement systems and supporting equipment are not properly calibrated, additional variation can manifest itself and compound the total study variability.

The compression tester and Kongsberg cutting table were used in addition to the bulge test apparatus. The compression tester and Kongsberg cutting table were not calibrated before this experiment began. Additionally, the Kongsberg cutting table suffers frequent maladies, such as cutting tool breakage and insufficient creasing.

The biggest problem faced in this study was the compression tester. If someone wants to use the bulge test apparatus, a compression tester must be used as well. In the case of this study, the bulge test apparatus was brand new, with no known tolerance. The compression tester has a known tolerance, but it was not confirmed prior to this study.

Future Work

To give prudence to the conclusion above, future work should be spent considering the possibility that the majority of the Gauge R&R Study Variation was contained within the corrugate material used. One way to approach this is by running another Gauge R&R using the wooden test containers. The experiment in this report will be mimicked, with 100 trials being done, taking care to record additional factors such as date, time, temperature and relative humidity. Once the trials are completed, a Gauge R&R is run, along with GLM ANOVA to rule-out any interaction between main effects variables being statistically significant sources of variation. A test for equal variances is done and compared to the results of this experiment.

The variation in measurements for the wooden containers should be extremely small due to it being tested multiple times, allowing persons interpreting the data to assume one of two things. First, the variation is all within the measurement system, or second, the variation lies within the material used to create the parts tested. These assumptions can then be applied to this study, concluding that if the machine is really only responsible for ‘this much’ variation, then the rest lies within the corrugate material, and vice-versa. The measured variation can be adjusted accordingly, giving a ‘best case’ and ‘worst case’ scenario.

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APPENDIX A

Gage R&R Study: X-Bulge versus Operator, Part

```
Factor Information

Factor    Type    Levels  Values
Operator  random       2  Anthony, Evan
Part      random       4  1, 2, 1, 2


ANOVA Table with All Terms

Source           DF   Seq SS   Adj SS   Adj MS     F      P
Part(Operator)    2  0.10247  0.10379  0.05190  1.98  0.144
Operator          1  0.07011  0.07011  0.07011  1.35  0.365 x
Repeatability    93  2.44114  2.44114  0.02625
Total            96  2.61373

x Not an exact F-test.


Alpha to remove interaction term = 0.25


Variance Components

                                  %Contribution
Source                  VarComp    (of VarComp)
Total Gage R&R        0.0266249           96.18
  Repeatability       0.0262489           94.82
  Reproducibility     0.0003760            1.36
    Operator          0.0003760            1.36
Part-To-Part          0.0010588            3.82
  Part(Operator)      0.0010588            3.82
Total Variation       0.0276837          100.00



Gage Evaluation

                                   Study Var  %Study Var
Source               StdDev (SD)  (6 * SD)       (%SV)
Total Gage R&R          0.163171   0.979028       98.07
  Repeatability         0.162015   0.972090       97.37
  Reproducibility       0.019391   0.116347       11.65
    Operator            0.019391   0.116347       11.65
Part-To-Part            0.032539   0.195234       19.56
  Part(Operator)        0.032539   0.195234       19.56
Total Variation         0.166384   0.998305      100.00


Number of Distinct Categories = 1
```

Gage R&R Study: Y-Bulge versus Operator, Part

```
Factor Information

Factor    Type    Levels  Values
Operator  random       2  Anthony, Evan
Part      random       4  1, 2, 1, 2


ANOVA Table with All Terms

Source          DF   Seq SS   Adj SS   Adj MS      F      P
Part(Operator)   2  0.65230  0.65010  0.32505  45.17  0.000
Operator         1  0.02298  0.02298  0.02298   0.07  0.815 x
Repeatability   93  0.66917  0.66917  0.00720
Total           96  1.34445

x Not an exact F-test.


Alpha to remove interaction term = 0.25


Variance Components

                               %Contribution
Source               VarComp    (of VarComp)
Total Gage R&R     0.0071954           35.42
  Repeatability    0.0071954           35.42
  Reproducibility  0.0000000            0.00
    Operator       0.0000000            0.00
Part-To-Part       0.0131214           64.58
  Part(Operator)   0.0131214           64.58
Total Variation    0.0203167          100.00



Gage Evaluation

                                 Study Var  %Study Var
Source             StdDev (SD)    (6 * SD)       (%SV)
Total Gage R&R        0.084826    0.508954       59.51
  Repeatability       0.084826    0.508954       59.51
  Reproducibility     0.000000    0.000000        0.00
    Operator          0.000000    0.000000        0.00
Part-To-Part          0.114549    0.687291       80.36
  Part(Operator)      0.114549    0.687291       80.36
Total Variation       0.142537    0.855221      100.00


Number of Distinct Categories = 1
```

Gage R&R Study: Z-Bulge versus Operator, Part

```
Factor Information

Factor    Type    Levels  Values
Operator  random       2  Anthony, Evan
Part      random       4  1, 2, 1, 2


ANOVA Table with All Terms

Source          DF     Seq SS     Adj SS     Adj MS      F      P
Part(Operator)   2  0.0126903  0.0126600  0.0063300  25.11  0.000
Operator         1  0.0002101  0.0002101  0.0002101   0.03  0.872 x
Repeatability   93  0.0234411  0.0234411  0.0002521
Total           96  0.0363415

x Not an exact F-test.


Alpha to remove interaction term = 0.25


Variance Components

                              %Contribution
Source               VarComp   (of VarComp)
Total Gage R&R     0.0002521          50.11
  Repeatability    0.0002521          50.11
  Reproducibility  0.0000000           0.00
    Operator       0.0000000           0.00
Part-To-Part       0.0002509          49.89
  Part(Operator)   0.0002509          49.89
Total Variation    0.0005030         100.00



Gage Evaluation

                                Study Var  %Study Var
Source               StdDev (SD)  (6 * SD)       (%SV)
Total Gage R&R         0.0158762  0.095257       70.79
  Repeatability        0.0158762  0.095257       70.79
  Reproducibility      0.0000000  0.000000        0.00
    Operator           0.0000000  0.000000        0.00
Part-To-Part           0.0158400  0.095040       70.63
  Part(Operator)       0.0158400  0.095040       70.63
Total Variation        0.0224268  0.134561      100.00


Number of Distinct Categories = 1
```

APPENDIX B

Raw Data

Part	Operator	X-Bulge (in.)	Y-Bulge (in.)	Z-Bulge (in.)	Temp (°F)	RH (%)	Date
1	Anthony	0.0530	0.0020	0.0198	66.8	37.5	1/15/2011
1	Anthony	0.5922	0.2866	0.0532	66.9	36.3	1/15/2011
1	Anthony	0.2322	0.2372	0.0366	67.0	36.0	1/15/2011
1	Anthony	0.6218	0.2590	0.0560	67.5	35.8	1/15/2011
1	Anthony	0.8258	0.2398	0.0682	67.6	35.7	1/15/2011
1	Anthony	0.6122	0.1974	0.0700	67.8	35.4	1/15/2011
1	Anthony	0.5552	0.0988	0.0176	68.0	35.0	1/15/2011
1	Anthony	0.8368	0.3304	0.0268	68.1	34.9	1/15/2011
1	Anthony	0.4474	0.1228	0.0624	68.3	34.8	1/15/2011
1	Anthony	0.6388	0.3338	0.0126	68.7	34.7	1/15/2011
1	Anthony	0.8560	0.3286	0.0266	68.8	34.6	1/15/2011
1	Anthony	0.5442	0.0594	0.0210	69.1	34.3	1/15/2011
1	Anthony	0.6780	0.1374	0.0192	69.9	33.5	1/15/2011
1	Anthony	0.5206	0.1412	0.0125	69.9	33.6	1/15/2011
1	Anthony	0.6876	0.1418	0.0230	69.7	33.7	1/15/2011
1	Anthony	0.6766	0.2796	0.0020	69.9	33.5	1/15/2011
1	Anthony	0.6302	0.1636	0.0188	70.2	33.1	1/15/2011
1	Anthony	0.7174	0.2528	0.0448	70.5	32.7	1/15/2011
1	Anthony	0.5400	0.3930	0.0604	70.8	32.2	1/15/2011
1	Anthony	0.0000	0.0000	0.0000	0.0	0.0	1/15/2011
1	Anthony	0.7434	0.2502	0.0474	70.1	28.8	1/18/2011
1	Anthony	0.3162	0.0228	0.0312	70.4	28.5	1/18/2011
1	Anthony	0.6248	0.2598	0.0230	70.5	28.5	1/18/2011
1	Anthony	0.5880	0.3888	0.0266	70.7	28.2	1/18/2011
1	Anthony	0.5990	0.1536	0.0254	70.7	28.0	1/18/2011
1	Evan	0.0284	0.0034	0.0594	70.1	31.4	1/21/2011
1	Evan	0.6738	0.1070	0.0138	70.3	31.3	1/21/2011
1	Evan	0.6010	0.1550	0.0270	70.5	31.2	1/21/2011
1	Evan	0.5106	0.1318	0.0320	70.8	31.1	1/21/2011
1	Evan	0.8800	0.3934	0.0202	71.0	30.9	1/21/2011
1	Evan	0.8142	0.1010	0.0210	71.3	30.6	1/21/2011
1	Evan	0.5440	0.0000	0.0188	71.5	30.4	1/21/2011
1	Evan	0.4570	0.0712	0.0226	71.6	30.3	1/21/2011
1	Evan	0.7264	0.3690	0.0208	71.8	30.4	1/21/2011
1	Evan	0.6950	0.2996	0.0284	72.0	30.6	1/21/2011
1	Evan	0.6816	0.2416	0.0276	72.5	30.8	1/21/2011
1	Evan	0.4872	0.1604	0.0214	72.4	31.2	1/21/2011
1	Evan	0.5536	0.0207	0.0370	72.3	31.3	1/21/2011

Raw Data, continued

Part	Operator	X-Bulge (in.)	Y-Bulge (in.)	Z-Bulge (in.)	Temp (°F)	RH (%)	Date
1	Evan	0.9862	0.5562	0.0160	72.4	31.4	1/21/2011
1	Evan	0.4770	0.1578	0.0236	72.6	31.3	1/21/2011
1	Evan	0.9988	0.3322	0.0246	72.6	31.2	1/21/2011
1	Evan	0.4946	0.2062	0.0436	72.7	31.0	1/21/2011
1	Evan	0.9020	0.0572	0.0064	72.9	31.0	1/21/2011
1	Evan	0.7016	0.1422	0.0228	73.0	30.8	1/21/2011
1	Evan	0.5228	0.1502	0.0660	73.0	30.6	1/21/2011
1	Evan	0.4928	0.1404	0.0764	73.1	30.5	1/21/2011
1	Evan	0.6246	0.1110	0.0250	73.1	30.5	1/21/2011
1	Evan	0.7488	0.1974	0.0030	73.1	30.4	1/21/2011
1	Evan	0.6262	0.2036	0.0574	73.2	30.3	1/21/2011
1	Evan	0.4570	0.1790	0.0356	73.3	30.2	1/21/2011
2	Anthony	0.6560	0.0094	0.0000	67.8	30.4	1/24/2011
2	Anthony	0.5464	0.0074	0.0002	68.0	30.8	1/24/2011
2	Anthony	0.5430	0.0112	0.0128	68.1	30.8	1/24/2011
2	Anthony	0.6044	0.0300	0.0002	68.3	30.9	1/24/2011
2	Anthony	0.5308	0.1794	0.0354	68.5	30.3	1/24/2011
2	Anthony	0.6534	0.0382	0.0016	68.7	30.4	1/24/2011
2	Anthony	0.6876	0.0144	0.0310	68.8	30.2	1/24/2011
2	Anthony	0.6232	0.1654	0.0054	68.8	30.2	1/24/2011
2	Anthony	0.5122	0.2646	0.0172	69.2	30.0	1/24/2011
2	Anthony	0.5834	0.0336	0.0068	69.2	29.8	1/24/2011
2	Anthony	0.0072	0.0004	0.0004	69.3	29.7	1/24/2011
2	Anthony	0.7074	0.0312	0.0040	69.4	30.1	1/24/2011
2	Anthony	0.7916	0.0070	0.0000	69.6	30.1	1/24/2011
2	Anthony	0.5866	0.0274	0.0000	69.8	29.8	1/24/2011
2	Anthony	0.0156	0.0216	0.0402	69.8	29.6	1/24/2011
2	Anthony	0.5324	0.0196	0.0026	69.9	29.6	1/24/2011
2	Anthony	0.5626	0.0188	0.0014	69.9	29.7	1/24/2011
2	Anthony	0.4914	0.0000	0.0476	70.0	29.4	1/24/2011
2	Anthony	0.5160	0.0080	0.0084	70.2	29.3	1/24/2011
2	Anthony	0.5738	0.0084	0.0006	70.1	29.4	1/24/2011
2	Anthony	0.5540	0.0306	0.0038	70.3	29.2	1/24/2011
2	Anthony	0.0002	0.0000	0.0034	70.3	29.4	1/24/2011
2	Anthony	0.5512	0.0192	0.0040	70.3	29.3	1/24/2011
2	Anthony	0.5688	0.0042	0.0000	70.3	29.4	1/24/2011
2	Anthony	0.5718	0.0046	0.0100	70.5	29.3	1/24/2011
2	Evan	0.5540	0.0138	0.0025	70.1	28.7	1/24/2011
2	Evan	0.5512	0.0014	0.0022	70.4	28.7	1/24/2011
2	Evan	0.6288	0.0028	0.0008	70.4	28.7	1/24/2011

Raw Data, continued

Part	Operator	X-Bulge (in.)	Y-Bulge (in.)	Z-Bulge (in.)	Temp (°F)	RH (%)	Date
2	Evan	0.5042	0.0110	0.0040	70.4	28.7	1/24/2011
2	Evan	0.4818	0.0004	0.0012	70.4	28.4	1/24/2011
2	Evan	0.5856	0.0010	0.0016	70.4	28.4	1/24/2011
2	Evan	0.6886	0.0302	0.0072	70.4	28.3	1/24/2011
2	Evan	0.4980	0.0015	0.0008	70.4	28.6	1/24/2011
2	Evan	0.4572	0.0021	0.0280	70.4	28.5	1/24/2011
2	Evan	0.5986	0.0040	0.0014	70.5	28.5	1/24/2011
2	Evan	0.5436	0.0078	0.0028	70.5	28.6	1/24/2011
2	Evan	0.5210	0.0030	0.0012	70.5	28.8	1/24/2011
2	Evan	0.5332	0.0068	0.0014	70.5	29.2	1/24/2011
2	Evan	0.5752	0.0078	0.0010	70.6	29.2	1/24/2011
2	Evan	0.6332	0.0120	0.0022	70.6	28.9	1/24/2011
2	Evan	0.5878	0.0372	0.0104	70.5	28.3	1/24/2011
2	Evan	0.5488	0.0082	0.0004	70.7	28.2	1/24/2011
2	Evan	0.6216	0.0008	0.0006	70.7	28.2	1/24/2011
2	Evan	0.7914	0.2650	0.0138	70.7	28.2	1/24/2011
2	Evan	0.6250	0.0018	0.0208	70.7	28.6	1/24/2011
2	Evan	0.5546	0.0088	0.0312	70.7	28.3	1/24/2011
2	Evan	0.6700	0.0012	0.0022	70.8	28.4	1/24/2011
2	Evan	0.6584	0.0004	0.0018	70.8	28.5	1/24/2011
2	Evan	0.5182	0.0013	0.0486	70.7	28.9	1/24/2011
2	Evan	0.5112	0.0068	0.0066	70.7	29.1	1/24/2011