6-2015

The Development of a Composite Additive to Increase Safety and Performance of Wooden Baseball Bats

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MER 498 Final Report
3/16/2014
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Abstract

Many youth baseball leagues are in the process of doing away with metal bats and using solely wood bats. They claim the game will be safer since ball exit velocities off of wood bats are lower than that of their metal counterparts; however, they are overlooking the fact that wood bats shatter causing new safety concerns that are not experienced with metal.

It was the goal of this project to develop and test new additive materials to coat wood baseball bats in order to improve strength without decreasing performance. Polyurethane sealant, carbon fiber fabric, and duct tape were chosen to be tested because they offer an array of strength and hardness differences. In order to test the strength of each material-bat combination, a three point bending test was conducted. Since it is also unknown whether a hard or soft bat is more ideal for performance, a hardness test was conducted in order to classify each material. These results where then compared to a performance (swing) test meant to analyze how each added material affected the ball exit velocity off of the bat. The comparison of the performance test and the hardness test helped give insight as to what type of bat is desirable.

After testing, it was found that Carbon fiber and polyurethane sealant increased the strength of the specimens, satisfying the first goal of the project. Duct tape actually decreased the strength, which allowed for its removal from consideration. Following the performance test, it was concluded that none of the materials are viable for actual implementation because they severely decreased ball exit speed. Duct tape produced a result closest to that of plain wood, suggesting that a softer material might be more desirable for performance since carbon fiber

and polyurethane were found to be harder; however, there were concerns with the application process which may have affected the performance results.

Motivation

Over the past few years, there have been several serious head injuries in baseball which sparked great debate on how to make the game safer. Steps have already been made, seen in the new metal bat standards which banned nearly 70% of metal bats on the market [1]. After analyzing the statistics gathered over the past 50 years, player performance is well below that of even the wood bat days of the early 1970s: specifically when it comes to batting average and runs scored [2]. Therefore, it seems inevitable that a complete switch to wood bats is in the near future; however, wood bats bring their own dangers that do not exist with metal bats. For instance, wooden bats tend to shatter, sending debris out onto the playing surface. These situations are highly dangerous, especially if the ball is still sent into play when the bat breaks, resulting in two projectiles at the same time. Although bats can be easily made safer by adding thickness, such a solution is not viable because it decreases performance.

Objective

For the reason described above, it was suggested that a new material be developed and analyzed to ensure proper bat safety with minimal reductions to performance. Since the rules would still require the bat to be wood, only a surface coating or liquid infusion was permitted (composite wood bats are permitted). Some possible solution materials included high strength elastic materials, meshes of substances such as plastics or fabrics, or even form hardening substances to “encapsulate” the bat. All of the above materials are used in what are called

"composite metal bats," which is ironic because very little of the bat is actually metal. In some cases, carbon nanotubes are even incorporated into designs; however, this is too expensive for a project like this.

While increasing bat strength was a fairly easy objective, accomplished by simply adding stronger materials to its surface, increasing performance was a much more unclear task. For the purpose of this project, higher performance is directly related to a higher ball exit speed velocity. However, a simple solution does not exist when it comes to improving performance. There are actually two main conflicting theories behind what qualities a bat should have. The more common belief is that hard woods such as maple should be used. The supporting concept behind this belief is that when making contact with the ball, a harder bat will be more resistive to permanent dents [3]. Since dents require energy to create, it is theorized that as the level of denting decreases, more energy will be returned to the ball after the collision. The alternative theory is that although a soft bat may dent more easily, it will also decrease the amount of deformation the ball experiences during collision. In some cases, baseballs are compressed up to 60% of their original volume, providing evidence that an energy loss occurs (mainly to heat) [4].

In summation, the main question asked was what really makes a wood bat perform better: being either hard or soft? In order to answer this question, a hardness test and a swing test was performed. In order to address the strength of the bat, a bending test was also performed. The specifics of these tests are further defined below.

Causes of Bat Failure

Fractures in wood bats most commonly occur at the handle of the bat, except when a ball strikes the cupped end resulting in a small sliver of wood being dislodged. The standard belief amongst players is that the handle is most prone to fracture because it is where the smallest diameter exists, which translates to an increase in stress. This assumption is only partially true. While the highest stress during a bat-ball collision does occur at the handle region of a baseball bat (roughly 10.1 inches above the handle knob), it is not primarily due to its small diameter [5]. Instead, the stress is highest due to the behavior of wood grains, as well as the amplification of stress due to a bat bending frequency [3,5].

The grains within wood are often times the first thing analyzed when failure occurs in wood structures. This is not only because it is easy to identify when fractures occur at the grains, but also due to the smaller bond forces at such locations [5]. These weaker bonds are even more important for baseball bats because the impact stresses are not only high in magnitude, but the impact occurs over and over throughout the bat's lifetime. This repetition causes more and more small fractures to occur within the grains. Eventually, these small fractures add up and decrease the bat's ability to handle stress, resulting in failure [5]. The most common instance where such effects can be seen is when a ball strikes a bat at a fairly ideal contact spot, but still causes the bat to fracture.

An ideal contact spot can best be explained by discussing the major reason as to how and why wood bats break. With that being said, the grains are a cause of failure, but only play a minor role since it is more related to fatigue over time. When a ball contacts a bat, the collision forces the bat to behave like a wave in regards to the way it bends. Refer to figure 1 in order to

better understand this bending. Notice that the highest amplitude occurs at the handle, regardless of where the ball strikes the bat as seen in the general case image on the right. This shows that the stress is amplified greatly by the wave-like frequency response; the only other factor to consider is by how much the stress is amplified. That is when the contact point of the ball must be considered. Referring to figure 1 once again, notice that the left image has node and antinode location labeled on it. The reason behind this is that if a ball were to strike an antinode, it would cause the bat to experience maximum wave amplitude during the collision [3]. Depending on the velocity of the incoming ball, the bat may fracture. In the best case scenario, it will remain rigid but send a shooting pain to the player's hands, otherwise known as a "sting."

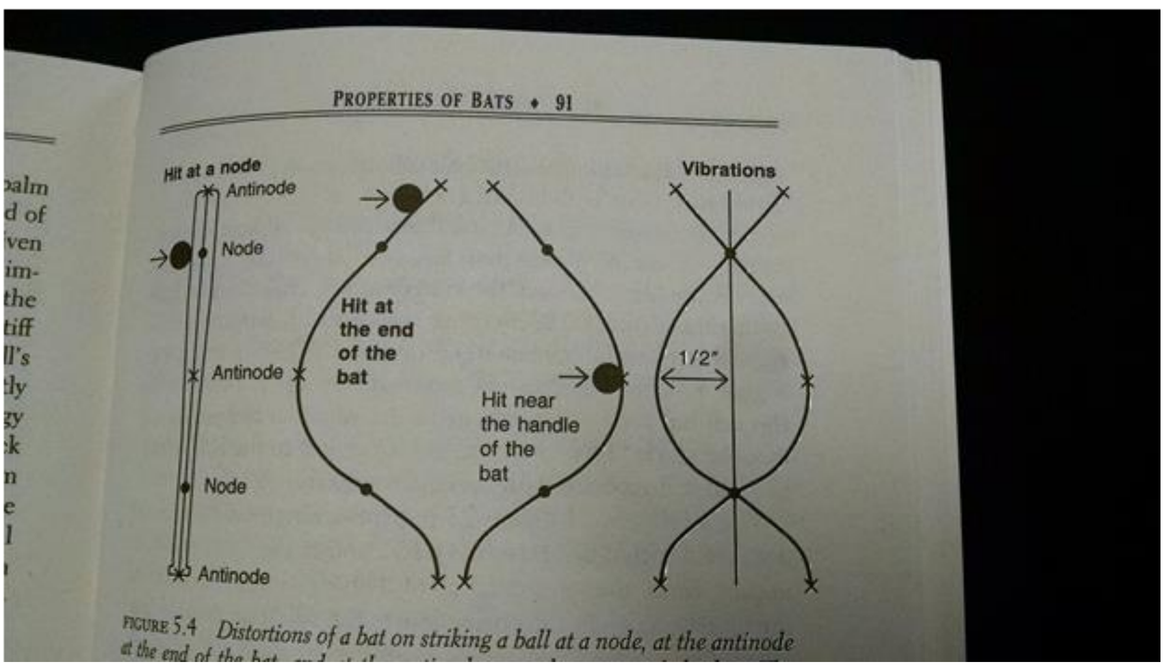

Figure 1 – Wave-like behavior during bat-ball collision [3]

The "sting" a player feels when making contact with a ball is a non-performance based reason why baseball players prefer to use metal bats over wood bats: especially in cold weather. Since there is a secondary amplitude location roughly where a player would hold the bat, their hands feel an increased vibration as the wave amplitude increases. Going back to the concept of frequency response, metal bats are better designed to minimize such reactions. Due to their higher elastic modulus, metal bats actually vibrate at a higher frequency than wood bats do [4]. The resulting behavior shows that the wave amplitude is decreased in metal bats since it wants to bend in the opposite direction to its motion before it reaches the expected amplitude.

Material Selection

After identifying the two types of failure modes described above, material selections were made to address at least one type, if not both. The first material chosen was the nylon mesh, which was to be wrapped tightly around the bat. The mesh material was chosen because not only it added more resistive forces to bending, but it also provided a failsafe if the bat were to break. For instance, if the bat were to fracture, the mesh material most likely would stretch without rupturing. Since the mesh would still maintain its structure, it would keep the bat from shattering into multiple pieces and sending debris flying out into the playing field.

For a similar reason, carbon fiber fabric was the next material chosen. However, while it provided a failsafe like the nylon mesh, it also provided other perks such as being lighter, as well as more rigid. Even though bat weight is not being considered in this project since a level swing can be guaranteed during testing, it still may help prove to be an important asset if the material were to be implemented into an actual swing. The other improvement that carbon

fiber offers is that if hardened, it has a higher elastic modulus than wood (typically 20 Msi [6], 1.74 Msi for ash wood [7]). This could mean two things, both of which help move toward the goal of this project. First, it may cause the wood bat to act more like a metal bat, increasing the frequency of its wave-like reaction. This would result in the bat being less likely to break. The other improvement may be seen in the "hardness" of the bat. This is considered an improvement based on the theory that harder bats are more desirable for better performance. While this theory may not be true, which would result in a decrease of performance, the material selection is still useful because it gives further insight into what characteristics are desired in wood bats.

The next two materials, the polyurethane wood sealant and SBR rubber, focus on a different method to increase the safety of wood bats. Unlike the previous two choices, the main goal is to reduce the probability of a fracture occurring instead of protecting against when one does exist. In other words, the new additive materials would decrease the overall force of impact during the bat ball collision.

Since rubber is a softer, more elastic material (Young's Modulus of 1 Msi [8]), it deforms well and almost completely returns to its original shape. This deformation takes away some of the energy from collision, which should decrease performance, but also decreases the stress felt in the bat. For this reason, the rubber would most likely be added to the regions that cause the frequency response to be of the highest magnitude; i.e. the handle and the end of the bat. The reason behind this thinking was that if contact were to occur at these positions, the ball would not travel very far even if fracture did not occur; therefore, absorbing collision energy into the rubber in order to prevent fracture is well worth the tradeoff of sacrificing some

performance. Note that the ideal contact area (the barrel) would remain free of the rubber since it is highly unlikely that a fracture would occur when the ball strikes this region.

The polyurethane wood sealant was chosen for the same reason that rubber was. However, this material is stiffer and therefore may not absorb as much energy. This change goes back to the idea of increasing performance, or at least not decreasing it too much. If the polyurethane were to accomplish the same goal as the rubber while maintaining a better performance, it would clearly be more ideal to use. Another advantage to using a stiffer substance is the possibility of coating the entire bat and not just the areas of contact that cause fracture. This may prove beneficial because with rubber, stress may be amplified at uncoated regions and increase the likelihood of fracture. Polyurethane also has other non-stress related advantages. It is more durable, which means that deterioration with time was less likely to occur than with rubber, increasing the lifetime of the bat. It also provides a very strong barrier to the outside environment. This barrier provides protection from elements such as dirt and water, both of which weaken the bat if they are able to penetrate its surface.

Tests and Procedures

The first test involved applying bending stresses to a dowel rod coated with the new additive and measuring the permanent deformations, as well as the load required for fracture. This test was most directly related to the strength aspect of the bat/material combination. The initial experimental procedure was developed using only simple methods learned in strength of materials. The dowel rod was to be laid horizontally across a gap, and clamped at both ends. At the center point, a suspended load was to be applied at an increasing interval while using a measurement tool to determine deflections at each load. Eventually, the dowel rod would fail

and the test would be complete. This experiment was then planned to be conducted using a more accurate machine in Professor Bucinell's lab (1st floor Butterfield Hall, Room 101) that involved three point bending. A dowel rod was placed between and suspended by 3 pins: two on the ends spanning a gap of 24 inches, and one at the center. The crosshead was moved in the downward direction over time, causing a load to be felt on the middle pin. The machine was capable of applying 24,000 pounds, which was much more than necessary to break the dowel rod. These results are far more accurate than the simple test that was originally developed. This machine also saved time during testing as well. Ideally, the results would have shown that the new materials increased the wood's resistance to deflections, as well as the ultimate breakage strength. A schematic of the test set-up can be seen below. Note that the image is not exactly what the actual test machine looked like, but it does provide a good understanding of what is occurring.

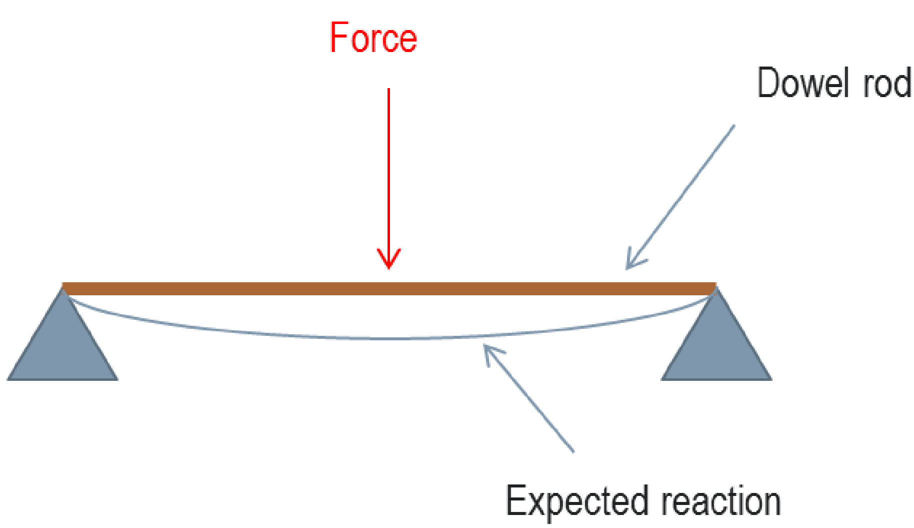

Figure 2 – Experimental Set-up for the bending test

The second test involved applying a compressive load to the barrel of the bat/material combination in order to see the permanent deformations and its ability to return to shape. This most directly relates to the hardness of the bat, or its ability to resist denting. In other words, if the bat were to permanently deform upon the load, it would theoretically absorb more energy from the ball resulting in a slower ball velocity off the bat. Just as in the first test, it could be completed using a simple methodology. Initially, a clamp was to be fit snug around the barrel of the bat, and would slowly be closed until it reached a pre-determined point (i.e. 5 turns etc.). Using pressure gages, the total load was to be measured in a more engineering acceptable way than just the number of turns of the crank. At the completion of the test, the new diameter of the bat was to be measured. It was expected that the new materials would decrease how much the bat deformed under pressure, meaning that the bat would be as close to its normal diameter as possible. Other concepts can be related to this test as well, such as the many theories behind what makes a wood bat perform better: either it being hard or soft. The results were to be compared to the final performance test to determine which theory is more accurate.

The third test was to measure directly the ball speed off of the new bat/material combination. In order to limit extra variables such as bat speed, angle of contact, etc., a mechanical device was developed to “swing” the bats using a simple bungee cord. The objective was to swing the bat at an equal speed every time and measure the ball speed leaving the bat. The experiment required the use of a high speed camera to measure the distance the ball traveled during the immediate post impact time frame. All these precautions were meant to limit the amount of extra variables present with ball speed such as trajectory, Bernoulli

affects, drag etc. These results were directly related to performance, showing that a faster ball velocity meant a better performing bat. Therefore, the new designs were meant to increase the ball exit speed velocity. The swing mechanism designed can be seen in figure 3 below. It was reviewed by Paul in the machine shop and was considered to be complete.

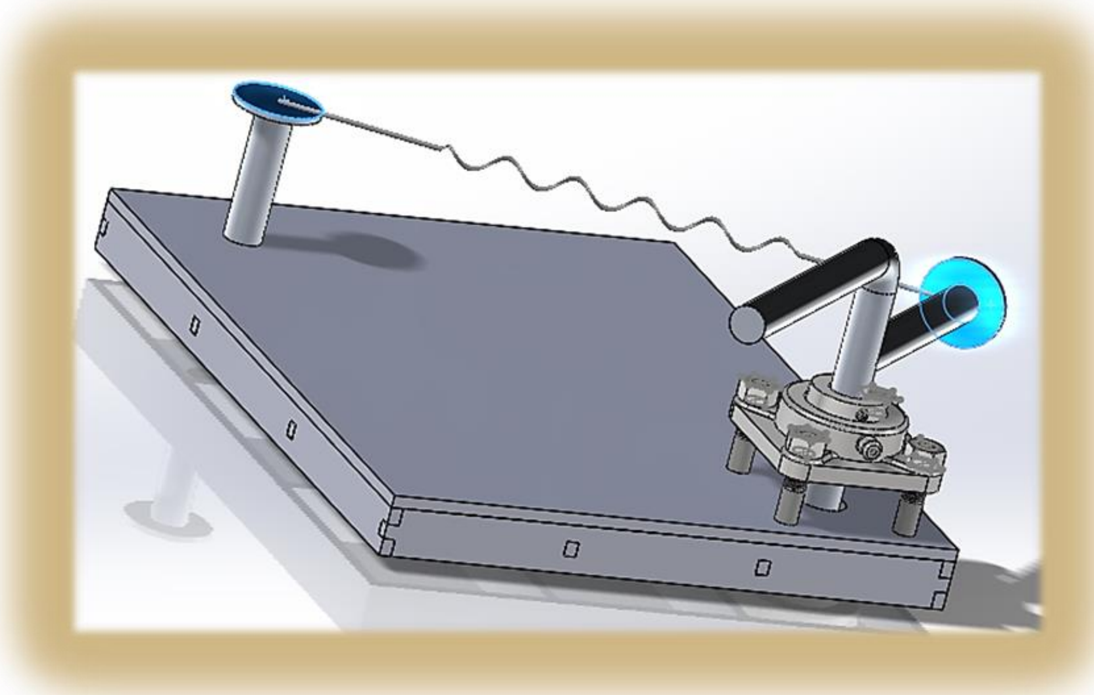

Figure 3 – Design of the swing device

Some important features about the swing test design were in its framework. The platform itself had several different components, all of which were manufactured using the water-jet cutter. This not only ensured accuracy, but also saved time for the machine shop workers. These pieces also had notches in them, which acted as guides when assembling the structure. Since the parts fit together like a puzzle, they remained in place without the use of

hands to hold them. This made welding much easier, which saved time, hassle and created a more professional look for the device.

At the completion of experimentation, the results were expected to yield that an increase in bat strength had been achieved with at least one newly developed material. In an ideal case, the performance of the bat was to also have improved. Even though this project was done as an advanced part of my education, I truly believe that the findings can benefit many generations of future baseball players. Not only will the game be safer to play, but it will also have a more nostalgic feel when America's past time is played using the bats of its founders.

Material Acquisition and Financial Analysis

A large portion of my project relied on the development of materials, as well as running tests to failure. This meant that certain items may not be used multiple times such as the dowel rods. Therefore, a large amount needed to be acquired, which actually was a very minimal cost. Thirty 36 inch dowel rods were purchased, meaning that 30 tests could have been run. Ideally, five materials were to be created, each of which would undergo five tests where the average breaking load would be calculated to reduce the random error present. With the best performing material additive, ten more tests were to be run applying the material at random spots on the rods to see where the bat broke when it is not entirely coated.

The majority of the cost was in the wooden bats and swing mechanism. Five different materials were to be developed completely to use on an actual bat: one mesh, one rubber, one form hardening, one laminate and a combination. These material choices all required testing because they all bring something unique when it comes to adding strength: meaning that some were elastic, some were rigid, some were heavy, and some were light. The best performing

design was also to be tested by applying the new material only in high stress areas, which may be more acceptable to the NCAA if they were to consider adopting the idea. This meant that five bats were required to test the new materials. The sixth bat was used as a control without an additive to compare whether or not the new materials performed better than a typical bat. The high cost for the bats and swing mechanism was justified because all of the research, no matter how conclusive, could not be confirmed until the performance test. Otherwise, the new material may have been able to make bats stronger, but it was not possible to know if performance was sacrificed. All other costs were related to the new additive materials and their application such as rubbers, epoxy, nylon mesh, carbon fiber sheets and polyurethane wood sealants. The length and quantities of the carbon fiber sheets and nylon meshes were based on their application on the dowel rods and bats: meaning that enough material was purchased to wrap five dowel rods for the bending test and a baseball bat for the performance test.

In order to procure the necessary materials for the experiments, nearly $500.00 needed to be obtained. The complete cost breakdown can be seen below in table 1. Fortunately, Union College has a program in place called a student research grant meant specifically for independent senior projects like this. After developing my testing methods and finalized list of necessary materials, an application was submitted. The notification of decision on whether or not the requested funds are granted came on December 4th, resulting in an award for the full $500.

Table 1 – Breakdown of the Experiment Cost

	Item	Source	Quantity	Cost per	Total Cost
	1/2" x 36" Dowel rods	Craftparts.com	30	0.50	15.00
	ash wood 3-bat pack	JustBats.com	2	99.99	199.98
	SBR Rubber Sheets 12"x12"	McMaster	1	10.82	10.82
	Polyurethane wood sealant	Lowe's	1	32.90	32.90
	Wear-Resistant Nylon Mesh	McMaster	1	27.84	27.84
	18-Ounce Bottle of Gorilla Glue	McMaster	1	21.35	21.35
	Carbon Fiber Sheeting	Mcmaster	1	54.74	54.74
"Swinging" Test Device	Square Flange Ball Bearings	McMaster	2	34.74	69.48
"Swinging" Test Device	Aluminum Rod 3/4" Diameter, 3' Length	McMaster	1	12.82	12.82
"Swinging" Test Device	Aluminum 1/4" Thick, 12"	Discountsteel.com	1	55.05	55.05
				Total	499.98

497 Progress

The efforts during fall term can be summarized in three very different and distinct phases. The first and probably largest portion of the term was spent researching existing literature on the topic. As seen in the report, the goals of my research were to better understand how and why bat fracture occurs, as well as how to improve the performance of wood bats. My efforts proved successful, considering that the chosen materials were based on these reasons for failure and the two theories behind bat performance.

The second portion of the term was devoted to designing the swing device for the performance test. At first, multiple designs were created, many of which were very complicated involving pulleys, springs, etc. The design was simplified as much as possible until it became what is seen in the test and procedures section. Communication with Paul in the machine shop was maintained throughout the process, mainly for suggestions about functionality and manufacturability.

The last portion of the term was spent taking care of the written portions of the project such as the progress report presentation, student research grant and final report. The time spent on these pieces was much more than originally anticipated.

Plan for MER 498

While fall term was based mostly on research and preparing for testing, winter term was when all of my efforts proved worthwhile and actual results were obtained. At the start of the term, all of the materials were to be purchased as soon as possible, allowing more than enough time for delivery. By the second week, the bending test was to commence followed by the compression test and performance test. The initial plan was to have two week time slots allotted for each test, leaving two weeks to gather materials and two weeks to assemble and analyze the results. It is important to note that some tests were more time consuming than others due to their pre-testing preparation. For instance, the bending test required material application to about 30 dowel rods which took much longer than coating the 5 bats required for the performance test. With this in mind, it was expected that the performance test would take less than two weeks to complete, saving some time if the bending or hardness tests were to take longer.

Project and Material changes

Decisions made during the first term of this project were based on concepts and research; therefore, a few unforeseen issues manifested themselves during the second term which primarily consisted of testing. While most of these testing procedure changes will be discussed in their respective sections, it is important to note some crucial changes that involve the entire project.

The most influential alteration was based on the material additives being tested. When the physical specimen of nylon mesh was received from the supplier, some concerns were raised about its deficiencies in pliability. For instance, application of the nylon to the dowel rods required a very quick and short curve like deformation, meaning that the force it exerts to become flat again was be amplified. Although the material was not immediately thrown out of consideration, it turned out that it was nearly impossible to apply it to the dowel rods. Not only was it difficult to bend, but it was difficult to glue as well because of its mesh orientation. The smaller surface area in contact with the dowel rod lead to a weaker bond force, ultimately causing the mesh to detach fairly easily. It was also considered to use a weight once the mesh was placed in the correct position on the dowel rod, but this too proved unworthy. When the weights were removed, it would also be glue to the dowel rod because of the gaps in the mesh where glue seeped through.

The final decision was made to take nylon mesh out of consideration for the entirety of the project. The rubber options were also not used because I was unable to find a rubber that could be melted without burning. With two materials being thrown out, another material was desired to take their place and offer a softer alternative to the carbon fiber. Since a decision

needed to be made quickly with little room in the budget, it was decided that Duct tape offered a similar advantage to that of the nylon mesh; therefore, it was introduced to the list of additive materials.

Bend Test

As described above, the bend test was performed using the load frames in Professor Bucinell's lab. The exact device used was the 20 KIP Load Cell with the identification tag reading BUT101-02(20KIP). Since the load frame is normally set up for a uniaxial stress test, a special device was used in order to achieve the three point bending case desired. This device can be seen in figure 4 below. Note that the three points of contact made with the dowel rod were the rollers on the two arms of the device and the metal rod in the center of the load cell. A load was placed on the dowel rod when the device moved in the downward direction; this load was measured as the reaction force felt by the load cell where the metal rod was in contact with the dowel rod. The other desired result was the deflection the dowel rod experienced, which was measured as the distance the crosshead traveled between the start of the test and when fracture occurred. Using the resulting load and displacement data, the elastic moduli for the different wood-additive combinations was calculated.

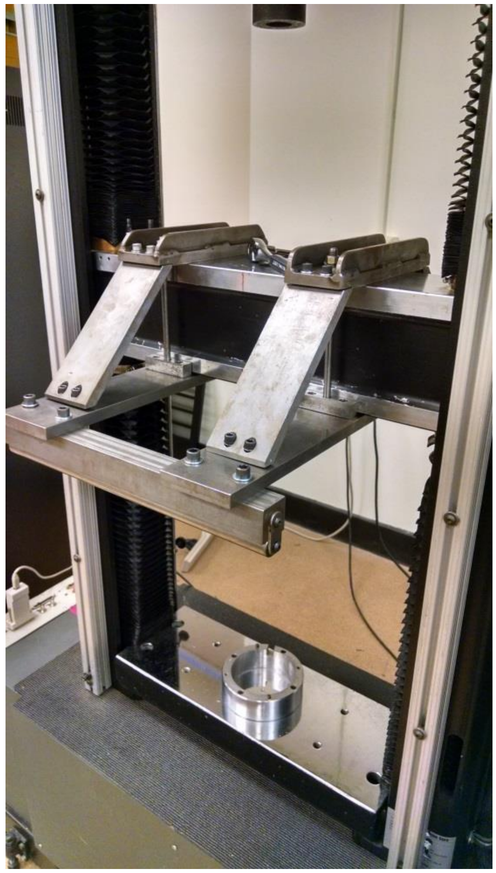

Figure 4 – Bend test special device

There were also some test specific settings to note about my project. The first test run was setup as seen in figure 5. Note that the dowel rods were placed directly on the special device's rollers. The motion of the load frame was also set to travel 0.1 inches per minute. Unfortunately, this setup did not provide sufficient results since the test had to be stopped early. The reason for the premature ending was that the dowel rod had actually bent farther than expected, causing the crosshead to nearly come into contact with the load cell. Such a collision would damage and possibly destroy the machine.

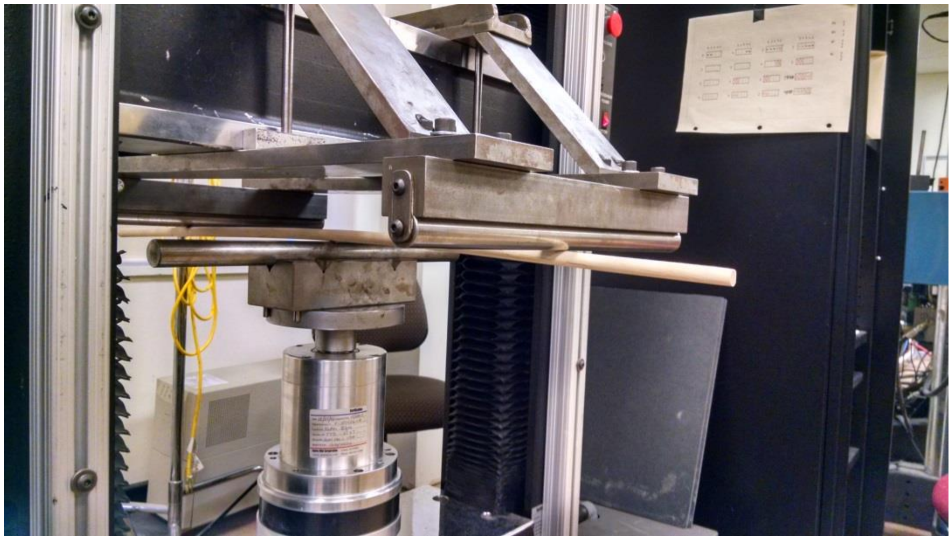

Figure 5 – Original setup of the bending test

In order to make the test more ideal, two changes were made. First, the frequency was increased to 0.2 inches per minute to save run time. The second alteration was the design and introduction of an extra piece in order to increase the gap between the load frame and load cell. This extra piece took the form of a self-aligning washer in combination to a machined part that “swiveled” as the dowel rod bent. The swiveling motion was meant to ensure that the piece would move with the rod instead of reaching a point where it might lose contact and fall off. This new setup can be seen in figure 6 below, which was used for all of the remaining tests.

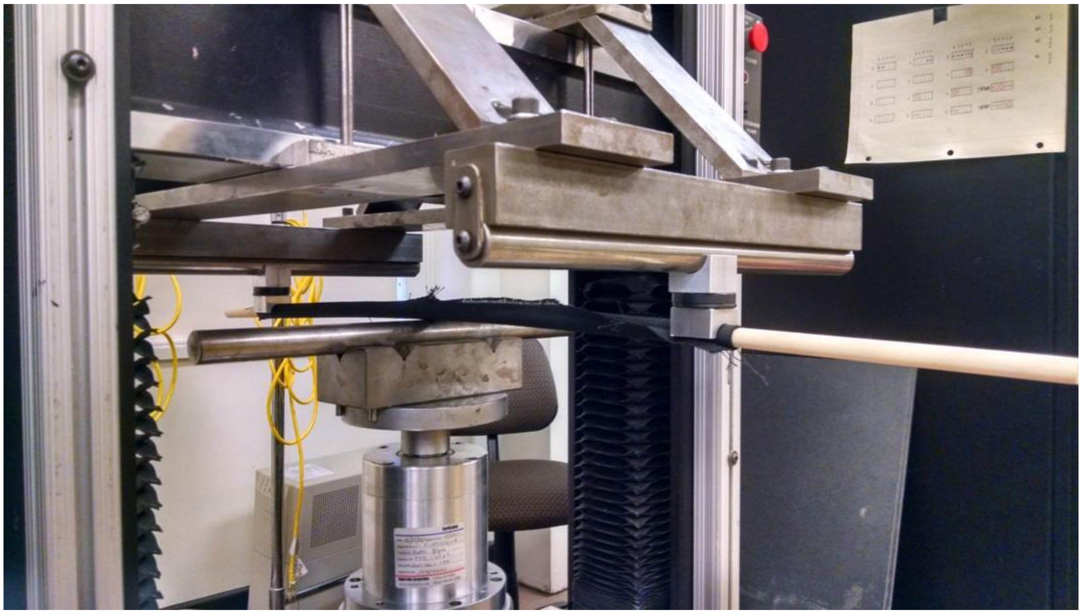

Figure 6 – Final bending test setup

In order to ensure consistent results that were reliable for comparing the materials, some other qualitative measures were taken. The most important was that each dowel rod was aligned during testing so that the grains were vertical. According to research and common belief among baseball players, this orientation is thought to be ideal when it comes to minimizing the likelihood of fracture [3]. Even if these beliefs were not true, the setup still offered consistency among tests, allowing for a good comparison even if the loads are not in fact the maximum loads for the materials. To go along with this concept, dowel rods with abnormal grain orientations were not used during this test. They were put aside to either be used in the hardness test, or not at all.

Bend Test Results and Discussion

The original goal of the bend test was to determine which material-additive combination was the strongest; however there are multiple characteristics that may define a

strong material. For instance, each test produced a maximum deflection, maximum load, and a calculated elastic modulus. All three will be summarized below.

The most direct result relating to strength is the maximum load the dowel rods experienced before fracture, mainly because it exemplifies an impact force. A summary of these results can be seen below in table 2 below.

Table 2 – Summary of the maximum loads

Max Load (lbf)						
Material	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
Plain	34	47	43	41	38	40.6
Polyeurethane	39	40	43	45	50	43.4
Carbon Fiber	42	53	49	59	42	49
Duct Tape	33	36	46	44	28	37.4

Recall that each material was tested five times, which is apparent in the number of specimens. As can be seen, both polyurethane and carbon fiber coated dowel rods experienced a higher maximum load than the plain dowel rods. Although the average result for carbon fiber is a bit inflated due to the one test where it experienced a load of 59 lbf, it still averaged out to a load of 46.5 lbf without it: significantly higher than the plain dowel rods. Another thing to note is that carbon fiber consistently experienced a maximum load greater than 40 lbf; this is yet another sign that the results are consistent and reliable.

Even though carbon fiber was clearly the most successful when it comes to maximum load, it must not be forgotten that the polyurethane coating also improved strength. It too produced consistent results, while only falling below 40 lbf once (39 lbf).

While the results seem to be extremely successful in proving the additives help increase strength, the duct tape actually decreased the maximum load capabilities of the dowel rods. Even when the low measurement of 28 lbf was thrown out, the average was still only 39.75 lbf,

almost a pound below that of plain dowel rods. There is one hypothesis that might explain why this occurred. As the dowel rods bent, the material coating stretched as well. A key difference between duct tape and carbon fiber was their respective elasticity's. Duct tape was actually weaker than the dowel rods, meaning that the wood determined the amount of deflection. As the dowel rod bent, the duct tape stretched and compressed the dowel rod at the same time. This meant that the load experienced by the dowel rod was actually amplified because it is loaded in multiple planes. The carbon fiber experienced this as well; however, the carbon fiber fabric was much stronger than that of wood. This meant that it dictated the deflection amount and not the dowel rod. Therefore, more of the load was focused within the carbon fiber instead of the weaker wood dowel rod.

Another area where carbon fiber proved its superiority in strength was in the maximum deflection experienced by the dowel rods. As you can see summarized in table 3, both carbon fiber and polyurethane provided the dowel rods with the ability to deflect more than if they were not present. Once again, duct tape was inferior to the other two additives and the plain dowel rod.

Table 3 – Summary of the maximum deflections

Max Deflection (in)						
Material	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Average
Plain	2.2639	2.3889	2.2103	2.3250	2.4660	2.3308
Polyeurethane	2.0850	2.3783	2.9860	2.0397	2.4240	2.3826
Carbon Fiber	2.8110	1.9890	2.3863	1.9000	3.1143	2.4401
Duct Tape	1.7280	2.4023	2.0850	1.6934	1.5650	1.8947

While these results seem to support the evidence found during the maximum load analysis, there were a few aspects that need to be discussed. First, notice how sporadic the deflections were, ranging from 1.6934 inches to 2.4023 inches for duct tape and 1.9000 inches

to 2.9860 inches for carbon fiber. This was highly different from the plain specimens that were all very similar. For this reason, the evidence may not be as reliable as it appeared. However, this leads to the second aspect about whether or not the deflection values were even important. For example, a steel rod does not deflect as much as a wood rod before failure, but it would never be claimed that wood is stronger because of this. If anything, a smaller deflection with a higher maximum load capacity may be more ideal when it comes to the performance test; mainly because energy is expended in order to cause bending.

To further display the differences between the new material-dowel rod combinations, all of the load-displacement curves have been combined on the same graph in figure 7. Notice that the graph is only composed of twelve curves instead of the expected twenty. This is because data was lost due to a power outage during one of the testing days. With a limited budget and lack of resources, the test could not be redone. Luckily, the maximum deflections and loads for all tests were written in the notebook as they were completed.

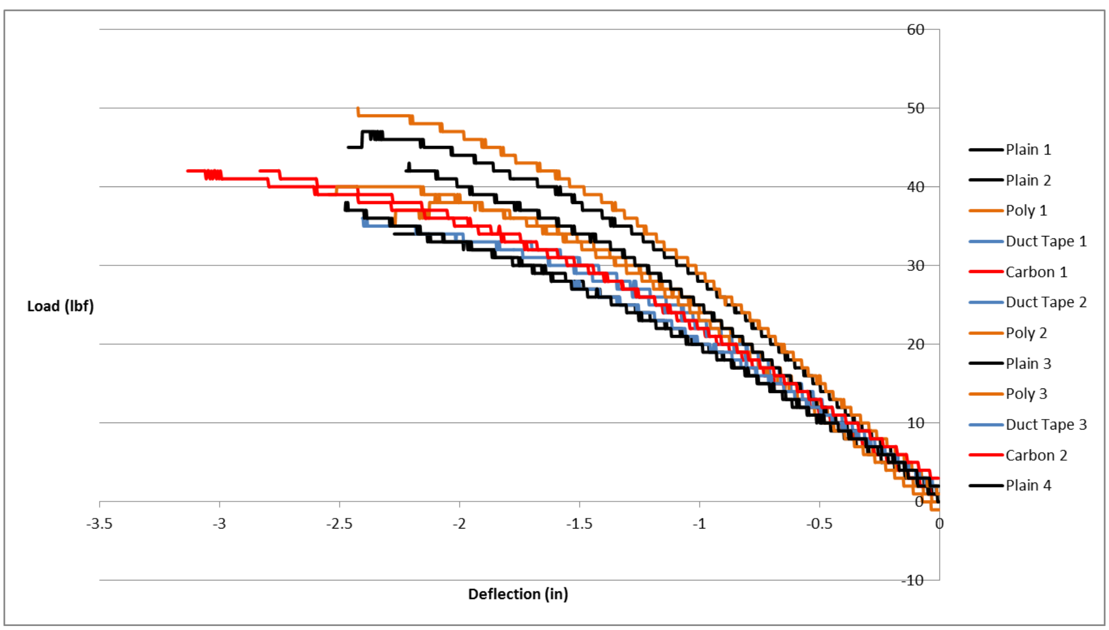

Figure 7 – Compilation of the load-displacement curves from the bend test

Using the elastic portions of the load-displacement curves, the elastic moduli for the various material additives were calculated and summarized in table 4. Once again, these values do not necessarily mean much when it comes to strength: it is just one of the material properties that should be mentioned.

Table 4 – Summary of the calculated elastic moduli

Elastic Moduli (psi)					
Material	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Average
Plain	19.6	27.9	24.7	17.9	22.5
Polyeurethane	24.9	24.8	28.0		25.9
Carbon Fiber	21.4	19.5			20.5
Duct Tape	22.1	21.1	18.8		20.7

Even though the quantitative results from the bend test were not as clustered together as desired, they did provide some helpful insight. It is now known that the strength of the rods has been increased by two of the material additives while maintaining relatively the same maximum deflection. If deflection has anything to do with bat performance, the project seems to be heading in the right direction.

There were also some qualitative results that must be noted about the bend tests; specifically, how the materials fractured. In the case of carbon fiber, the fabric was never punctured. This accomplishes a secondary goal of the project in which stated that all pieces of the broken bat be contained instead of flying out into the field. Duct tape also accomplished this goal to a degree. The duct tape was punctured every time, but never resulted in a complete break. This is more ideal than a shatter, which took place for about 50% of the plain and polyurethane coated dowel rods.

In summation, it may be noted that there were distinct differences in strength among the material additives. The carbon fiber fabric and the polyurethane coating both proved to

withstand a greater load than the plain dowel rods. These two were monitored closely during the hardness and performance tests because of their success in the bend test. As for the duct tape, it could not even withstand a load equal to that of a plain dowel rod. Although this result shows that it may not increase strength, it retained the broken pieces during fracture showing that it may add a positive element to a baseball bat.

Hardness Test

As stated earlier in the report, there are multiple theories behind what characteristics makes a baseball bat perform better: some claim softer bats and some claim harder bats. In order to analyze these theories, a test was required to distinguish the specimens in terms of their hardness. These results were then compared to that of the performance test in the next section.

Originally it was thought that the Rockwell C Hardness testing machine would not be viable since it is usually used to test harder materials such as steel. This proved not to be the case. An initial test was performed in order to see how consistent and at what magnitude the hardness measurements would be. It turned out that after around twenty tests, the hardness results were consistently in the low teens, ranging from about 9 to 15 Rockwell C. Although this proved that consistent results could be achieved, it was still uncertain whether the machine would show differences between the materials. To nullify this concern, duct tape was added to a section of the dowel rod to see if the readings changed. Another round of testing occurred and the results increased from that of the plain wood, ranging from about 12 to 17 Rockwell C consistently. After seeing that it could produce consistent results while showing differences between materials, the Rockwell C Hardness test machine (Model: 3HM, Tester #: 3F45HM)

was chosen to perform the formal hardness test. The device and how the dowel rod was oriented can be seen below in figure 8.

Figure 8 – Rockwell C hardness test machine with a mounted dowel rod

Now that the test device was chosen, certain steps needed to be taken to ensure that the results were strictly driven by the added materials. For instance, one dowel rod may be harder than another; also, the dowel rod may be harder when measured against the grain as

opposed to with the grain. Therefore, it was decided that one dowel rod was to be used for all experimentation, designating certain areas to the different material additives. This dowel rod can be seen below in figure 9.

Figure 9 – Image of the dowel rod setup used for hardness testing

As stated above, the grains must also be taken into account while testing because it may affect the hardness measurements. Since contact may be made at any point on a bat, it was decided that hardness measurements should be made to resemble just that: both in grain and against it. Therefore, tests 1-4 and 8-9 were taken in grain, while tests 5-7 and 10 were taken against the grain. Since this was the case for every material, comparisons between them may be made for every test number.

Hardness Test Results and Discussion

The results of the data can be seen below in table 5. The material that stood out the most from these results was the carbon fiber. Notice that the hardness was not only much greater than that of every other material, but it also read below 20 Rockwell C only once. This result was somewhat intriguing at first since the fabric felt rather soft as opposed to plain wood. Therefore, a theory was developed that the glue used to apply the carbon fiber to the dowel rod may have been the cause for an increase in hardness. After consulting with Professor Bucinell, this result was not as unexpected as first thought. Although the carbon fiber was produced as a fabric and felt soft to the touch, it still obeyed relatively the same strength and hardness characteristics that rigid carbon fiber would. Referring to past experiences with rigid carbon fiber used in hockey sticks, it then made sense that it was much harder than any of the other additives as well as the plain dowel rods.

Table 5 – Summary of the hardness test results

Hardness Tests	(Rockwell C)			
Test Number	Plain	Carbon Fiber	Duct Tape	Polyurethane
1	15	20	16	19
2	15	22	19	16
3	16	21	13	12
4	10	25	12	16
5	10	30	7	8
6	9	20	15	10
7	11	20	18	9
8	16	20	9	23
9	21	22	12	22
10	8	12	7	8
Average	13.1	21.2	12.8	14.3

While carbon fiber was clearly the hardest of the additives, polyurethane also increased the hardness of the material-dowel rod combination. The increase was only slight, which may

prove beneficial since it maintained relatively similar to that of the plain dowel rod. The benefits may even be furthered if a harder bat (carbon fiber) were to not perform as well during the swing test. Duct tape also remained relatively equal to that of the plain dowel rod, but slightly dropped in hardness. It never measured above 20 Rockwell C, and fell into single digits three times. This may have helped determine whether a softer material is ideal for a bat if it ended up performing better in the swing test.

Recall not many conclusions can be drawn from the results of this experiment. Since it was unknown whether a hard or soft bat performed better when it came to ball exit velocity, more conclusions were made following the swing test. To summarize what can be said, carbon fiber was clearly the hardest. Polyurethane and duct tape were relatively the same as a plain dowel rod, but note that a slight difference did separate the three.

Performance (Swing) Test

The performance test was considered the most critical test when determining if the material additives were viable options for future use. While it has been proven that some additives being tested have made the bats stronger, no players would want to use them if the bat performance was severely decreased.

The idea of the performance test was to use a mechanical device to swing a bat at a consistent speed, measuring the ball exit speed after it contacted the bat; the higher the ball exit speed, the better the bat is performing. The Solidworks design of the swing mechanism has been exhibited earlier in the report, but reference figure 10 to see the final set-up after it was manufactured. There were some important things to note about the set-up to ensure reliable results. The first is that the entire mechanism was securely fastened to the table by the clamps,

which remained the case for the entirety of testing. This was done to ensure every test would be conducted in the same position and orientation to the tee. There also was a line drawn on the base of the mechanism for reference when conducting tests. This reference meant that when aligned with the handle of the bat, the bungee cord experienced an equal load every test. To further ensure that this remained true, a fishing scale was used every time a new bat was clamped into the device. If the tension fell below the measured 12.25 pounds from the first test, the bungee was tightened to achieve it.

Figure 10 – Set-up of the swing mechanism

The original procedure for the swing test called for the use of a high speed camera to measure the ball exit speed velocities. After several attempts, a few issues arose that did not allow for its use. First, the camera required excessive amounts of lighting, of which could only be achieved by scheduling or renting the use of high powered lamps. With time running out in the term, such a solution was not achievable. Also, the camera had to be extremely close the

ball even with the greater amount of light. Since ball trajectory was fairly unpredictable, it was not ideal to risk ruining the expensive camera. A solution to this problem was to design a protective housing for it. This once again would take too long, and also would require extra funds to develop.

Although losing the use of the high speed camera was a setback, two new ways were developed to obtain results from the swing test. The first was to still use the camera, but only use the slow motion setting after filming at regular speed. This resulted in a reading of 30 frames per second (fps), which was still nowhere near the desired 240 fps. The second method involved the use of a screen and a stopwatch. For each test, the screen was setup so that the distance between it and the ball was twelve feet. Using the stopwatch, the time it took for the ball to reach the screen after contact with the bat was measured; the resulting times in combination with the distance to the screen produces a ball exit velocity.

Performance Test Results and Discussion

Unlike previous testing, the results were not in favor of the additive materials. It turned out that the best performing bat was the plain one with no additives. The results can be seen below in table 6.

Table 6 – Results of the timed swing test

Trial	Plain	Polyurethane	Duct Tape	Carbon Fiber
1	0.52	0.51	0.50	0.60
2	0.57	0.57	0.59	0.62
3	0.51	0.59	0.54	0.55
4	0.51	0.59	0.51	0.56
5	0.56	0.51	0.55	0.54
Average (s)	0.534	0.554	0.538	0.574
Velocity (ft/s)	22.5	21.7	22.3	20.9

After five tests, the average velocity of the ball coming off of a plain bat was 22.5 ft/s, which was noticeably higher than that of any other bat. Surprisingly, duct tape performed almost as well as the plain bat. This was somewhat unexpected since it was almost discounted during the previous tests. Another surprising result was that carbon fiber produced such a small ball exit velocity. Since part of this test was to compare the results to the hardness test, it was first thought that maybe a softer material really was more ideal. That could be why the duct tape performed so well and the carbon fiber performed so poorly; however, there were some qualitative results that were observed during testing.

During the carbon fiber tests, it was noticed that a large “woofing” noise was being made. Following the completion of its tests, the carbon fiber bat was swung regularly by the technician and the same noise was heard even louder. After comparing the feel of swinging both the carbon fiber and plain bats, it was felt that the carbon fiber required a lot more force to swing. Therefore, it was concluded that a significant drag force was experienced by the carbon fiber. Whether or not the drag was just a characteristic of the material or the way in which it was applied, this conclusion helped explain the significantly lower ball exit velocity: it was not necessarily because it was a harder material.

In the case of the polyurethane, there was also a characteristic evident to possibly explain the inferior ball exit velocity. Knowing that the drag could not be too large of an issue because the application was done well and was very smooth, the concerns were focused on the weight: mainly because polyurethane is essentially a liquid. It turned out that the polyurethane bat weighed 793 grams, which is considerably more than the 735 grams of the plain wood bat. This heavier weight meant that the bungee needed more tension to swing the bat at an equal

speed. Since the tension was held constant for all tests, the bat swing speed itself must have been slower than the other tests.

The duct taped bat really did not exhibit much concern about lost energy during testing, which may explain why it most closely resembled that of the plain wood bat in performance. However, this also may prove that softer bats are less ideal than hard bats. Recall that the duct tape was found to be the only material additive softer than plain wood.

While it may be argued that errors can occur when a non-computerized timing method is used, the errors in this case do not affect how the bats performed comparatively. As mention before, the camera was also used to measure the balls' travel at 30 fps. These measurements, although similar in each case, support that of the timed results. The balls hit by the plain bat took about 9 to barely 10 frames to strike the screen after contact. Similarly, the duct tape took barely 10 frames consistently, while polyurethane took 10 frames to almost 11 frames and carbon fiber was consistently almost 11 frames. Note that a lesser number of frames meant a faster traveling ball. This order of performance directly corresponded to that of the timed results, further supporting the results obtained during the swing test.

Conclusion

Overall, the project was a success with two additives proving to increase the strength of wood baseball bats. The carbon fiber was the most successful, experiencing an average load 8.4 pounds larger than that of the plain dowel rod. It also contained the fractured wood within the carbon fiber housing, which in a baseball bat case would prevent bat fragments from flying out into the playing field. The polyurethane also increased the average max load experienced by 2.8 pounds. So while it did prove stronger than plain wood, the margin is small making it not as

definitive of an increase like in the carbon fiber case. Duct tape was a failure because it experienced a lower maximum load than the plain wood did.

The results obtained from the performance test were not as ideal, with every material additive decreasing the performance of the bat. Duct tape was fairly similar to plain wood, but that did not mean much since it did not accomplish the main goal of increasing bat strength. The decrease in performance of the other two additives was very severe, to the extent that actual use in baseball bats is not ideal. Although there were theories behind what caused such a large gap, at this point it must be assumed that these materials cannot be solutions to the growing concerns for wood bat safety.

Future Research and Changes

Even at an undergraduate research level, the background and methods of this project were very solid. Although the results were only partially ideal, there is great potential for future work to be done on the topic. Some improvements have already been mentioned, such as better applications of the carbon fiber and adjusting the swing test to ensure a constant swing speed when bat weight varies; however, more complicated and specific changes can also be made. For instance, a bat ball impact is very sudden, which was not directly simulated during the bend test. Instead, a load was applied at a slow rate, ignoring the fact that strain rates significantly influence the behavior of materials. On the same note, it might be beneficial to oscillate the load to simulate the frequency response a bat experiences after contact with the ball.

These improvements are based on a combination of both experiences during testing, as well as things restricted by budget. If a much larger budget were achieved in the future, not

only could the tests be conducted more smoothly, but the materials tested can be of a greater variety. This includes combinations of materials that may be tested together, such as carbon fiber coated in duct tape. A solution like this might add the strength required to make the bat safer, while also providing a softer surface which appeared to perform better as a result of the swing test. More sophisticated materials may also be considered, such as titanium power encapsulated within a polyurethane coating. Aerogels may also be a good option as well or at least worth the research to find out.

Acknowledgements

I would like to thank Professor Cortez for making this project possible, as well as offering advice and assistance throughout. I would also like to thank Professor Bucinell for his aid in the bending test, Professor Keat for providing several reference books on the topic, and Paul Tompkins in the machine shop for manufacturing the swing device and the swivel mounts for the bend test. Finally, I would like to thank the Student Research Grant committee for awarding me the funds to conduct the experiments.

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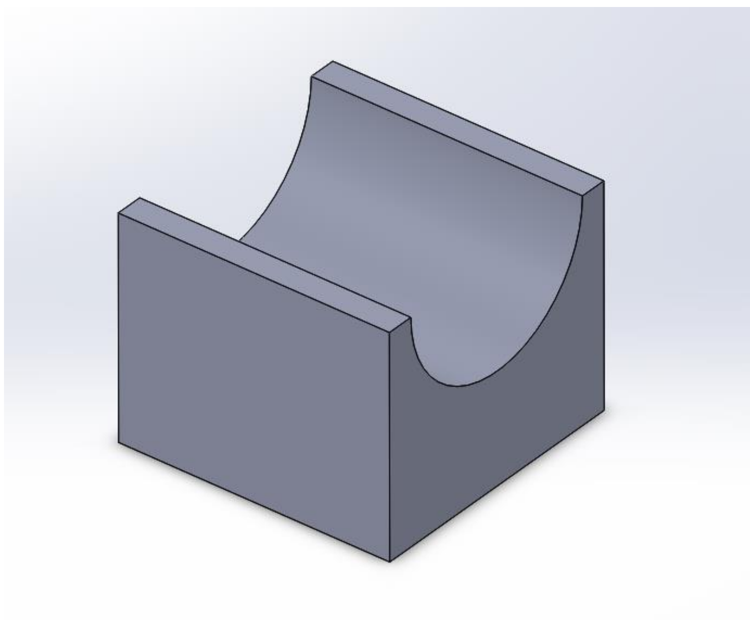
Appendices

Finding the elastic modulus:
The results from the bend test were refined in order to plot only the linear (elastic) section. The slope (elastic modulus) was then found by fitting a line to the data for each individual test.

Equation for the performance test:
$$v = distance\ x\ average\ time$$



Manufactured pieces that were attached to the swivel washer during the bend test.