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School-Books on Tape: The Tensile and Adhesive Strength of Duct Tape in a College Backpack

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School-Books on Tape:

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Honors Thesis

Robin Elizabeth Ker

Department: Mechanical Engineering

Advisor: Margaret Pinnell, Ph.D.

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Abstract

Two categories were used to assess the strength of duct tape constructions: adhesive strength and tensile strength. Previously made duct tape backpacks frequently suffered from adhesive failure around shoulder straps. When a backpack is lifted, it experiences a force which is greater than the resting weight. The hypothesis states that there is an area of application between two pieces of duct tape such that they will behave as a uniform piece and experience tensile failure, that two sufficiently overlapped pieces can hold within 5% of the load carried by a single piece, and that there is a relationship between the resting weight of a loaded backpack and the load applied to the straps when lifted. Five types of tape underwent tensile and lap shear testing in an Instron 4486 load frame. The tension test specimens were of uniform length, the lap-shear specimens had lengths which varied with the areas of overlap. There were two types of lap shear specimens: with adhesive layers in contact (LSA), and with the adhesive of one half adhered to the backing of the other (LSN). Maximum load and extension data was collected. Three backpacks were tested to determine the apparent load carried by the shoulder straps and handles when various static loads were applied. The backpacks were lifted with a Desik analog push-pull gauge which recorded maximum load.

Dedication and Acknowledgements

To Andrew Hofmann: Thank you for the many hours spent listening to me talk about duct tape. Thanks to Dr. Pinnell for her advice and assistance throughout the entire thesis process, and to Sidaard Gunasekaran for his assistance in the lab.



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Introduction

Duct tape is a widely-used material which is known for its high tensile strength and plethora of uses. It has been the topic of multiple episodes of the Discovery Channel series, *Mythbusters*, hailed as the equal and opposite force to WD-40 (“One only needs two tools in life: WD-40 to make things go, and duct tape to make them stop.”), and compared to the Force from the Star Wars franchise (“Duct tape is like the Force. It has a light side, a dark side, and it holds the universe together.”) [1, 2].

Through almost five years of experience working with duct tape to form various constructions ranging from small sculptures, to painting reproductions, to stop-motion videos, an awareness of the utility and limitations of duct tape was formed. The first and least prevalent type of failure was tensile failure where the polymer or fibers in the tape broke and the strands split apart. The success or failure of these various duct tape constructions was, in many cases, primarily dependent upon the ability of the adhesive to adhere to other strips of duct tape. When this was not sufficient, adhesive failures were observed in place of tensile failures. From this history of observed failures, the thesis writer decided to quantitatively determine the adhesive strength of several types of duct tape in order to inform the design of future duct tape constructions (such as backpacks).

In order to experimentally assess the adhesive strength of various types of duct tape, both tensile and adhesive tests were conducted to find adhesive overlap area threshold necessary for the adhesive strength to be as high as or higher than the tensile strength of the duct tape. This experimental data was used in order to design and construct two duct tape backpacks. The constructed backpacks were designed to hold a full load of college textbooks (25 lbs., with a safety factor of 2.0). Additional testing was done to determine the load which would be put on the shoulder straps when a fully loaded backpack is lifted to shoulder-height. A configuration of duct tape was chosen to enhance the integrity of the backpack, while minimizing the amount of material used (thereby reducing both cost and weight). The two types of tape which held the minimum required load before breaking were used for the backpacks: a heavier grade which held more than the required load (resulting in a heavier final backpack), and a lighter grade which had barely more than the minimum required loading capacity (resulting in a lighter final backpack).

Literature Review

When considering the strength of duct tape constructions, there are two basic categories: adhesive strength and tensile strength. Adhesive strength is the strength of the adhesive as it bonds the components of the duct tape to the surface to which the tape is applied. Tensile strength is the ability of the non-adhesive components of the tape to withstand forces applied in tension on a continuous piece of tape. Generally, when duct tape is in use, the adhesive side is affixed to one or more surfaces so that the tape can hold a load. As long as the area of application on a surface is large enough, adhesive strength is generally assumed to be the stronger of the two. This was the working assumption made by the Mythbusters in the episodes *Duct Tape Hour* and *Duct Tape Hour 2* [3, 4]. On these episodes, the Mythbusters conducted tensile testing of the duct tape; however they did not assess the adhesive strength [3, 4]. In the Mythbusters episode, *Duct Tape Hour*, the Mythbusters conducted tensile testing on duct tape by suspending a single strand over a horizontal distance about thirty feet and then pulling on the middle of it with a force gauge until the tape failed [3]. In the Mythbusters' test setup it appeared as though they had between six inches and one foot of tape which was secured to itself around a metal bar at each end. They reported that the tape held about 70 lbs. before it failed [3]. When the Mythbusters conducted a similar test in *Duct Tape Hour 2*, they reported that the tape failed at 67 lbs. [4]. In an interview, the Mythbusters said that they used Nashua duct tape in their construction of a duct tape bridge made only out of duct tape in *Duct Tape Hour 2* [5, 6]. Additional research determined that the particular tape was Nashua 357 [7, 8].

Based on previous experience with the construction of duct tape backpacks and taking into account the failure modes of traditional nylon backpacks in which no duct tape was used, a diagram of the failure modes of backpacks was created (see Figure 1). The failures which the thesis author has most often observed in standard backpacks are tearing and ripping around the top of the shoulder straps, as well as tearing where the handle is affixed to the top of the backpack. This is rational, as these areas are responsible for bearing the majority of the load while being the narrowest features in the backpack resulting in higher stress in these regions of the backpack. In prior duct tape backpacks constructed from a combination of various Duck Brand duct tape types, ripping near the

shoulder straps or handle was combatted by using additional layers of tape to reinforce the joints between the shoulder straps and the main bag, and refraining from extended use of the handle when the backpack was carrying a load. When these precautions were taken, the most common failure modes observed in duct tape backpacks was adhesive failure at the bottom (i.e. narrowest and potentially thinnest portion) of the shoulder strap, and general adhesive failure where small strips of tape were used. A small strip of tape is one which is approximately 3 in. or shorter in length, or has a width less than the full strip width of 1.88 in.

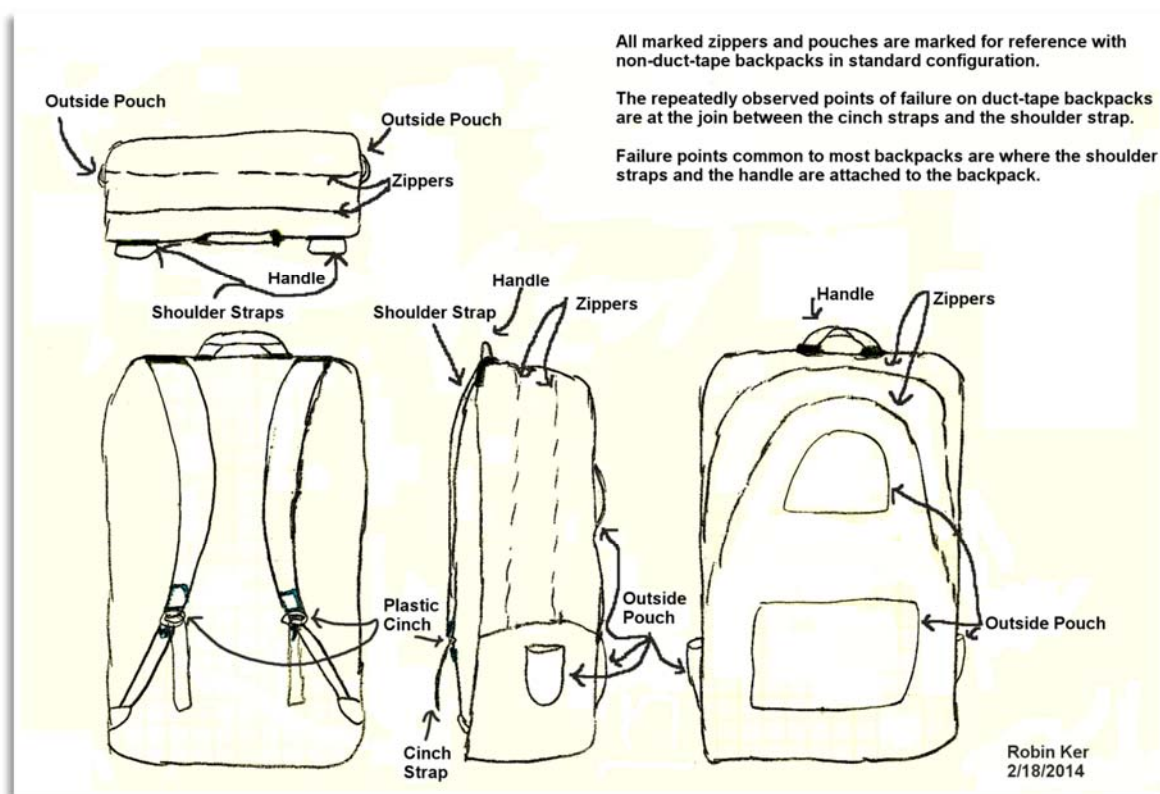


Figure 1. Backpack Failure Mode Schematic: *All marked zippers and pouches are marked for reference with non-duct-tape backpacks in standard configuration. The repeatedly observed points of failure on duct tape backpacks are at the join between the cinch straps and the shoulder strap. Failure points common to most backpacks are where the shoulder straps and the handle are attached to the backpack.*

Regardless of the brand or type, duct tape has two basic parts in its composition: a backing layer which is usually made up of some type of polymer (i.e. polyethylene) and

fibers (i.e. cotton mesh), and an adhesive layer (i.e. a rubber-based adhesive) [9]. The precise materials and construction of these layers is dependent upon the manufacturer [9]. When a single strip of duct tape is loaded in pure tension with both ends secured, it fails when the backing has reached its failure point and broken (tensile failure). An additional failure mode is observed at the points where duct tape is secured to another strip of tape or some other material via the adhesive. This failure is of the type where the adhesive slowly ceases to adhere to the area of application, but the backing is intact (adhesive failure). Tensile failure was observed in testing conducted by the Mythbusters, and adhesive failure was observed by the author of this thesis in previously constructed duct tape backpacks [3, 4]

The weight (lbs.) of a loaded backpack is a force, not a mass. Therefore, if the backpack is accelerated (i.e. lifted or lowered) then the apparent weight (i.e. the weight due to the acceleration of gravity plus the acceleration caused by being lifted) of the loaded backpack will not be the same as its static weight (i.e. the weight purely from acceleration due to gravity). This apparent weight caused by normal use is what the constructed duct tape backpack will need to be able to withstand.

A three-part hypothesis was formulated:

- 1) There is an area of application between two pieces of duct tape such that the two pieces will behave as a uniform piece with regard to the failure mode and will experience tensile failure.
- 2) When the joined strips have an area of overlap which meets or exceeds the critical adhesive overlap area, the maximum load will be within 5% of the maximum load in a tensile test on a continuous strip of tape.
- 3) There is a general relationship between the resting weight of a loaded backpack and its apparent weight when it is lifted.

Confirmation of the hypothesis will allow for overlapping pieces of tape to be used in order to create complicated geometries, while the maximum loads found in testing will be used in conjunction with the apparent weight under loading to determine which type of tape should be used in construction.

The research was of two types: experimental and theoretical. The experimental research involved tensile testing and adhesive testing of duct tape (Hypotheses 1 and 2),

as well as load testing on backpacks which were lifted in a manner comparable to normal modes of lifting and carrying backpacks (Hypothesis 3). The theoretical research focused on the design and construction of backpacks.

Two kinds of tests were conducted on duct tape: (1) tensile testing where the tape was subjected to unidirectional stress, and (2) unidirectional lap shear testing to test the adhesive strength of duct tape joints [10, 11]. The lap shear testing served as a practical measure of the strength of the adhesive, both when applied to the adhesive layer or the non-adhesive side of a separate piece of duct tape [10, 11]. The lap shear testing, when conducted on duct tape, has many of the same elements, except that the adhesive will be tested on its ability to grip onto another piece of tape. These results are important to the construction of a duct tape backpack because any duct tape construction is a series of lap joints. When these joints have sufficient areas of overlap such that the adhesive does not fail before the backing material, their load-bearing capability is determined by the tensile strength of the duct tape and not the adhesive strength. In smaller areas of overlap, the adhesive fails before the backing material. Part of what the testing was designed to indicate is the area threshold at which the strength of the adhesive is equal to or higher than the strength of the backing material, as indicated by maximum load carried before failure [12].

As was previously outlined, there has been some prior research by the Mythbusters into the strength of duct tape. In order to use the Mythbusters' results as a point of comparison, Nashua 357 was one of the tapes chosen for the tensile and lap shear testing [5, 6, 7, 8]. If the tensile testing on a single strand of Nashua 357 duct tape yielded a tensile strength which was close to the values reported by the Mythbusters (67-70 lbs.), then that would help to confirm that the results are in line with what has been previously established [3, 4].

At the conclusion of testing, two duct tape backpacks were constructed which were able to support a 25-lb load (with a safety factor of two) when the loaded backpacks were lifted from the ground into the air by the shoulder strap. The design for these backpacks combined the most-recommended features of good backpacks with the results and insights obtained from testing in order to produce backpacks which could hold the desired load. This included having a design which has as few complicated joints as

possible, while using areas of contact which meet the minimum area necessary for the adhesive strength to be stronger than the tensile strength of the backing. A “complicated joint” would be one which required the same piece of tape to adhere to three or more surfaces. One backpack was constructed out of the strongest material as determined through tensile testing, regardless of weight, and one was constructed out of the material which leads to a backpack with the highest specific strength while still meeting the minimum strength requirement.

A padded back was used in the construction of the duct tape backpacks in order to reduce stress on the body of the user. This is recommended as a component of good ergonomic backpacks, along with wide, padded shoulder straps, multiple compartments, a waist strap, and ensuring that the backpack is lightweight [13]. The padded portion of the back was constructed of rolled strips of tape to form two corrugated layers. This method was selected based on its prior success as a component of a backpack which was previously constructed by the thesis writer.

Methods/Procedure

In order to determine the tensile failure load for duct tape, lap shear and tensile testing was conducted on five kinds of tape. This was followed by testing to determine the relationship between resting load and apparent load for backpacks. The results of both types of test were used to determine the necessary loading capacity of the tape used in a duct tape backpack, which types of tape were suitable, and what area of overlap each type of tape required in order to achieve the required performance. The statistical significance of quantitative results for both experiments was analyzed using IBM SPSS Statistics 22 ($p < 0.05$) and included in Appendix I.

A. Maximum Load and Area of Overlap for Duct Tape

To determine the tensile failure load for duct tape, five kinds of duct tape were tested. The company and model number of the duct tape is displayed in Table 1 below, along with the letter designation (to be used hereafter), width and length. If available, the backing material, adhesive type, and nominal percent elongation are included in Table 1. The tensile “strength” as provided by the manufacturers is stated in terms of pounds per inch (length, assuming a full width) of tape in use.

Table 1. Specifications and Letter Designations for Five Types of Duct Tape

<i>Tape</i>	A	B	C	D	E
<i>Brand</i>	Duck®	Duck®	Roberts®	3M™	Nashua®
<i>Model</i>	1118393	DUC1265013RL	50-555	3900	357
<i>Width (in)</i>	1.88	1.88	1.875	1.88	1.88
<i>Length (ft)</i>	165	60	180	180	180
<i>Backing</i>			Vinyl	Polyethylene	PE-coated cloth
<i>Adhesive</i>	Natural Rubber			Synthetic Rubber	Natural Rubber
<i>Tensile Strength (lb/in)</i>	18			22	50
<i>Percent Elongation</i>				15	13
<i>Reference</i>	[14]	[15]	[16]	[17,18]	[19]

The following test method was created with reference to ASTM D3163–01 (Standard Test Method for Determining Strength of Adhesively Bonded Rigid Plastic Lap-Shear Joints in Shear by Tension Loading) and ASTM D3983–98 (Standard Test

Method for Measuring Strength and Shear Modulus of Nonrigid Adhesives by the Thick-Adherend Tensile-Lap Specimen) [11, 12]. Tapes A through E were tested in both tension tests and in lap-shear.

The tension test specimens were of uniform length, regardless of the type of tape. Each specimen was loaded longitudinally in an Instron 4486 load frame (67400 lb. capacity) with a 1000 lb. load cell in tensile test configuration using pneumatic grips (Instron Model 2172-003, 200 lb. capacity), with the ends of each specimen wrapped around an impact-resistant polycarbonate bar (1/16" x 1" x 2", McMaster Carr #1749K72) and protected with a grip interface material consisting of two pieces of wear-resistant nylon strip (.062" x 1" x 2" Wide, McMaster Carr #873K18), see Figure 2. Load and extension data were collected using Instron Blue Hill V-2.16 software. The Instron load frame stretched each specimen at a rate of 0.5 inches/minute, stopping when the specimen failed (indicated by a drop in load of at least 60%, or upon manual override based on visual examination of the specimen). Time, extension, and load data were recorded for the duration of the testing of each specimen. From this, the maximum load carried by each specimen, the extension at maximum load, and the mode of failure (adhesive or tensile) were recorded for each specimen. For images of the test setup, see Figures 3 and 4.

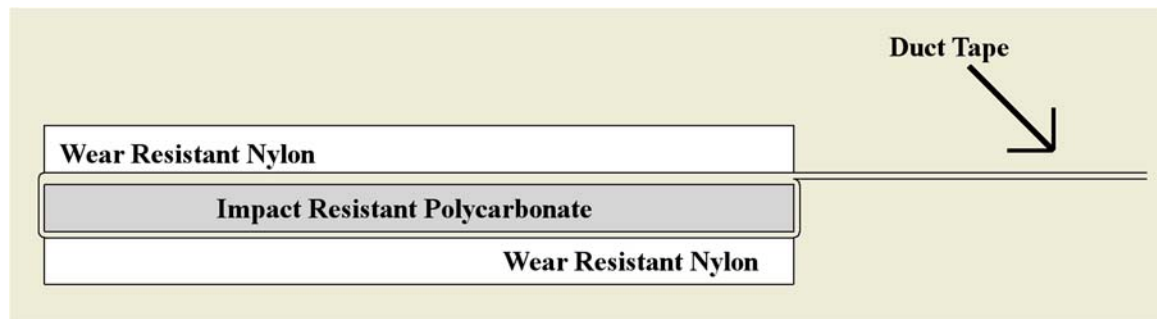


Figure 2. Diagram of End of Tape Specimen with Grip Interface

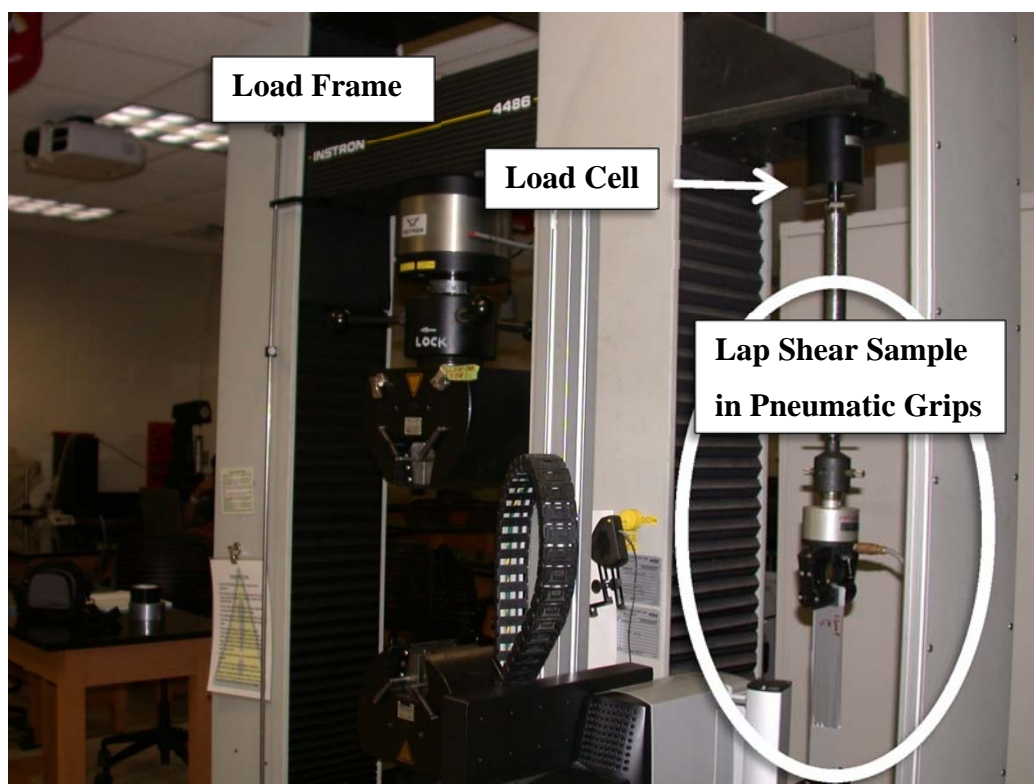


Figure 3. Test Setup with Lap Shear Sample at Right

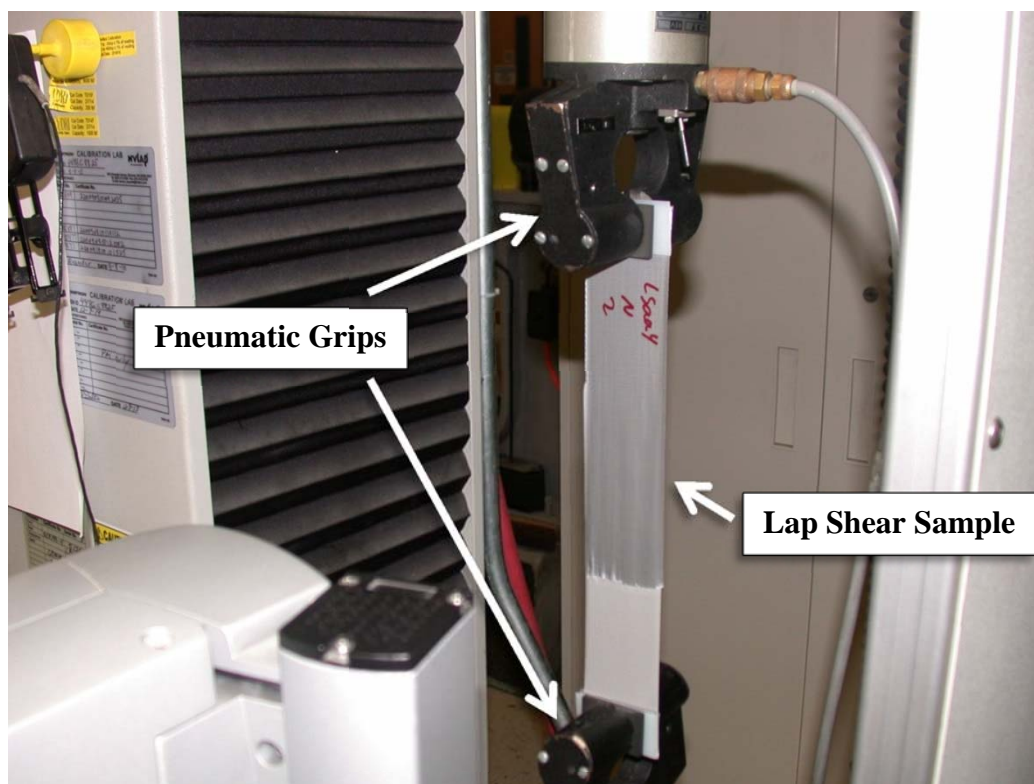


Figure 4. Close-Up of Test Setup with Lap Shear Sample in Pneumatic Grips

The lap-shear specimens had lengths of overlap from 1” to 5”, in increments of 1”. Because duct-tape is of nearly uniform width (all specimens were nominally 1.875 - 1.88 in.), areas of overlap can be compared using the length of the section where overlap occurs [14, 15, 16, 17, 18, 19]. Tests were conducted both with the adhesive sides of the strips of tape in contact (LSA), and with the adhesive of one piece in contact with the non-adhesive backing of the other piece (LSN), see Table 2 for the test matrix. The lap-shear specimens were subjected to the same testing protocol as the tension testing specimens (outlined above), with differences lying only in the design of the specimens themselves.

Table 2. Test Matrix with Number of Trials per Specimen Configuration and Type of Tape

<i>Configuration</i>	<i>Overlap (in)</i>	<i>Tape</i>				
		A	B	C	D	E
<i>Tensile</i>	0	6	6	6	6	6
<i>Lap Shear, A</i>	1	6	6	6	6	6
<i>Lap Shear, A</i>	2	6	6	6	6	6
<i>Lap Shear, A</i>	3	6	6	6	6	6
<i>Lap Shear, A</i>	4	6	6	6	6	6
<i>Lap Shear, A</i>	5	6	6	6	6	6
<i>Lap Shear, N</i>	1	6	6	6	6	6
<i>Lap Shear, N</i>	2	6	6	6	6	6
<i>Lap Shear, N</i>	3	6	6	6	6	6
<i>Lap Shear, N</i>	4	6	6	6	6	6
<i>Lap Shear, N</i>	5	6	6	6	6	6

All tensile test specimens were 14” long. All lap shear specimens were composited from two strips of tape, both with a length of 6” plus the length of overlap, resulting in a length per strip ranging from 7” to 11”, and a length per specimen ranging from 13” to 17”. See Table 3 for the resulting specimen lengths in each configuration. For the ends of each specimen (tensile and lap-shear), 3” of tape were wrapped around

the polycarbonate bar, and then the outside of the specimen was put between two wear-resistant nylon strips (see Figure 2, above) in order to protect the specimens from grip failure. For each type of tape, three thickness measurements were taken with Carrera Precision digital calipers, and then averaged to find the thickness of the specimens (See Table 4). Because the specimens did not have any measurable variation in individual thickness, the values reported in Table 4 can be taken as the thicknesses of each type of tape. See Figures 5, 6, and 7 for each specimen configuration (Tensile, LSA, LSN, using Tape C dimensions and lap-shear overlap of 1”).

Table 3. Length of Specimens

<i>Configuration</i>	<i>Overlap (in)</i>	<i>Length per Piece (in)</i>	<i>Length per Specimen (in)</i>
<i>Tensile</i>	0	14	14
<i>Lap Shear, A</i>	1	7	13
<i>Lap Shear, A</i>	2	8	14
<i>Lap Shear, A</i>	3	9	15
<i>Lap Shear, A</i>	4	10	16
<i>Lap Shear, A</i>	5	11	17
<i>Lap Shear, N</i>	1	7	13
<i>Lap Shear, N</i>	2	8	14
<i>Lap Shear, N</i>	3	9	15
<i>Lap Shear, N</i>	4	10	16
<i>Lap Shear, N</i>	5	11	17

Table 4. Tape and Average Thickness

<i>Tape</i>	<i>Thickness (in)</i>
A	0.005
B	0.008
C	0.006
D	0.008
E	0.013



Figure 5. Tensile Test Specimen Configuration



Figure 6. Lap Shear (LSA) Test Specimen Configuration (Shaded Area of Overlap)

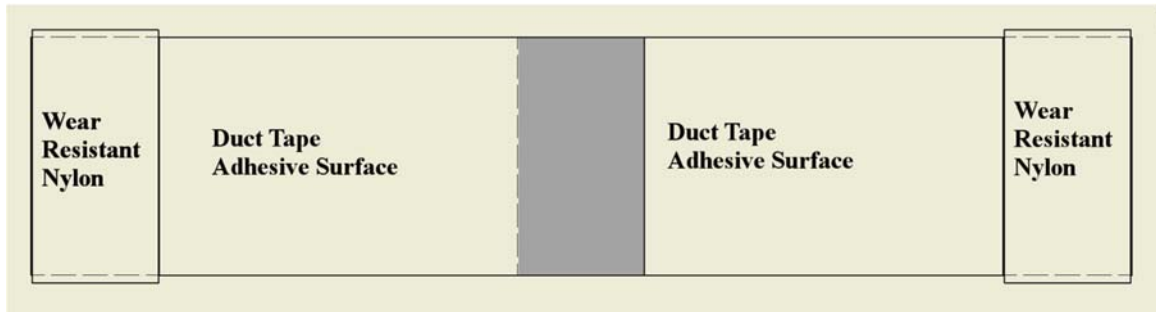


Figure 7. Lap Shear (LSN) Test Specimen Configuration (Shaded Area of Overlap)

After all tensile and lap shear tests were conducted, the average maximum load and standard deviations of maximum load were found for all testing configurations, types of tape, and lengths of overlap. The average maximum loads for each type of tape and length of overlap in LSA and LSN configurations were compared to the corresponding tensile test values for each type of tape. The percent differences were found according to the following formula:

$$\frac{(L_{LS}-L_T)}{L_T} \times 100\% = \%Difference \quad (1)$$

Where L_T is the average maximum load carried in tensile testing, and L_{LS} is the average maximum load carried in lap shear testing for the configuration (LSA or LSN) which is being examined.

Based on the thickness of each tape and the extension at maximum loading, the maximum stress and strain endured by each type of tape before failure was calculated according to the following two formulas:

$$\epsilon = \frac{x}{l} \quad (2)$$

$$\sigma = \frac{L}{wt} \quad (3)$$

Where x is the extension of the specimen at failure, l is the original length of the specimen, ϵ is strain, L is maximum load, w is the width of the specimen and t is the thickness of the specimen.

B. High-Load Locations in Backpacks

In order to determine the maximum load experienced by the shoulder straps and handle of a backpack, three cloth backpacks were tested. These two locations were chosen because they are regions of common failure, and because their function is to support the weight of the entire backpack and load, due to their role as straps. The specifications of each backpack are displayed below in Table 5. Two configurations were tested: the load supported by the center “handle” at the top of the backpack, and the load supported by one shoulder strap (See Figures 8 and 9). In order to ascertain whether the distribution of the load was affected by the load being carried, three backpacks were tested with various loads formed from up to four of a selection of five textbooks. Force measurements during testing were taken with a Desik analog Push-Pull Gauge (DL-100, resolution of 0.5 lbs.), set to display maximum load and fitted with the hook attachment. Before testing, baseline weights of the empty backpacks and each textbook were taken with the gauge set to display current load. The weights of each textbook are displayed in Table 6 and the test matrix is displayed in Table 7. Textbooks were used in order to represent realistic loading and weight distributions in the backpacks. See Figure 10 for the arrangement of the T-square which was used to measure height in the test setup. The design-stage uncertainty due to the Desik gauge is ± 0.56 lbs.

Table 5. Backpack Specifications

<i>Backpack</i>	<i>Brand/Model</i>	<i>Weight (lbs)</i>
<i>X</i>	NWT Sport	1.5
<i>Y</i>	Jansport	1.0
<i>Z</i>	L. L. Bean	1.5



Figure 8. Desik Gauge Attached to Center Handle of Backpack



Figure 9. Desik Gauge Attached to Shoulder Strap of Backpack

Table 6. Weight of Textbooks

<i>Textbook</i>	<i>Weight (lbs)</i>
1	3.0
2	5.0
3	6.0
4	5.0
5	8.5

Table 7. Test Matrix for High-Load Locations in Backpacks, with Number of Trials per Test Configuration

<i>Backpack</i>	<i>Lift Location</i>	<i>One Book</i>	<i>Two Books</i>	<i>Three Books</i>	<i>Four Books</i>
<i>X</i>	<i>Handle</i>	5	10	9	5
	<i>Shoulder Strap</i>	5	10	9	5
<i>Y</i>	<i>Handle</i>	5	10	9	5
	<i>Shoulder Strap</i>	5	10	9	5
<i>Z</i>	<i>Handle</i>	5	10	9	5
	<i>Shoulder Strap</i>	5	10	9	5

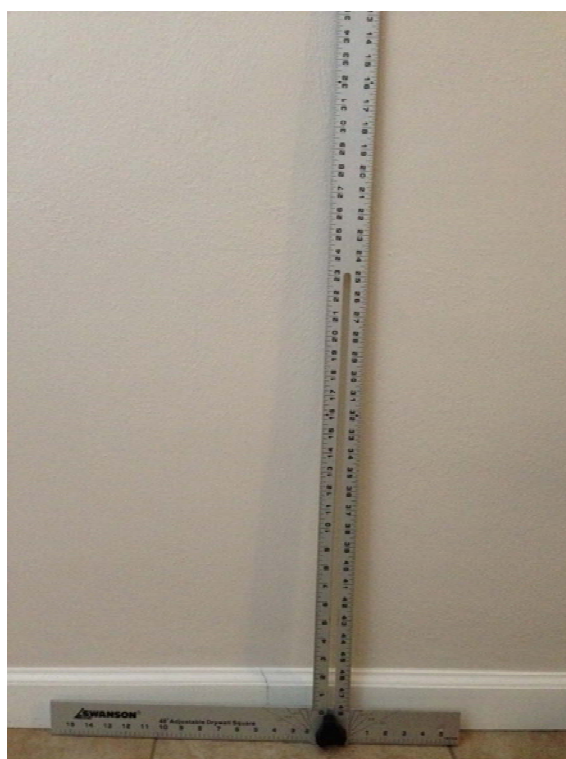


Figure 10. Test Setup with Adjustable T-Square to Measure Height of Lifted Backpack

For the first test configuration, the top handle of the backpack was used to lift the entire load. In each trial, the backpack was lifted, by means of the hook lifting the handle, from the ground to a height of three feet, and then returned to the ground. The maximum load was recorded for each trial.

For the second test configuration, one shoulder of the backpack lifted the entire load. The bottom of the shoulder strap was detached from the cinch-strap, and the force gauge was used to lift the backpack by the plastic cinch to a height of three feet before returning the backpack to the ground. The maximum apparent load was recorded for each trial. This test setup was designed to most realistically ascertain the maximum load carried by the straps while minimizing the augmentation which would need to be made to the backpack in testing conditions.

Results and Analysis

A. Maximum Load and Area of Overlap for Duct Tape

Figure 11 contains the average maximum loads for LSA testing, compared with data obtained from tensile testing of a single layer of duct tape. Only one kind of tape (Tape A) did not achieve an average maximum load for LSA which is close to what was achieved in tensile testing.

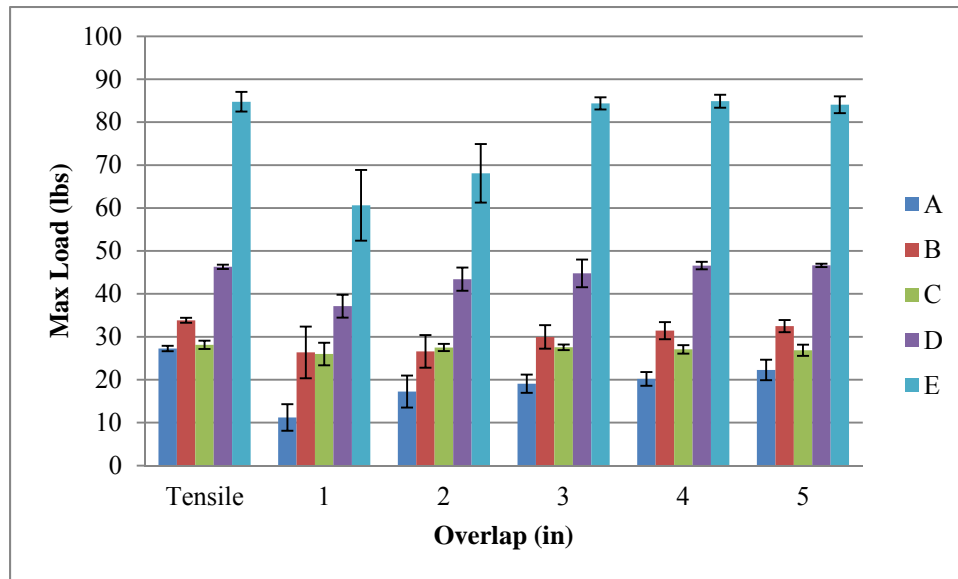


Figure 11. Maximum Load: Tensile Test vs LSA (St. Dev. Error Bars)

This is quantitatively confirmed by Table 8, which contains the percent difference between the average values of maximum load for tensile testing and LSA testing. The percent differences in Table 8 were calculated using Formula 1. Negative values mean that the average maximum load in lap shear was lower than the average maximum value in tensile testing. Values representing less than a 5% difference between tensile and lap shear maximum loads are in bold. Values representing a percent difference between 5% and 10% are underlined. Tape B achieved a difference of less than 5% at five inches of overlap, Tape C achieved this at 2" of overlap, and Tapes D and E achieved this at 3" of overlap.

Table 8. Maximum Load: Tensile Test vs LSA, Percent Difference

Overlap	A	B	C	D	E
1	-58.9%	-22.1%	<u>-7.6%</u>	-19.8%	-28.5%
2	-36.8%	-21.4%	-2.2%	<u>-6.2%</u>	-19.7%
3	-30.0%	-11.4%	-2.0%	-3.3%	-0.5%
4	-26.0%	<u>-7.1%</u>	-3.8%	0.6%	0.1%
5	-18.3%	-4.0%	-4.5%	0.7%	-0.8%

Figure 12 and Table 9 show the same comparisons as Figure 11 and Table 8, except they are conducted between tensile testing and LSN instead of LSA. Qualitatively, Tape B, Tape C, and Tape D appear to approach maximum loads comparable to those which were carried in tensile testing. The standard deviation for Tape E includes an upper range which captures the corresponding tensile test value, but the average values are not close. Quantitatively (using percent difference values as calculated from Formula 1), only Tapes B, C, and D had percent differences which were within 5%. Tape B achieved this at two inches of overlap; Tape C did as well, but did not consistently maintain it until four inches of overlap. Tape D achieved this at three inches.

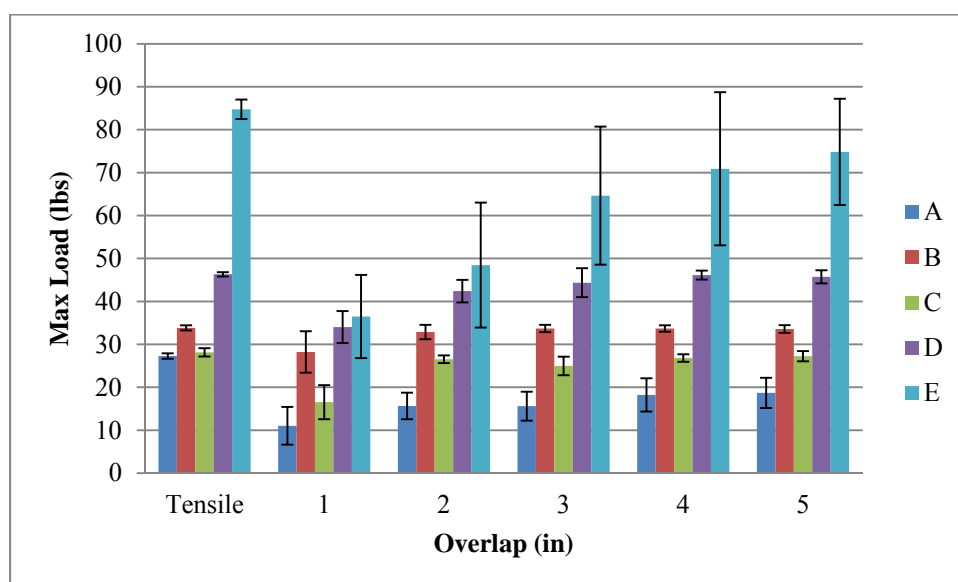
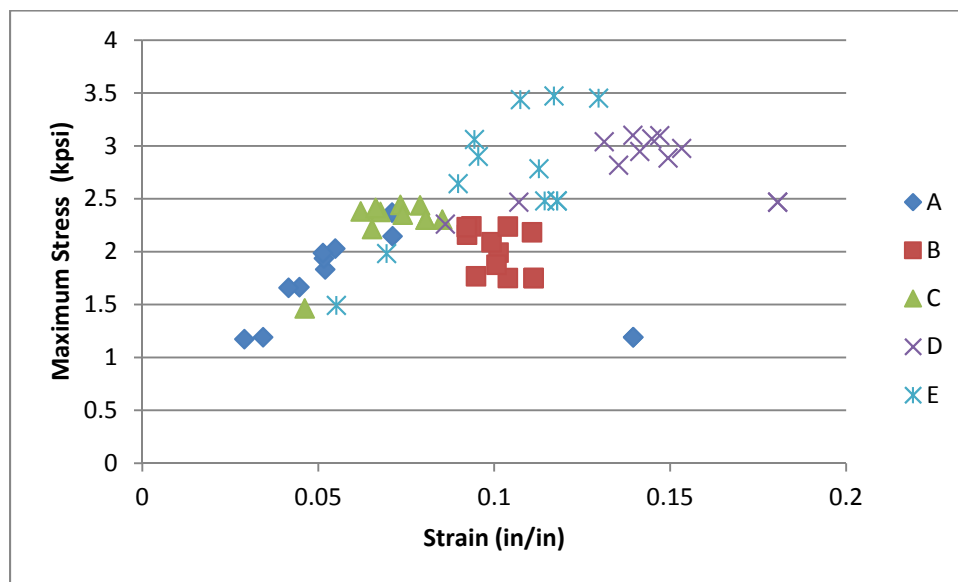
**Figure 12. Maximum Load: Tensile Test vs LSN (St. Dev. Error Bars)**

Table 9. Maximum Load: Tensile Test vs LSN, Percent Difference

Overlap	A	B	C	D	E
1	-59.6%	-16.6%	-41.3%	-26.5%	-56.9%
2	-42.6%	-2.9%	-5.7%	-8.4%	-42.8%
3	-42.8%	-0.5%	-11.2%	-4.2%	-23.7%
4	-33.2%	-0.4%	-4.7%	-0.4%	-16.3%
5	-31.5%	-0.8%	-3.2%	-1.3%	-11.7%

Figure 13 plots the average maximum stress vs strain of each type of tape for all testing configurations, to determine whether accounting for the thickness of each type of tape (via stress) normalizes the results such all of the types of tape have similar maximum stress-strain profiles. Tapes B, C, and D had very clustered results around 2000 psi at 0.1 in/in, 2400 psi at 0.07 in/in, and 3000 psi at 0.14 in/in, respectively. The other types of tape had more scattered results, but assessing maximum stress instead of maximum load did not remove distinctions between the types of tape. Tape D had the highest strain values, on average.

**Figure 13. Maximum Stress vs Strain for all Five Types of Tape**

B. High-Load Locations in Backpacks

The method of lifting the backpacks (handle vs shoulder strap) was statistically significant ($p < 0.05$) with regard to the apparent load ($p = 0.034$). Because of this, the apparent loads were evaluated with regard to loading method (See Table 11, Appendix A). Additionally, the backpack used in each test was not significantly significant with ($p = 0.964$). This allowed for analysis without consideration of the precise backpack which was used (See Table 11, Appendix A). As seen in Figures 14 and 15, the apparent load increased as the static load increased. The linear best-fit curve and equation based on the average values is included for Figures 14 and 15, and can be used to estimate the apparent load when given any static load.

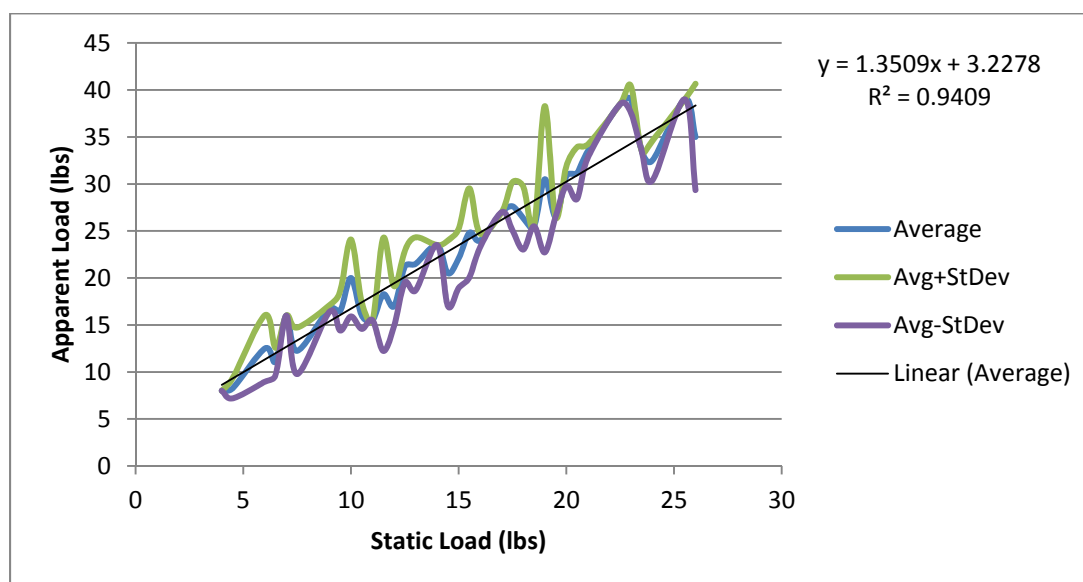


Figure 14. Apparent Load vs Static Load for Lifting by Shoulder Strap

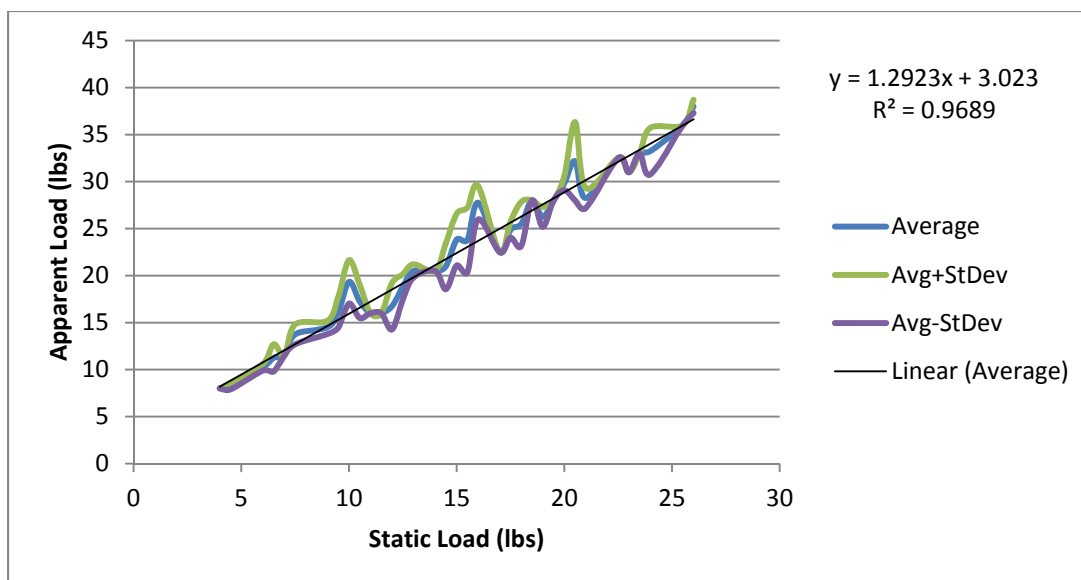


Figure 15. Apparent Load vs Static Load for Lifting by Handle

Discussion

Based on the testing results, a backpack which weighs 25 lbs. at rest needs to be made from material which is able to withstand 40 lbs. of force when the backpack is lifted. After a safety factor of 2.0 is applied, the backpack needs to withstand 80 lbs. of force. Because the minimum number of layers at any point in the backpack is two (so that no adhesive is exposed), each unbroken strand of tape needs to be able to withstand 40 lbs. of force before breaking. The two types of tape which allow for this are types D and E. Type D requires three inches of overlap between strips, whether it is applied to the adhesive or non-adhesive side of another strip of tape. Type E requires three inches of overlap when applied to the adhesive side of another piece of tape, and five inches when applied to the non-adhesive side. Type E was used for one backpack because, even though it did not have an average maximum load in the LSN configuration which was within the 5% margin of its tensile testing results, it did reach the minimum required capacity of 40 lbs. Based on these guidelines, two backpacks were constructed: One made completely out of type D tape and one completely out of type E tape. The backpacks are of identical basic dimensions, according to the schematic in Figure 16, with a final 3D configuration according to Figure 17. Paper templates were used in order to ensure consistent dimensions. Straps were omitted from both models, but were created using identical outlines for the straps of each backpack. Backpacks were constructed out of both kinds of tape in order to ascertain which type had lower overall weight in an application which requires at least two layers of tape (i.e. backpacks).

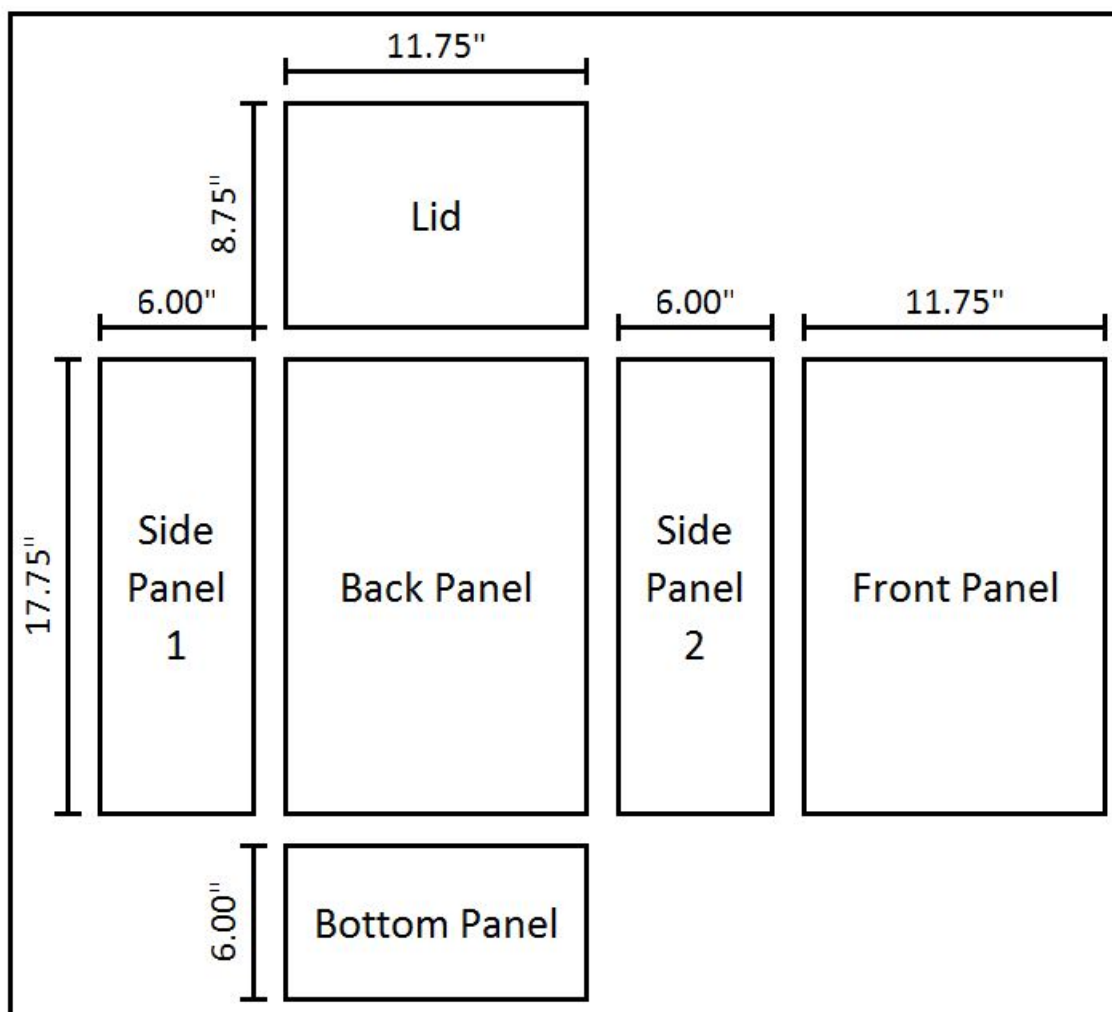


Figure 16. Schematic for Duct Tape Backpack Construction

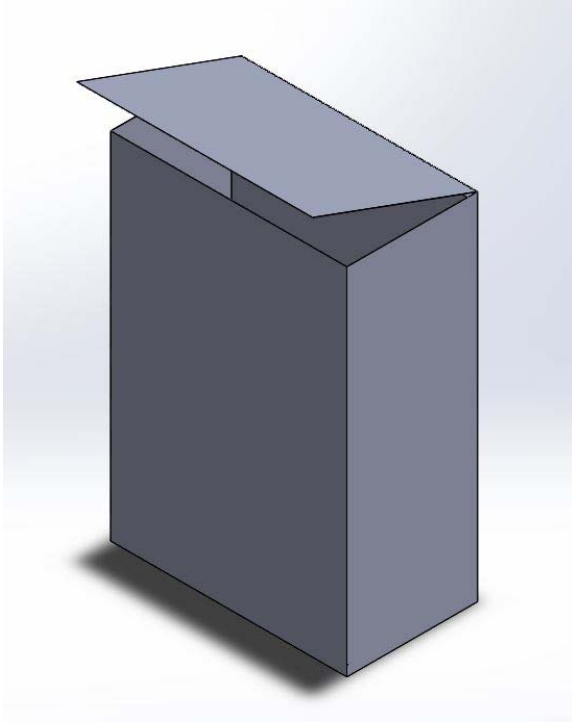


Figure 17. 3D Model of Completed Backpack (without straps)

The back and bottom panels of each backpack were constructed with two layers of cylinders of duct tape (constructed by rolling strips of tape with the adhesive side facing outward), arranged perpendicularly and placed between two flat layers of tape. The directionality of each successive layer is perpendicular to the layers on either side of it; see Figure 18 for a model of the panel layering and orientation. The in-progress back panel for the type D backpack is shown in Figure 19. The straps were constructed using a single layer of rolled duct tape cylinders, arranged to fit the desired profile, then wrapped with single layers of duct tape. As necessary, all joints and patches (to cover any exposed areas of adhesive) were made using the minimum area of overlap which was required for each type of tape.

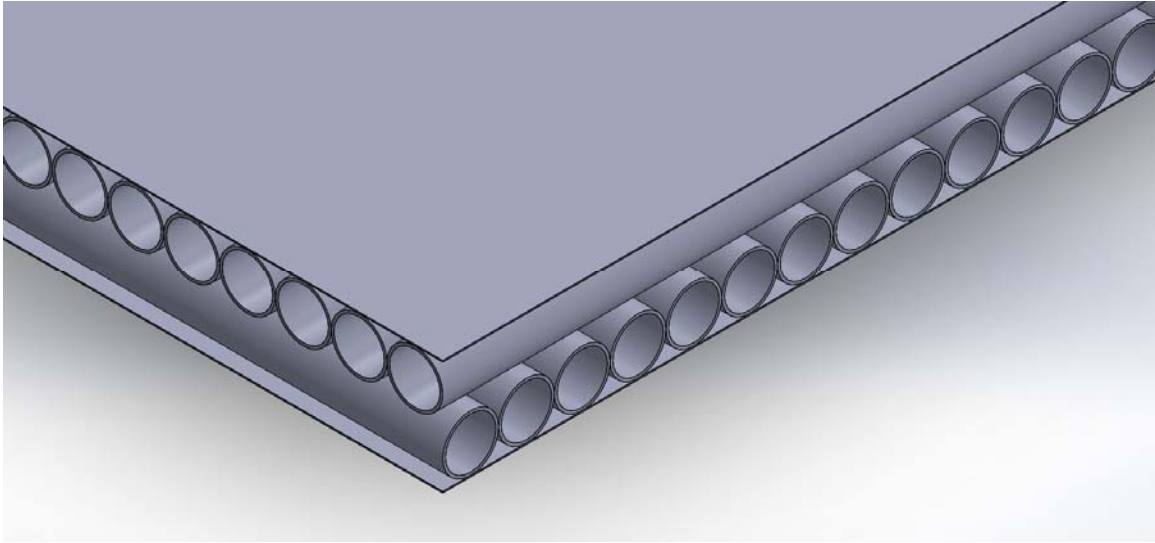


Figure 18. Model of Layering for Back and Bottom Panels



Figure 19. In-Progress Back Panel from Type D Backpack

The Type D backpack (Figure 20) had a final weight of 3 lbs. (made using 2.5 rolls of tape); while the Type E backpack (Figure 21) weighed 5.5 lbs. (also using 2.5 rolls of tape). Type D tape is generally less expensive than type E tape (\$14.03 and \$18.87 per roll, respectively, as of April 2015) [20, 21]. Qualitatively, when the two backpacks are compared by the thesis writer to assess comfort, the type D backpack is supportive without being too heavy. The type E backpack feels slightly more supportive, but it is also very stiff, which reduces overall comfort. This is quantitatively supported by the stress-strain relationships shown previously in Figure 13, where tape D carried a higher strain than tape E for the same amount of applied stress. This indicates that tape D

will stretch more before breaking. This flexibility is what makes tape D form a less-stiff construction when made into a backpack.



Figure 20. Type D Backpack



Figure 21. Type E Backpack

Due to the lower weight of the completed type D backpack, 3M 3900 tape with three inches of overlap is recommended (out of the five tested types) for the construction of any future duct tape backpacks. When compared to a backpack of the same design which was made using a heavier grade of tape, the 3M backpack wins in terms of weight, cost, and a qualitative assessment of comfort.

Conclusion

To account for the additional load exerted on a backpack when it is lifted from the ground to the shoulder, a backpack which has a static weight of 25 lbs. must be constructed from duct tape which can hold up to 40 lbs. per strand of tape. This accounts for a minimum of two layers of tape in all areas of the backpack in order to eliminate areas of exposed adhesive, and uses a safety factor of 2.0. Accordingly, the final backpacks were made from 3M 3900 tape and Nashua 357 tape, and weighed 3.0 and 5.5 lbs., respectively. 3M 3900 tape held approximately 45 lbs. per strand and required three inches of overlap, while Nashua 357 tape held approximately 80 lbs. per strand and required five inches of overlap. Based on qualitative and quantitative assessment of the completed backpacks with respect to comfort, weight, and final cost, the type of duct tape which is recommended for future backpack construction is 3M 3900 (type D).

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Appendix I

Table 10. Tests of Between-Subjects Effects for Test Method A (p<0.05)

Source		Sig.	Observed Power ^d
Corrected Model	MaxLoad	.000	1.000
	Extension	.000	1.000
	FailureMode	.000	1.000
Intercept	MaxLoad	.000	1.000
	Extension	.000	1.000
	FailureMode	.000	1.000
Configuration	MaxLoad	.000	1.000
	Extension	.000	1.000
	FailureMode	.007	.767
Overlap	MaxLoad	.000	1.000
	Extension	.000	1.000
	FailureMode	.000	1.000
Tape	MaxLoad	.000	1.000
	Extension	.000	1.000
	FailureMode	.112	.355
Trial	MaxLoad	.068	.687
	Extension	.582	.271
	FailureMode	.123	.600
Configuration * Overlap	MaxLoad	.070	.643
	Extension	.250	.420
	FailureMode	.026	.766
Configuration * Tape	MaxLoad	.024	.618
	Extension	.033	.571
	FailureMode	.007	.778
Configuration * Overlap * Tape	MaxLoad	.910	.104
	Extension	.562	.239
	FailureMode	.016	.808

a. R Squared = .947 (Adjusted R Squared = .935)

b. R Squared = .872 (Adjusted R Squared = .844)

c. R Squared = .620 (Adjusted R Squared = .536)

d. Computed using alpha = .05

Table 11. Tests of Between-Subjects Effects for Test Method B (p<0.05)

Source	Dependent Variable	Sig.	Observed Power
Corrected Model	ApparentLoad	.000	1.000
	PercentIncrease	.184	.933
Intercept	ApparentLoad	.000	1.000
	PercentIncrease	.000	1.000
Backpack	ApparentLoad	.964	.050
	PercentIncrease	.757	.061
LiftRegion	ApparentLoad	.034	.571
	PercentIncrease	.085	.406
TotalWeight	ApparentLoad	.413	.704
	PercentIncrease	.295	.767
BookWeight	ApparentLoad	.	.
	PercentIncrease	.	.
Backpack * LiftRegion	ApparentLoad	.758	.091
	PercentIncrease	.933	.060
Backpack * TotalWeight	ApparentLoad	.476	.648
	PercentIncrease	.885	.407
LiftRegion * TotalWeight	ApparentLoad	.459	.686
	PercentIncrease	.889	.435
Backpack * LiftRegion * TotalWeight	ApparentLoad	.150	.839
	PercentIncrease	.305	.741
Error	ApparentLoad		
	PercentIncrease		
Total	ApparentLoad		
	PercentIncrease		
Corrected Total	ApparentLoad		
	PercentIncrease		