Development of an Affordable Hybrid Golf Shaft Using Sustainable Materials

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Abstract

As with many industries, technology is improving in the golf world, but sacrifices made to improve performance have resulted in polluting materials and manufacturing processes. These cutting-edge designs support the specifications and playing abilities of a small professional minority while exceeding the needs of much of the golf community. To minimize the emissions created through golf shaft manufacturing, it was hypothesized that the needs of the amateur player could still be satisfied through a less capable yet more sustainable material. Research on and eventual introduction of these materials into commercial golf shafts will significantly improve the sustainability of the sport. This design aimed to use pre-impregnated unidirectional flax fiber sheets to create a structurally viable composite hybrid golf shaft. A hybrid golf club was selected for its commonplace use among amateur players and shorter existence compared to older club designs such as irons or drivers, suggesting that hybrids have more optimization potential than other club designs. The design process was reduced to an optimization problem with various performance parameters established prior to the design. Multiple iterations of the shaft design were simulated and compared to these parameters until a design satisfying all constraints was found. Testing and simulation processes particularly focused on swing weight calculations for each design and FEA analysis testing in SolidWorks to evaluate the stresses and deflections of the shaft under various loads. Once the design requirements were satisfied, physical prototypes of the design were constructed using an autoclave to cure the composite around a cylindrical mandrel.

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INTRODUCTION

Sports, a mainstay in modern culture throughout the world, faces blossoming opposition in the form of environmentalism. Demand to reduce waste globally stands in direct opposition to the many unsustainable, yet “modern” solutions for sports equipment. Given the juxtaposition between the cultural significance of sports and its unimportance relative to critical industries whose viability relies on unsustainable or polluting materials, sports are unlikely to disappear, but the unsustainable equipment they utilize may soon be a thing of the past.

Unsustainable sports equipment design is rooted in its dependency on carbon fiber. This is especially true in the sport of golf, where golf shafts for woods are predominantly made from carbon fiber, and club head design is beginning to implement the material as well. This project seeks to identify a viable product design using more sustainable materials and current manufacturing methods. The central change to the material components will be the replacement of carbon fiber with flax fiber, which has inferior characteristics for shaft design, but is much more sustainable than carbon fiber.

The game of golf has evolved significantly over time, and golf shafts have evolved right along with them. The sport of golf was initially invented near St. Andrews, Scotland in the 15th century, where the game quickly became so popular that it was banned by the King in response to common folk skipping work to play so often [1]. This stymied much of golf shaft development until the early 18th century, once the game had returned for some time, when people began to experiment with various hardwood species from which to make their golf clubs from. In those times, international trade was limited, so players typically stuck to the best hardwood in their region. Regionalization of shafts disappeared, however, when in the mid-19th century hickory shafts took over internationally – Robert Forgan, a Scottish clubmaker, prototyped the first set of hickory shafts in Scotland from a shipment of U.S. hickory intended for use as ax handles [1]. An example of these hickory shafts can be found in Figure 1.

Figure 1: Hickory golf clubs refurbished for present day use by enthusiasts [2].

Following this experimentation, hickory quickly became the shaft of choice around the world, until steel took over. In 1893, the first modern golf shaft prototype, a steel golf shaft, was forged. It was a long way from the steel shafts of today, but the idea that one day, a superior shaft could be achieved through a superior material, was enough that the prospect stuck, and by 1930, techniques to create seamless, stepped, and hollow golf shafts, as in Figure 2, had become prevalent [1].

Figure 2: Steel shafts with seamless, stepped, hollow design. Today, these shafts are typically used in irons [3].

Composites did not reach the golf industry on a major scale for another 40+ years. Although the first composite shaft technically debuted at a PGA trade show in 1969, the technology still had room to improve, and mass adoption of composite shafts did not begin until the mid-1970s [1]. As the technology improved, composites found their niche as the optimal golf shaft material for drivers, fairway woods, and hybrid golf clubs, just like the composite shafts today, found in Figure 3. Today, steel and composite shafts exist side by side with one another in the market but tend to address the needs of different club types: irons need the stiffness offered in a steel shaft, whereas the woods benefit from the weight and flex advantage of the composite shafts.

Figure 3: Closeup of composite golf shafts. These are typically identifiable by their colorful designs and wraps in comparison to the plain silver color of the steel shafts and are typically used in hybrids and woods [3].

In their current state, composite shafts rely on pre-impregnated carbon fiber sheets and thermoplastic resin to create a materially superior shaft with a density to stiffness ratio comparable to metals, and lower overall density than metals, as demonstrated by the Ashby chart shown in Figure 4, while keeping costs relatively low, particularly in comparison to titanium [4]. This combination of characteristics contributes to a shaft that is optimized for performance even with a straight taper design; the opportunity to layer different carbon fiber weaves gives carbon fiber construction the additional advantage of allowing for custom stiffness throughout the length of the shaft for a specific player's swing. Its most viable metal counterpart, titanium, cannot compare to this trait, and its price point is significantly higher than that of carbon fiber. These characteristics make carbon fiber an ideal choice for golf shaft design, and it was these characteristics that were considered when selecting an alternative material.

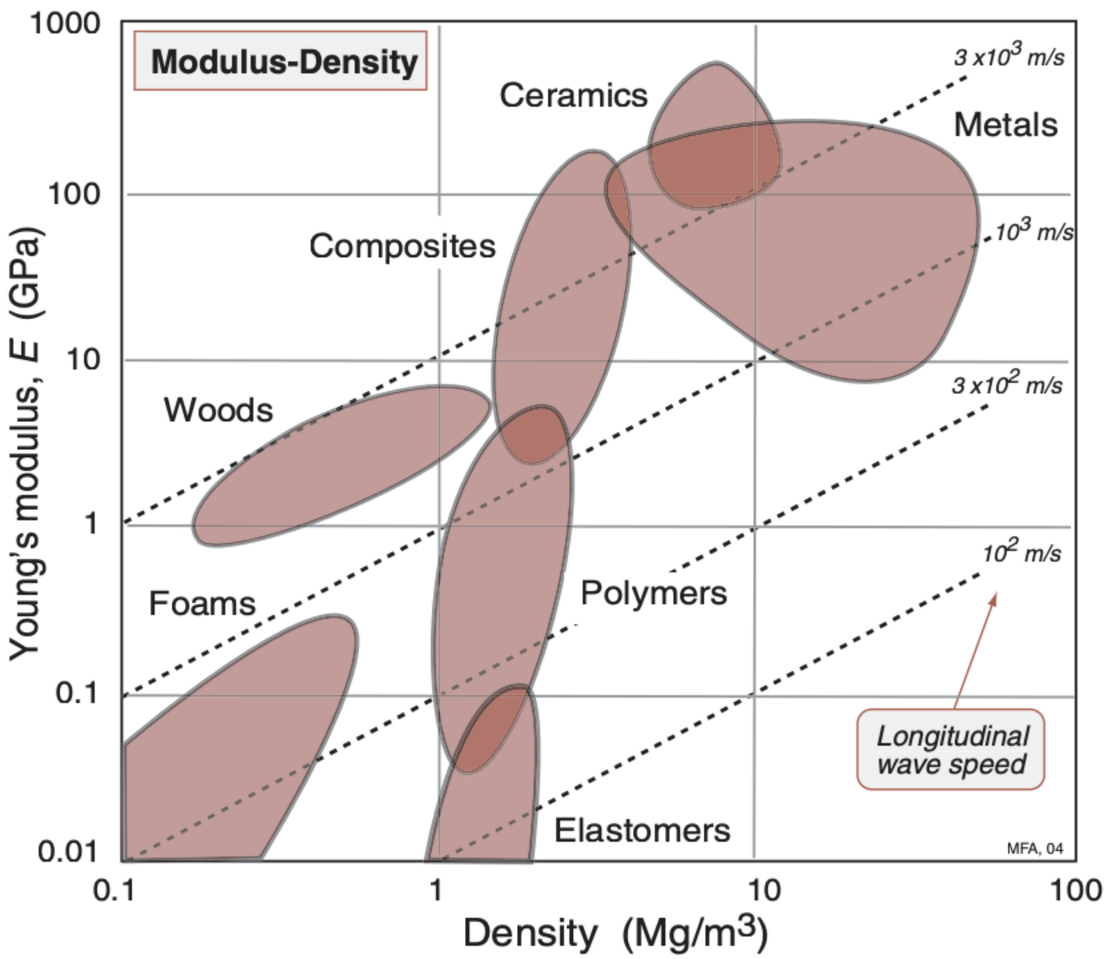

Figure 4: Ashby plot comparing stiffness to density. Carbon fiber reinforced plastics tend to exist towards the top of the depicted composites range. Flax fiber reinforced plastics sit slightly below center of the depicted composites range [4].

A composite golf shaft is composed of many components that were considered during this experiment. As demonstrated in Figure 5, the shaft runs from butt to tip, with a grip applied to the butt end of the shaft, and the tip end inserted into the hosel, the slot on the club head for attaching the shaft. From butt to tip, the shaft has a constant taper, in the case of a hybrid golf shaft, from a diameter of 0.600" to a diameter of 0.355". To manufacture a composite golf shaft in this way, uniquely cut layers of composite material, each called a "flag," are stacked and rolled around a mandrel such that the outer diameter of these flags, once the shaft is complete, follow the hybrid shaft taper profile previously described.

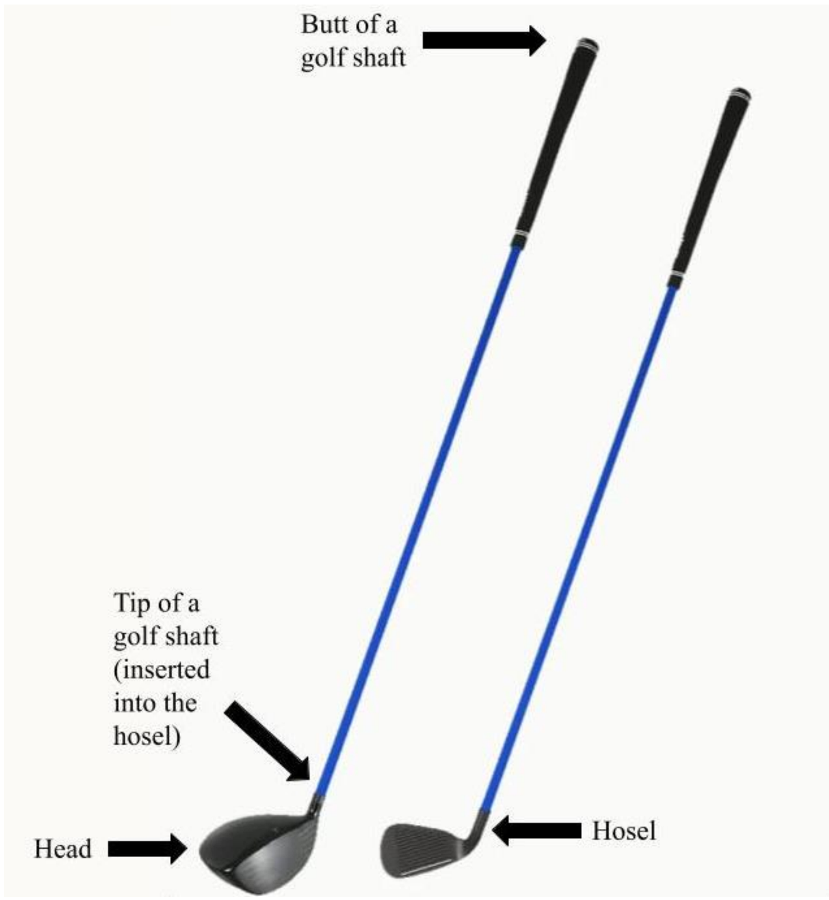

Figure 5: Parts of a golf shaft [5].

Given the potential design flexibility that composites allow for, composite shafts manufactured in this way are often designed for a specific set of characteristics. Swing weight, determined by the actual mass of the shaft and the shaft's balance point, is a description of the way a club feels when it is swung. When swung, a club will feel light (have a low shaft weight) when more of the weight is stored in the butt of the shaft and will feel heavy (have a high shaft weight) when more of the weight is stored towards the head [6]. The swing weight will also increase as the club weight increases as well, regardless of the weight placement [6]. Similarly, a composite golf shaft can also be designed around its bend profile. The bend profile is a description of the stiffness along the shaft, and how that stiffness might change between localized regions, as created through the placement of various flags within the golf shaft. Designing around a bend profile is helpful in calibrating necessary characteristics for a specific type of shaft. The hybrid shaft, for example, needs a stiff tip section, since its primary use is for long, rough grass – a soft tip section will not resist the frictional forces from the grass enough, causing the face of the club head to deloft undesirably.

Flax fiber, although with its drawbacks, offers a potential alternative for golf shaft design and construction. It has already seen use as an alternative to carbon fiber in other sports equipment applications, utilizes the same manufacturing processes, and is significantly more sustainable than its carbon-based counterpart [7]. However, flax fiber has its drawbacks as well: while stronger than glass fiber, it is not as strong as carbon fiber, tends to be about 40% heavier than carbon fiber materials post-cure, and is about 40% more expensive [7]. This tradeoff introduces some of the design constraints that will be considered.

The first stage of this process will be to design the golf shaft for a specific set of characteristics. This golf shaft will be designed for an amateur player of medium ability, with a medium swing tempo but whose swing shape lowers the launch angle below the desirable amount. As the material change would suggest, design of a golf shaft using flax fiber will be based on current composite methodologies for golf shaft design but will require different design choices to make up for the shortcomings of flax fiber, relative to its carbon counterpart, to be able to achieve the desired shaft. Flags of various characteristics will be layered throughout the shaft to achieve the desired characteristics.

To design the shaft, several performance characteristics were used to define the optimal solution. The primary characteristics considered will be the total mass of the club, the dimensions of the club, , the swing weight of the club, and the bend profile of the club. To ensure that these design considerations are performing as desired afterwards, static shaft deflection and dynamic testing will help to evaluate the success of the design.

These design parameters can be satisfied given the extended mass limit on the club. In a carbon fiber shaft, the typical mass of a hybrid golf shaft is typically kept under 75g, but given the material shortcomings of flax fiber, the mass limit of 100g established for the flax fiber golf shaft will allow for more material to be used to satisfy certain performance characteristics. Even before accounting for the additional available mass, flax fiber appears to have properties that will suffice for golf shaft construction, so it is potentially possible that the additional mass will not be needed. Indeed, considering the performance advantages of flax fiber over glass fiber, which was briefly used as a composite material in golf shaft design, suggests this design is feasible not just to manufacture, but to use as well [1].

Once the design is complete, pre-ordered sheets of prepreg flax fiber will be cut into flags on campus. These flags will then be wrapped around a mandrel and baked in Union College's autoclave. Given that the flax fiber is heavier than carbon fiber, the shaft will be left unpainted, unlike commercial shafts, to reduce unnecessary weight. After being left to cool, the shaft will be tested to ensure that it meets the desired specifications.

Following manufacturing, testing will proceed with the intention of evaluating the shaft's characteristic similarities and differences with that of a commercial shaft. Swing weight is a typical measurement taken in the golf industry, and analyses will be run to determine the similarities between commercial carbon fiber shafts and the designed shaft [8]. Following the success of these tests in meeting the design criteria, FEA analysis will be performed for shear [9] and tensile behaviors of shaft alternatives [10] to evaluate viability in an engineering context in comparison to commercial graphite golf shafts. In the same way, the bend profile will be determined from the stresses in the shaft under loading.

Finally, the shaft will undergo testing in conjunction with Justin Paschke's golf head project. This section will seek to measure the golf shaft's performance, feel, and structural viability. Performance will be dictated by consistency in ball flight distance and spin. Feel will be dictated by the reviews of a group of randomly selected individuals who will hit a graphite shafted golf club and the flax fiber club of identical swing weight, to determine if the feel of the club is satisfactory to the consumer. Structural viability will be determined by the shaft's ability to withstand this testing with no newly visible imperfections or defects. Results on the potential of flax fiber as a performance material alternative to carbon fiber for an amateur golfer will then be documented and reported.

While completion of the problem is possible, there are some limitations to be addressed. The main restriction is the limited resources afforded. Regarding time, this project needs to be completed in 20 weeks, as a mostly individual effort, with additional work from other classes and extracurricular activities in the background. Given that this project can only last for this period, the scope of the project must remain limited, and later steps in the project may need to be truncated or eliminated outright to complete the project on time. Project funding is also hard to come by: money for the project is only provided through grant applications, and the only grant that is supplied by Union College is limited to a total of $500. While the material costs of a single shaft might come well under budget, the need for ultimate strength and durability testing requires the manufacturing of multiple prototypes, which could pressure the project's budget. Finally, all else satisfied, the shaft may still not perform as desired, and it may be impossible to satisfy the design specifications with the material selected. Therefore, there is no guarantee that the project will succeed.

The final product will be a functional golf shaft prototype of increased sustainability that has measurable characteristics comparable to a graphite golf shaft. The shaft will provide a baseline for what is possible in sustainable shaft design, while also providing documentation of the player experience using a shaft of this design and viability, not just as a hypothetical design, but as a functional product. Results will highlight the necessary changes needed to improve the commercial viability of the product going forward in future iterations.

BACKGROUND

In this section, prior research will be detailed to establish a common foundation of knowledge through which design constraints are established. First, research on the design methods and manufacturing processes currently used in industry will evaluate how to best approach designing the club. Next, to demonstrate the potential sustainability benefits of switching from carbon fiber to flax fiber will be evaluated based on the emissions created from the manufacturing processes of each fiber process. After demonstrating the sustainability-based advantages of the flax-fiber, the properties of each material will be reviewed to compare the performance of the two materials. Research to evaluate the performance of a modern golf shaft will be used to set baseline design specifications that preliminarily demonstrate the viability of flax fiber in a hybrid golf shaft. Any gaps in research will be subsequently detailed, and methodologies for circumventing research gaps will be discussed. Ultimately, however, it appears possible to satisfy the design constraints with a flax fiber hybrid golf shaft.

Design and Manufacturing:

In modern golf, golf shafts designed for drivers, fairways woods, and hybrids typically use a multi-layered composite design. The cross-sectional geometry of the manufacturing method is detailed in U.S. patent No. 4,132,579, as shown in Figure 6 [11]. In this process, each flag is uniformly spaced with the others along the cross section and wrapped from the inside out around a central mandrel. As a result, the flags overlap one another as they wrap around the mandrel, contributing to the material properties created from the interactions between flags. Simultaneously, the design allows for the tapering of old layers and introduction of new layers along the length of the shaft to localize the desired performance characteristics. Once organized in the desired layering manner along the shaft, the shaft is placed in an autoclave where it is baked. The heat transfer into the mandrel and the composite shaft causes the two to undergo thermal expansion at different rates, separating the two systems and isolating the desired golf shaft product.

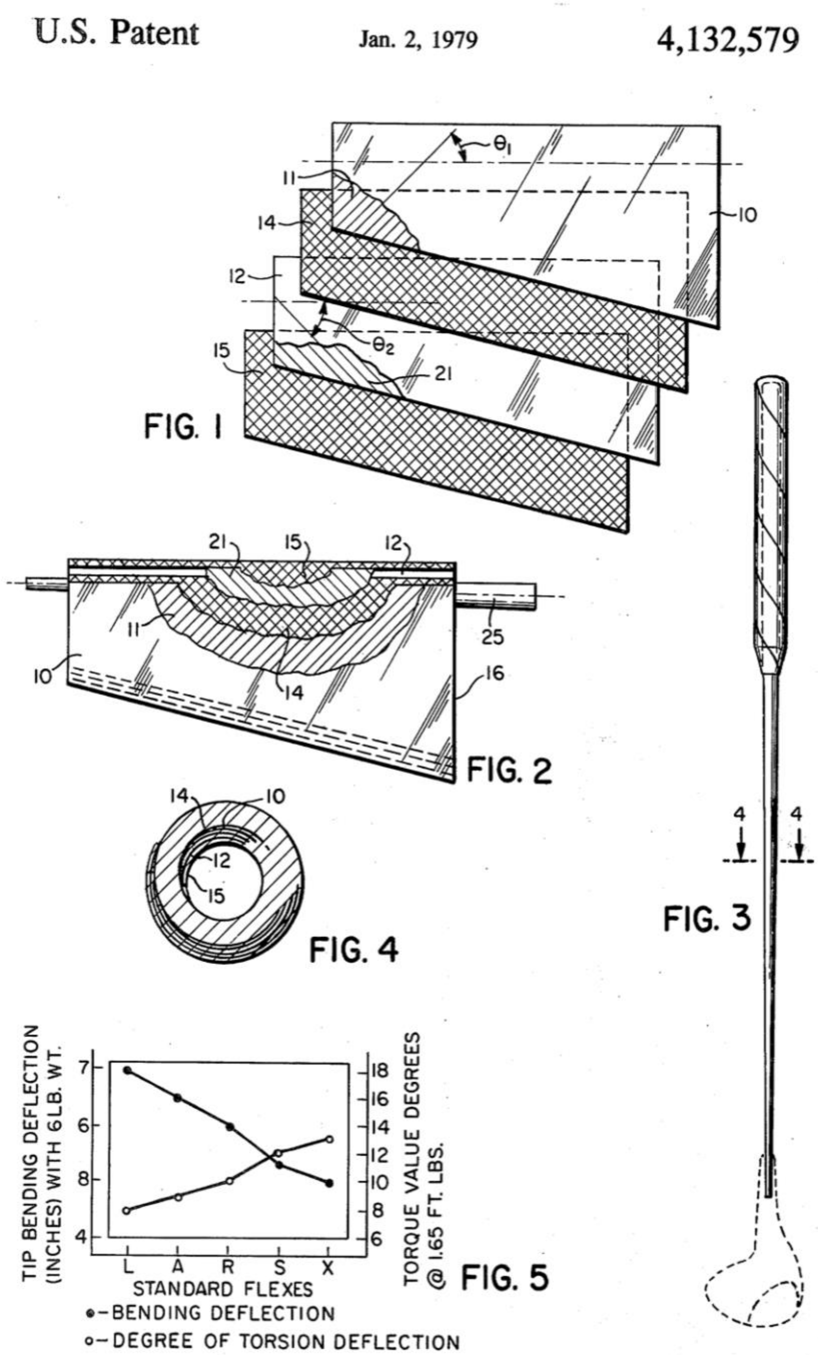

Figure 6: U.S. Patent 4,132,579, depicting the manufacturing methodology of a composite golf shaft. Fig. 1 demonstrates the idealized layering of multiple flags, with each flag in contact with unlike fiber orientations and weave patterns. Fig. 2 shows how the layers will appear on the shaft. Fig. 3 shows the full length of the shaft being considered in the patent. Fig. 4 shows the cross section of a composite golf shaft normal to the viewing plane, to demonstrate the staggered positioning of the flags when rolling them onto the mandrel [11].

The flags are layered in shaft design to provide various stiffnesses throughout the shaft, accomplished by stacking layers of material of various weaves and fiber orientations to prioritize the desired characteristics in specific regions of the shaft [11]. Certain weaves can provide higher strength at a lower cost of weight, and layering can help to redistribute shaft weight while accomplishing the same goals. Individual orientations of unidirectional fibers can provide strength in specific directions, including prioritizing the hoop strength of the shaft, the lengthwise strength of the shaft, or a combination of the two, depending on each flag's orientation [11]. By combining various flag types along a single cross-section, a multiple-layer design can be built that localizes desired properties to the specifications of the shaft design.

Materials:

The design specifications will not necessarily be easy to satisfy though: compared to carbon fiber, flax fiber is lacking more robust material properties. Carbon fiber is the material of choice for most golf shafts, namely due to its improved stiffness to weight and strength to weight ratios over other material classes but creates significant emissions during the fabrication processes. Depending on the fiber selected, stiffnesses can vary between 324 and 588GPa, and strength can vary between 3820 and 7000MPa [12]; however, it produces an average of 24.83 kg-CO2eq/kg of CO2 emissions per square meter of fabric, lacking the sustainability that is becoming necessary in an environmentally conscious world [13]. Compared to carbon fiber, flax fiber addresses this sustainability issue, while continuing to maintain a reasonable standard of performance relative to carbon fiber. Production of flax fiber has a negative global warming indicator through its ability to uptake CO2 through photosynthesis during the farming stage of flax production, and the lack of need to use or generate Halon 1211, Halon 1301, Indium, and Nitrates throughout the entire production cycle [14]. The best flax fiber tops out at stiffness of only 60GPa and a strength of 800MPa, but it should be noted that flax fiber is still rated to 50% better tensile performance than glass fiber [7]. Similarly, through a study of 490 fiber reinforced polycarbonate specimens under unidirectional tensile loading, flax fibers were found to have 23% higher strength retention than glass fibers across a matrix of three different temperatures and four different environmental conditions [15]. These results make flax fiber a strong choice for a sustainable alternative to other composites.

Shaft Expectations:

When designing any golf shaft, the most important static engineering considerations are the shaft's tensile behavior and its shear behavior. Through ultimate stress testing, it was found that a thermoplastic composite golf shaft that has a breaking load of 8.96kN and a Young's modulus of 0.8015GPa in tension, demonstrating that any shaft able to withstand this load should be plenty capable in recreational golf applications [10]. Likewise, Ramnath's studies also found an ultimate strength of 6.76kN and a stiffness of 0.5932GPa in shear loading on a golf shaft, which comprises the upper bound of shear properties for golf applications [9]. Should the flax fiber be capable of these performance characteristics, it would confirm that flax fiber is a capable choice for the design. For a more typical loading scenario, loading of 1350lb_f was initially used, as was determined by Justin Paschke through an assumed ball mass of 1.260oz, swing speed of 100mph, and contact time of 2ms. Further analysis of this scenario made this estimation seem a bit high however, and further research was conducted to determine a better approximation of these forces. Through this research, it was found that the loading for a professional PGA golfer, the forces experienced were found to be 414N [16]. This value was taken to be an upper bound for the analysis, since the impact force was determined from a professional player, and not from an amateur one. During the FEA analysis on the golf head, the force was applied to the center of the face of the club head. Since the center of the face of the club head does not lie on the central axis of the golf shaft, a torque of 1.65N*m was also applied, determined from the 414N located 1.57in from the axis of the golf shaft.

Static tests may help to confirm the overall viability of the shaft, but dynamic testing reveals much more about shaft design and its most important considerations. Notably, the minimum radius of curvature curves reveals much about where the softest, and stiffest parts of the shaft are found, and how that might vary between clubs, swing types and other preferences [17]. Various shaft materials and designs tested in Subic's study produced varying results in their dynamic bend profiles, despite similarities in their static testing results. These findings establish that while static testing might allude to the shafts' structural viability, dynamic testing is necessary to understand how the shaft truly performs and feels to the user [17]. In a driver shaft with a thermoplastic core, the minimum radius of curvature was found to be 30cm - 40cm above the hosel and continued to grow up the shaft until 10 cm from the grip, where the radius of curvature began to decrease [17]. These results will help to determine region sizing for various flexes throughout the shaft and provides insight into how a club's uses drive decisions for its bend profile. In the case of a hybrid club, which typically sees use in the rough or other situations with more difficult lies, a stiffer tip design will be needed to overcome any frictional "grab" the terrain might have when swinging the club. Unfortunately, due to limitations in the capabilities of the available SolidWorks license, it will be impossible to complete dynamic testing in simulation, so this research can be applied to the design only in a qualitative sense and will not contribute to the quantitative design specifications in a meaningful way.

As the number of successful, unique designs in the commercial golf world demonstrates, there is no single right answer to determining the universally best shaft on a performance basis, primarily because of differences between player's swing path and swing tempo, and preferences on club feel [8]. Swing weight, the mathematical measure of the feel of a club when it is swung, plays an important role in measuring the feel of a shaft. The swing weight of a club is a function of the total mass of the club and the balance point of the club along the shaft and is represented on a lorythmic scale (A0-G9) [18]. The heavier the club is, and the closer the balance point is to the head of the club the heavier the shaft the club feels when swinging it due to centripetal forces, and the heavier the shaft weight [18]. To adjust the shaft weight, a few rules are necessary to consistently adjust club feel:

1. Shortening the shaft by 1 inch can be offset by adding 12 grams to the head of the club [8]
2. For every 20 grams the weight of the golf shaft is decreased, increase the swing weight of the club by one point [8]
3. A swing weight that is too light for a player is one that causes them to swing with too fast a tempo and struggle to strike the ball consistently. A swing weight that is too heavy for a player will cause them to push the ball, and the club will feel cumbersome for them to swing [8]

Shaft weight standards are forever changing, however, as they seek to meet the standards of the modern golfer and the modern performance materials that are available to them. Initially, D1 and D2 swing weights were considered industry standard (Ping the notable outlier) until TaylorMade's decision in 1994 to raise the swing weight to D7 on their Burner Bubble driver, as was needed to maintain the feel of the swing [18]. Since then, introduction of shaft materials with improved strength to weight ratios have resulted in progressively heavier shaft weights, as the club head contributes higher and higher proportions to the shaft weight [18]. Commercial options for shaft weights now reach into the F range for hybrid golf clubs, and as fiber weave technology is implemented with higher frequency in club head design, club shafts will need even further mass reductions to maintain the same balance of centrifugal forces.

Also important to the design of the club is the playing ability of the desired customer, and the desired characteristics that best compliment their swing. Softer shafts contribute to higher launch angles and higher spin, which may be more optimal for a more novice player trying to improve their distance through higher lofted ball flights [19]. For those with faster swing tempos, whether novice or professional, a stiffer shaft is needed to increase swing consistency through its increased tendency to resist tensile and shear forces. Moreover, more experienced players will look to increase their swing speed to add distance and use stiffer shafts with their clubs that will result in low launch, low spin shots, working to maintain accuracy during a harder swing. In the case of this club, however, the amateur and the difference in club type changes the design with decreased stiffness overall, particularly through the middle of the shaft, but with maintained, or even increased, stiffness at the tip of the shaft, to decrease shaft lag when friction from ground contact opposes the club head acceleration.

Inconclusive Research:

There are numerous design parameters potentially limiting the problem, and potential complexity added when reapplying the results of various studies to approximate these design parameters. Without strong market demand for a flax fiber golf shaft, there has been little research published on the subject, and thus, carbon-fiber based results are needed to compare flax fiber to. Similarly, driver shaft studies are much more numerous, and since the shaft being designed is for a hybrid golf club, many results must be extrapolated from driver-based studies and reapplied. While these reapplications have properly bounded the design problem, there are still instances where the bounds of the design constraints may not be accurate to the reality of the problem. Regardless, given the research that has been done, flax fiber appears to be a potential alternative to carbon fiber, and this project will seek to demonstrate that there is a feasible alternative to carbon fiber for use in commercial hybrid golf shafts.

DESIGN SPECIFICATIONS

Purpose:

In the current golf market, golf shaft manufacturers design shafts around newly designed golf heads that are soon to be released to the public. Depending on the type of player, the shaft manufacturer will design the shaft around potential characteristics of stiffness, strength, durability, swing weight, and bend profile.

Given the material limitations of alternatives to carbon fiber, this club will be primarily focused on providing a useable design for the amateur player, who might not be as capable as a professional golfer, and therefore will not require the same level of performance characteristics as supplied by todays current golf shaft market.

Features:

From the literature researched, several features were extracted that have been considered important for consideration in determining the necessary features of the golf shaft. The features are as follows, in order from most to least important:

1. Sustainable
2. Affordable
3. Maintains the dimensions of a standard hybrid golf shaft

4. Maintains the feel of a standard hybrid shaft
5. Flexes as desired when swinging the club
6. Easy to assemble with a golf head and golf grip
7. Increases the velocity of a golf ball after being struck by the golf head
8. Can withstand cyclic loading applied through hitting a golf ball in a controlled environment

Intended Market:

The intended final product will be a golf shaft prototype designed for the amateur golfer, with lower to medium swing speeds, which has been selected to be 100mph. Given the material limitations of flax fiber, it is not likely a material ready for use in professional settings, and thus created the limitation in the intended market.

Performance Requirements:

Based on the literature previously discussed and considering the features important to the design of the golf club, several performance requirements were created to mathematically quantify the necessary performance of the golf club. The performance requirements are tabulated in Table 1.

Table 1: Performance requirements for a flax fiber golf shaft prototype

Performance Criteria	Value
Length	39.5”
Butt End Diameter	0.600”
Tip End Diameter	0.355”

Total shaft mass	<100g
Material	Flax Fiber
Swing Weight	E-1-E-2
Deflection	Physically possible (in simulation)
Layering Order	No/minimum interactions between like-oriented composite fabrics

Lifecycle:

Ideally, the golf shaft should be able to undergo at least a single day of testing in the simulator without breaking. Given that flax fiber applications in golf shafts and the research surrounding them are sparsely documented, it is unlikely to assume that both design and construction will be perfect with the first manufactured prototype, and as such, expectations for the lifecycle for the golf shaft are not high.

FEASIBILITY DISCUSSION

For each of the processes discussed previously, the feasibility of each process, given the resources available, will be evaluated and discussed. The feasibility of the design project will be based primarily on the likelihood of completing a prototype that satisfies the desired characteristics of a commercial golf shaft designed for amateur players. Design specifications previously established, material procurement, and manufacturing processes will all be individually considered in the establishment of these characteristics.

The design specifications represent potentially feasible goals for the shaft, but the feasible chance of success varies depending on the process. Regarding the design specifications, the general dimensions of the shaft have been set, and all design iterations have properly accommodated the dimensions without issue. Similarly, fabric layering decisions were made to minimize contact between like-oriented fabrics, which was typically easy to accomplish with each design iteration, since the ordering of the flags largely was independent of other design specifications outside of the bend profile, which was not determined until after the flag ordering was determined. Of the initial design considerations, perhaps the most tedious design requirement is the swing weight, since it is a function of the mass, geometry, and position of each of the flags, the grip of the shaft, and most importantly, the simultaneously designed club head. Changes in design iterations made for the club head project forced frequent redesign of the shaft to accommodate each new mass of the head, since these changes in mass could significantly skew the swing weight. While easy to change, it had implications for other design choices such as the total weight of the shaft, and made the overall design more complex, albeit still feasible.

The least feasible step, however, or perhaps the step that is the most unpredictable, is the feasibility of the shaft meeting the expectations of the bend profile. Approximations necessary for FEA analysis in SolidWorks, which are described in Appendix B, complicate the simulation, to the point of limiting its accuracy and feasibility in providing accurate results. Specifically, initial FEA testing revealed that either approximations made to simplify either the geometry, or materials, or both, were insufficient for producing realistic results, as demonstrated by the initial result in Figure B.1, which shows a tip deflection of over 73m for a shaft approximately 1m long. A second trial with newly revamped properties was subsequently run, shown in Figure B.2, in which the shaft deflected a total of 105m. Therefore, the bend profile was the unruliest portion of the design constraints, and therefore the least feasible. While simulating the absolute stiffness of the shaft may be impossible, preserving relative stiffnesses between sections of the shaft will help to dampen any residual effects on performance of the shaft during normal swings in consistent, contained environments, and when resisting the tensile and shear forces from club head interaction with golf balls and rough terrain.

Material procurement is the most feasible part of the project. While some manufacturers are rumored to have low supply for a multitude of composite products, a few companies have confirmed high supply of the various flax fabrics and their accompanying data sheets, confirming that the desired materials are in stock. As such, this process is expected to be straightforward and completable.

Since composite golf shafts are not new to the market, and flax fiber can be manufactured using the same manufacturing processes as used with composite, a golf shaft can certainly be manufactured with the right tools, expertise, and materials. While materials are easier to come by, the proper tools to manufacture golf shafts, namely a custom mandrel and the proper commercial autoclave, are both more niche tools that Union College does not have access to, so more simplistic approaches were explored. Given the limitations of the scope of the project, the project will be completed with a simple mandrel design fabricated from extruded aluminum rod with circular cross section, and Union College's smaller, yet still capable, autoclave. While not a truly professional manufacturing process, the design offers a close compromise to the true manufacturing methods used in industry today.

Unfortunately, limitations in time have prevented completion of some of these later steps, starting with the manufacturing of the design. Given issues with resolving the swing weight and testing the bend profile in SolidWorks, time ran out before the prototype manufacturing processes could begin. Post-completion and submission of the thesis research, the shaft may still be manufactured for testing, but official testing results could not be completed in the allotted time for this project.

PRELIMINARY DESIGN

The design determined through the first stage of this project is based on a driver shaft design that was specifically modified to prioritize performance characteristics better suited to a hybrid golf shaft. The design utilizes 18 flags, with a total mass of 98.57g. A full breakdown of each flag and its dimensions, fiber types, and fiber orientations for each design iteration can be found in Appendix C; a graphical representation of the geometry and location of each flag used in the final design can be found in Figure C.3. The hybrid shaft design was modified from an official Fujikura driver shaft flag specification sheet, which details the orientation, fiber type, and custom dimensions for each flag. Each flag was resized for the dimensions of a hybrid shaft by scaling the flag profiles down to a hybrid shaft size, and then each flag was considered for their additive benefit to the characteristics of a driver shaft, and how those characteristics might translate to the ideal characteristics for a hybrid shaft, before orientations, fabrics, and occasionally flag dimensions would be changed to better reflect these desired hybrid shaft characteristics.

A hybrid, having a different use case than a driver in the game of golf, is primarily intended for 2nd or 3rd stroke shots on par 4s and par 5s, particularly when the lie of the ball is less favorable for a more unforgiving club, such as an iron. To this end, the original Fujikura driver design has been modified to reprioritize higher stiffness towards the tip of the shaft, particularly with the addition of Flag 1, since a hybrid shaft will likely have to resist much higher frictional forces than a driver shaft. Given the general performance requirements of a hybrid shaft, a shortening of the shaft's length in comparison to the driver, a difference in swing profile, a difference in head shape and mass, and the use of a material generally less capable than carbon fiber, the mass of 98.57g was needed to satisfy the other design constraints, remaining under the

100g limit previously established. To keep the feel of the club like that of a commercial-grade hybrid shaft, a swing weight of E-1 was used in the design, like the E-2 swing weight of the Cobra hybrid commercial example. The flags used in this final design iteration can be viewed in Figure 7, and full analysis can be found in Appendix C. Unfortunately, due to complications with the SolidWorks FEA analysis, completion was not possible with the allotted time for the project. Informal work will continue beyond the project to complete the remaining work subsequently detailed. The closest simulation to the expected behavior of the shaft deflected 20m and can be found in Figure 8. A record of the progress made throughout multiple iterations of this FEA analysis can be found in Appendix B.

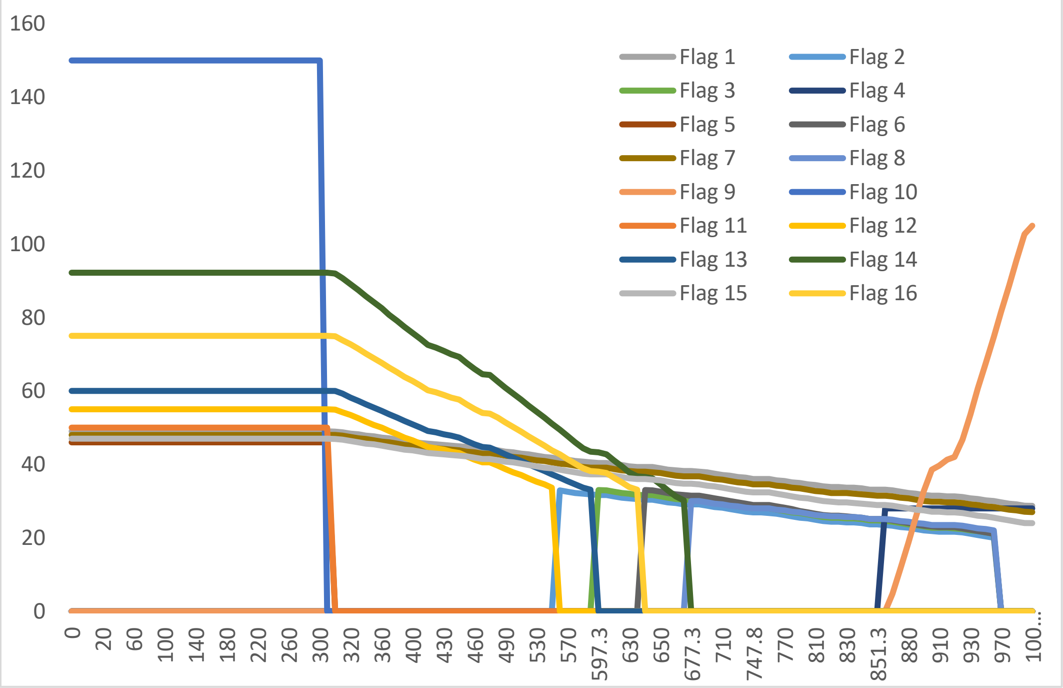

Figure 7: Visual representation of the shape and location of individual flags in the final iteration of the shaft design.

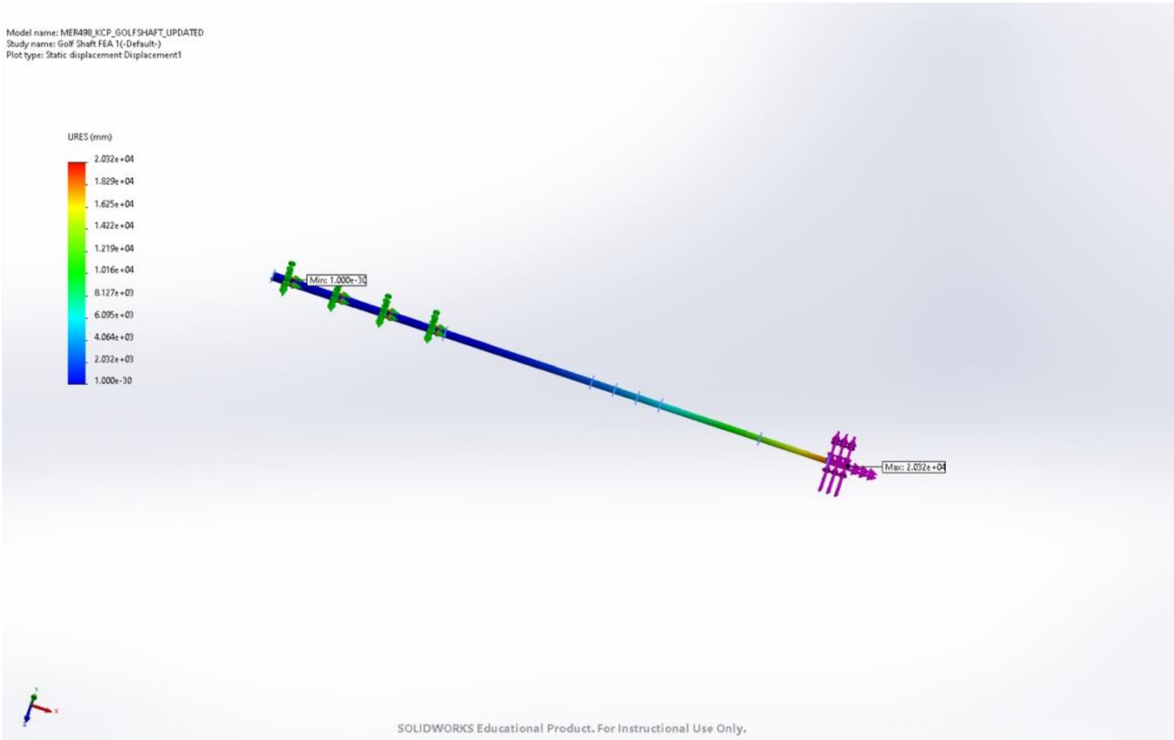

Figure 8: Deflection plot of the golf shaft as simulated in SolidWorks from a profile viewpoint, in the final simulation. Highest deflection is found at the tip with a total deflection of approximately 20m.

Once the shaft has been made, additional testing can be performed to evaluate the true performance of the shaft. The testing process begins with standardized static deflection testing, in which a mass is hung from the tip end of the shaft, which is oriented vertically, supported by a brace at the butt end the shaft extending between 150mm and 200mm along the shaft towards the tip. The amount of mass added to the tip will be determined from the centrifugal forces of the club head on the shaft, determined from an estimated amateur swing speed of 100mph, club head mass of 281.6g, and a shaft length of 1003.3mm. This testing will help to characterize the overall stiffness of the shaft in comparison to commercially available shafts using an industry standard, researched method, which is patented under JPH11253585A [20]. A depiction of this testing method is displayed in Figure 9.

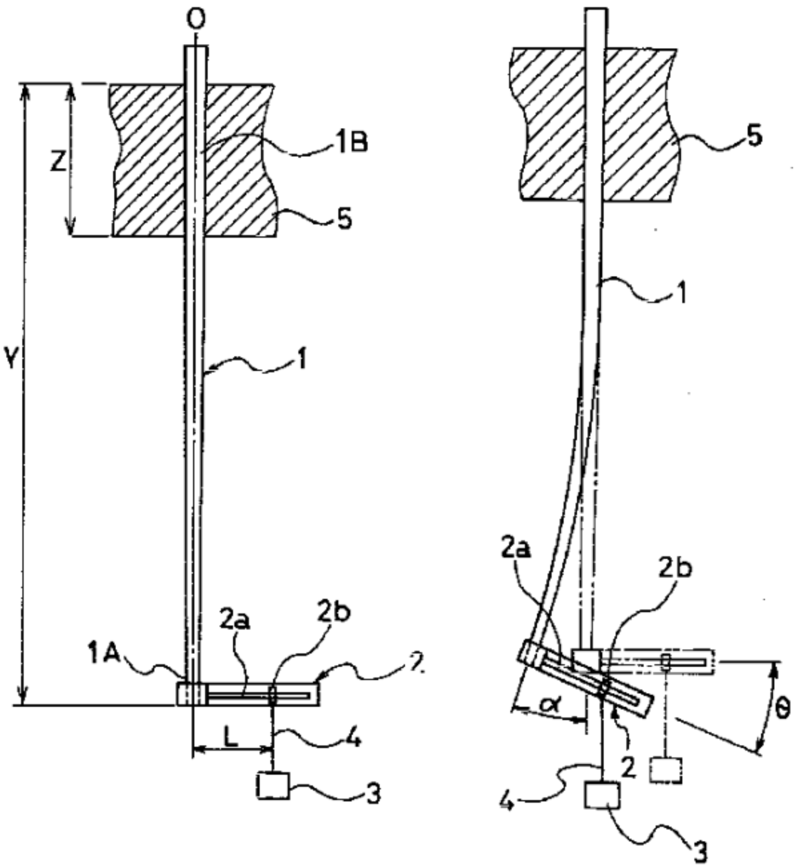

Figure 9: Depiction of the deflection testing method. 1 is the golf shaft. 1A is the modified tip portion of the shaft that holds the projection. 1B is the brace holding the shaft in place. 2 is the projection system. 2A is the projection itself, and 2b is the suspension mechanism holding the mass. 3 is the mass itself, hanging from the position of the golf shaft determined to be the location of the center of mass of the golf club. 4 is the string connecting the mass to the center of mass location that it hands from. Y is the full length of the shaft. Z is the full length of the brace. α is the deflection angle, calculated through the measurement of θ [20].

Next, ultimate stress tests will be performed on some of the prototyped shafts in both shear and tension, to evaluate the true strength of the shaft in comparison to its idealized simulation, and how it compares to the expectations of commercially available shafts. The shafts not destroyed in ultimate shaft testing will be tested in conjunction with Justin Paschke's golf club head, to evaluate the overall performance of the shaft. The completely constructed golf club will be taken to Union College's golf simulator to undergo testing in a controlled environment with idealized conditions that make the club's performance easier to isolate. Data recorded at the golf simulator will help to confirm the real-life performance of the shaft. First, the location of the club's minimum radius of curvature along the shaft will be evaluated along the shaft. A minimum radius will be found through recording videos of swings from a perspective perpendicular to the shoulders of the player, and then evaluating them with Tracker software. If this minimum radius of curvature is found to be in the proportional range determined from the location of the minimum radius of curvature for the driver shafts, it will confirm that the middle region of the shaft is the softest section, as desired. Testing the club in the golf simulator will also help to demonstrate the durability of the shaft, and if it can withstand long-term use. Finally, the swings will be videoed from behind the player and compared to evaluate how club travel can vary under similar swing paths, evaluating the consistency and predictability of the club. Shaft consistency will be measured as the droop tip deflection on contact with the ball off the desired swing plane, as determined from the positioning of arms and hands during the swing. With the same videos, coupled with their resultant ball flight results, the optimal swing speed for the club, with distance maximization in mind, can be determined through regression analysis on the recorded data. While this optimal swing speed is as dependent on the player as much as it is the club, the club, if designed properly, should amplify the effect of an amateur player's slower swing speed through a softer shaft stiffness in the shaft, elasticity in the shaft will cause the shaft to act like a spring that launches the ball further than it would otherwise. The success of this evaluation in finding the optimal swing speed of the club will be determined by its proximity to the assumed 100mph swing speed, demonstrating that the club is truly intended for the amateur player. This work confirms that the shaft performs as desired, and that the shaft could reasonably be used by an amateur player on a real course.

To perform these tests, four different shafts will need to be manufactured, with one lost to evaluating the ultimate tensile strength, one lost to evaluating the ultimate shear strength, and one lost to evaluating the durability of the shaft. With the need for four shafts in mind, and with the testing schedule as established, the shafts will be manufactured two at a time, in stages, to evaluate in the first two prototypes how manufacturing methods might be tweaked to improve the overall final product. Each shaft will be manufactured using the standard process for manufacturing modern composite golf shafts: laying out the individual flags in their specific orientations along the shaft, and then collectively rolling these flags in their desired positions around a mandrel, which has been sprayed with anti-adhesion spray to enhance separation caused by the differing thermal expansions of the mandrel and the composite. The unit is then baked in an autoclave at 185ºC and 60psi for 300 minutes, and then 250ºC at 60psi for 90 minutes, before letting the shaft cool inside the autoclave until it reaches room temperature. Upon removal from the autoclave, the shaft is separated from the mandrel using an extractor and is ready for use.

On a per shaft basis, the manufacturing costs of each shaft are relatively inexpensive. If all the manufacturing equipment is provided, the only marginal cost for another prototype is the cost of the flax fiber. The sheets are pre-impregnated with epoxy, and heat is the only necessary tool to soften and then cure the epoxy, so it is the manufacturing methods and tools that are often the barriers to manufacturing. In an ideal case, uniquely designed mandrels and autoclaves would be used to manufacture the shaft, but the resources provided by Union College suffice in providing good enough substitutes to commercial manufacturing methods, and ultimately keep costs low.

To use one of these shafts, one more manufacturing process and a simple 3-step assembly process is needed to completely construct the golf club. First, a golf grip will need to be applied to butt end of the shaft. Grips can often be applied to the shaft by sliding them directly on, and allowing the adhesive applied to the inside of the grip to cure around the butt end of the shaft. Once application of the shaft grip is complete, the shaft can be attached to the golf head, and is nearly ready for use. To attach the shaft to the golf head, simply insert the tip end of the shaft into the hosel of the golf club head. Using a key system, or any other locking mechanism, secure the shaft into the hosel by locking the mechanism in place with the provided tools. Finally, examine the connection to ensure that the shaft and head have been connected in the proper manner.

CONCLUSION AND DISCUSSION

In this report, a sustainable composite hybrid golf shaft prototype was designed as part of an effort to develop an alternative to modern commercial carbon fiber golf shafts, potentially helping to limit the golf's future environmental impact as a sport. While the performance characteristics of flax fiber may be slightly limited in comparison to its less sustainable counterparts, it was hypothesized that the flax fiber will suffice as a substitute for the amateur player, who is typically incapable of pushing the capabilities of equipment designed for professional players. The use of a less capable, but more sustainable material in production of equipment for what is a majority amateur demographic will significantly reduce waste in the sport without compromising the amateur players' abilities. This project intends to evaluate the capabilities of sustainable composites for use in amateur golf settings to further this sustainability goal.

The project consisted of a design stage and planning of manufacturing processes and testing stages for an affordable, sustainable hybrid golf shaft. First, an optimization problem was structured through research on golf clubs to establish design constraints for a hybrid golf shaft, irrespective of material. Next, a design was formulated that satisfied the design constraints over multiple iterations, and FEA modeling was run to simulate the effectiveness of such a design. With the design constraints fulfilled in simulation, the shaft will be manufactured with a mandrel and an autoclave, and then tested in a golf simulator with Justin Paschke's sustainable hybrid golf head to evaluate the real-life performance of the shaft.

The ultimate results found on the performance on the final design iteration demonstrated that the design of the shaft is approaching a feasible shaft design but is likely insufficient for current golf applications. The 20m deflection case is likely an upper bound, and geometric approximation adds uncertainty that might contribute to the deflection of the shaft, the swing speed of 100mph, is likely higher than most amateurs would swing the golf club, but these consolations are not enough to confirm that this shaft could come close to performing as desired in testing. Moreover, even if these approximations were enough to explain all discrepancies between simulation analysis and an experimental testing behavior synonymous with commercial golf shafts, it would be inadvisable to release this shaft design, given that the approximations would be even less capable in providing a sizable factor of safety that would be acceptable in a commercial setting.

In the future, changes will need to be made to the golf shaft to potentially complete a feasible design. While a mass limit of 100g was introduced, this limit will have to be increased to accommodate the addition of more flags, as approximately 1g was left to spare in the final design iteration for this project. While this mass limit increase will cause the design to stray even further from the current performance expectations for modern composite shafts, it will likely stay under the masses of typical steel and hickory shafts, which tend to be much more massive. The increase in mass limit may not be a poor design decision from the perspective of the user, either: hybrid golf clubs tend to be manufactured with both metal and composite shafts, depending on the preference of the user, so the feel of a heavier composite shaft, which is still less massive than a potential steel counterpart, could still be tuned to a desirable swing weight, and have commercial applications even with more flags added.

While this project was completed alongside Justin Paschke's senior project, future projects should likely not take place simultaneously. In professional manufacturing settings, golf club heads are designed first, so that the shafts can be designed around the head. In this project, fluctuations in the head design, particularly later in the project, forced redesign of the shaft on multiple occasions and made designing the shaft difficult and time consuming, and eventually contributed to the project being cut short. If work was done on the head for one year, and work done on the shaft the next year, the alternation between projects would help to alleviate any crossover in changing design that might affect the work for the shaft portion of the project.

Regarding the shaft itself, future work will likely lie in deeper research in one of the fields applying to the golf shaft. Since this project was intended as a potential proof of concept for the amateur player, research to improve the material properties of pre-impregnated flax fiber for a shaft design would be very helpful in potentially expanding the market for flax fiber golf shafts. Similarly, a further dive into some of the engineering parameters discussed in the report could be researched further to more precisely quantify the necessary quantities to create a commercially viable product, or even to introduce new design constraints not considered in this design to further optimize the resultant shaft.

While the two projects completed this year revolved around the shaft and club head, another direction for a future project would be one important part of the shaft that was not considered in either project contributing to the construction of a golf club: the grip. While seemingly simple in design, the investigation of manufacturing processes to induce the maximum possible hand comfort during a swing using a specific taper profile, use of sustainable materials and processes in the manufacturing of the grip, and experimentation with grip textures to maximize the friction in the grip could all be considered important improvements in the creation of a completely sustainable golf club.

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APPENDICES

Appendix A: Excel Work and Hand Calculations

Throughout much of the iterative design process, Excel workbooks were used to keep track of the individual design iterations and were designed to make each design iteration clear to the user and easy to modify. Each design iteration's Excel workbook was broken down into sheets tabulating the dimensions and location of each flag, a sheet for visualizing the positioning of the flags relative to one another along the shaft, and a sheet dedicated to the calculation of the swing weight. This setup contributed to a working format that made subsequent design iterations convenient to build off and kept old design iterations properly organized.

Within the workbook for a given design iteration, most of the worksheets are dedicated to the individual flags of the design. Each flag has its own sheet, which details the amount of material each flag has along incremental cross sections of the shaft, the center of mass of the flag as a point along the axis of the shaft, the total mass of the flag, the general shape of the flag, and the orientation of the flag.

When iterating, it is important to be able to visualize the shaft to see where flags might need to be added or removed, and as such, a worksheet dedicated to amalgamating the work completed in the individual flag sheets was built to enable this visualization. The resulting graphs for each design iteration are displayed in Figures C.1, C.2, and C.3 for the first, second, and final design iterations, respectively.

Finally, was the calculation of the swing weight, which can be calculated as a function of the masses and centers of mass of the golf shaft, club grip, and club head. The swing weight is calculated using the following algorithm [6]:

1. Measure the balance point (center of gravity) of the entire golf club, in inches.

2. Subtract 14 inches from the total number found in (1).
3. Multiply the resulting number in (2) by the total mass of the golf club in either ounces or grams.
4. Use the provided table to determine the swing weight on a lorythmic scale, as swing weight is typically presented in the golf industry (Table A.1).

Keeping the swing weight calculations within the dimensioning workbook made checking this initial design consideration convenient to tune for, and the calculation process could be largely automated once set up in the Excel spreadsheet. Once a solution was found that satisfied material availability constraints and the swing weight specifications previously established, the model could then be rebuilt in SolidWorks for further evaluations and testing.

Table A.1: Swing weight lorythmic conversion scale [6].

Swing weight	A-0	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9
Inch-grams	4550	4600	4650	4700	4750	4800	4850	4900	4950	5000

Swing weight	B-0	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9
Inch-grams	5050	5100	5150	5200	5250	5300	5350	5400	5450	5500

Swing weight	C-0	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9
Inch-grams	5550	5600	5650	5700	5750	5800	5850	5900	5950	6000

Swing weight	D-0	D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9
Inch-grams	6050	6100	6150	6200	6250	6300	6350	6400	6450	6500

Swing weight	E-0	E-1	E-2	E-3	E-4	E-5	E-6	E-7	E-8	E-9
Inch-grams	6550	6600	6650	6700	6750	6800	6850	6900	6950	7000

Swing weight	F-0	F-1	F-2	F-3	F-4	F-5	F-6	F-7	F-8	F-9
Inch-grams	7050	7100	7150	7200	7250	7300	7350	7400	7450	7500

Appendix B: SolidWorks Simulation Process

Once a design iteration satisfying the design constraints in its Excel spreadsheet was determined, that design could be rebuilt in SolidWorks for FEA testing. Given the complex geometries of each flag and the limitations of composite analysis in SolidWorks, several approximations were made to evaluate the resulting golf shaft under loading. The largest of these approximations was SolidWorks' inability to process complex geometries in the composite flags along the shaft. The SolidWorks approximation of the geometry used was a geometric golf shaft sectioned into near-uniform, fixed-flag sections of the golf shaft with concentric, uniform layers running the length of the section. To best approximate the full effect of the flags in each section, the average wrapping length of each flag in each section was taken, which was then used in a calculation to determine a rough approximation of the number of times each flag would wrap around the shaft. Then, according to the layering order described in Table C.3, the flags in that section would be arranged from the lowest numbered flag on the outside to the highest numbered flag on the inside. If a flag was determined to have approximately enough material to wrap more than once around the shaft, then those flags were placed underneath the first layers, so that the lowest numbered flag in the second wrap was placed underneath the highest numbered flag in the first wrap. This process was repeated for subsequent wraps until every wrap was accounted for. As a result, this approximation ignored any considerations for tapering or any of the other complex flag geometries described in Figure C.3, since each section could only be described in terms of the sections of uniform, conical layers, and ultimately limited the intended effects of regional characteristics in the shaft brought about through these interactions. Moreover, any flag depicted in Figure C.3 that stretched over multiple sections of the golf shaft had to be split into multiple sections, which ultimately ignored the stresses and strains that would be absorbed across an entire flag, instead localizing them in the section of the flag closest to the tip, and potentially mitigating properties of the shaft by underapproximating the properties that each flag contributes to the overall shaft design.

Another large approximation was the use of imperfect material properties for the flax fiber composite used in the design. The material properties used were supplied by Professor Bucinell for a flax fiber product that is like, but fundamentally slightly different from the flax fiber that is being used in shaft construction. Since it was not possible to obtain the necessary material properties for the flax used in construction of the golf shaft, the properties used were taken from testing performed on a similar flax fiber in Professor Bucinell's lab. For context, the two materials are both unidirectional flax fiber weaves, of similar fiber to matrix ratios (60% fiber volume in the actual flax fiber, 50% fiber volume in the simulated material properties), use the same type of flax fiber fabric, and likely have similar epoxy matrices as well. As such, the simulated flax fiber material, having a slightly higher volume fraction of matrix, will likely be somewhat softer than the actual flax fiber, causing some underperformance in the simulation.

With these approximations mind, the shaft was rebuilt in SolidWorks using the section method detailed above. The first design iteration simulated in SolidWorks was the final design iteration, as described in Figure C.3 and Table C.3. The geometries described in Figure C.3 and Table C.3 were split into 8 sections, which are detailed in Table B.1.

Table B.1: Specifications of the sections used for the third design iteration, as used in SolidWorks.

Section Number	Flags in Section	Approximate Wraps per Flag	Orientations in section
1	[5, 6, 8, 9, 10, 12, 13, 14, 16, 17, 18]	[2, 1, 1, 1, 1, 2, 2, 1, 1, 4, 2]	$[0 / 0 / 0 / 90 / 0 / 45 / -45 / 0 / 90 / 0 / 90 / 0 / 45 / -45 / 0 / 90 / 0 / 0]_T$
2	[5, 6, 8, 9, 10, 12, 13, 14, 16]	[2, 1, 1, 1, 1, 2, 2, 1, 1]	$[0 / 0 / 0 / 90 / 0 / 45 / -45 / 0 / 90 / 0 / 45 / -45]_T$
3	[5, 6, 8, 9, 10, 12, 13, 14, 15]	[1, 1, 1, 1, 1, 1, 1, 1, 1]	$[0 / 0 / 0 / 90 / 0 / 45 / -45 / 0 / 45]_T$
4	[5, 6, 10, 11, 12, 13, 14, 15]	[1, 1, 1, 1, 1, 1, 1, 1]	$[0 / 0 / 0 / -45 / 45 / -45 / 0 / 45]_T$
5	[5, 6, 7, 10, 11, 14, 15]	[1, 1, 1, 1, 1, 1, 1, 1]	$[0 / 0 / 45 / 0 / -45 / 0 / 45]_T$
6	[4, 6, 7, 10, 11, 14, 15]	[1, 1, 1, 1, 1, 1, 1, 1]	$[-45 / 0 / 45 / 0 / -45 / 0 / 45]_T$
7	[1, 2, 3, 4, 6, 7, 10, 11, 14, 15]	[1, 1, 1, 1, 1, 1, 1, 1, 1, 1]	$[45 / 90 / 0 / -45 / 0 / 45 / 0 / -45 / 0 / 45]_T$
8	[1, 2, 3, 6, 10, 14]	[3, 1, 1, 1, 1, 1]	$[45 / 90 / 0 / 0 / 0 / 0 / 45 / 45]_T$

Using these sections and the material properties provided by Professor Bucinell, it was found that the results found in SolidWorks appeared inconsistent with expectations for the real-life case. Using the initial material properties supplied, the deflection for an approximately 1m long shaft would be 738m, as demonstrated in Figure B.1. The material properties used in this case are shown in Table B.2.

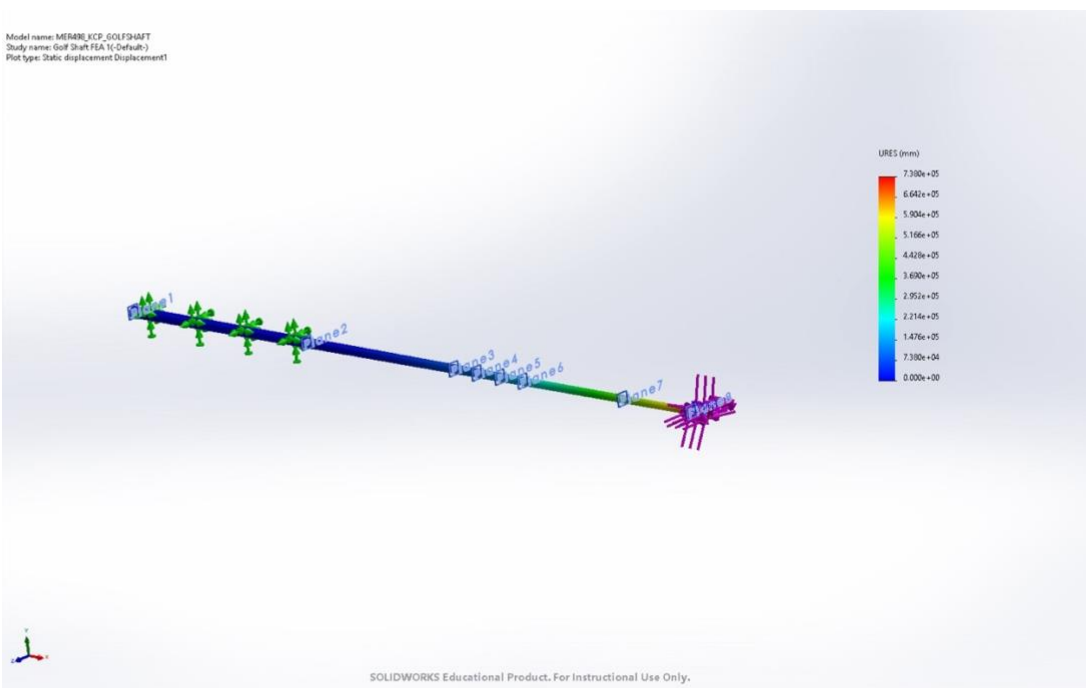

Figure B.1: Deflection plot of the golf shaft as simulated in SolidWorks from an isotropic viewpoint. Highest deflection is found at the tip with a total deflection of approximately 73m.

Table B.2: Tabulated material properties for the FEA analysis shown in Figure C.1.

1st FEA	Young's Modulus, XX	Young's Modulus, YY	Ultimate Tensile Strength, XX	Ultimate Tensile Strength, YY
Material:	32.62 GPa	6.83 GPa	394 MPa	89.4 MPa
Flax Fiber	Poisson's Ratio, XY	Poisson's Ratio, YZ	Shear Modulus, XY	Ultimate Shear Strength, XY
	0.4275	0.3819	4.036 GPa	53.2 MPa

Further changes were made to the model to try to mitigate these discrepancies between the simplified simulation model and its real-life counterpart. Finally, using these changes to resolve issues within the simulation, the FEA was run, with results depicted in Figure B.2. The shaft was found to deflect a simulated 1005m. Material properties for this simulation can be found in Table B.3.

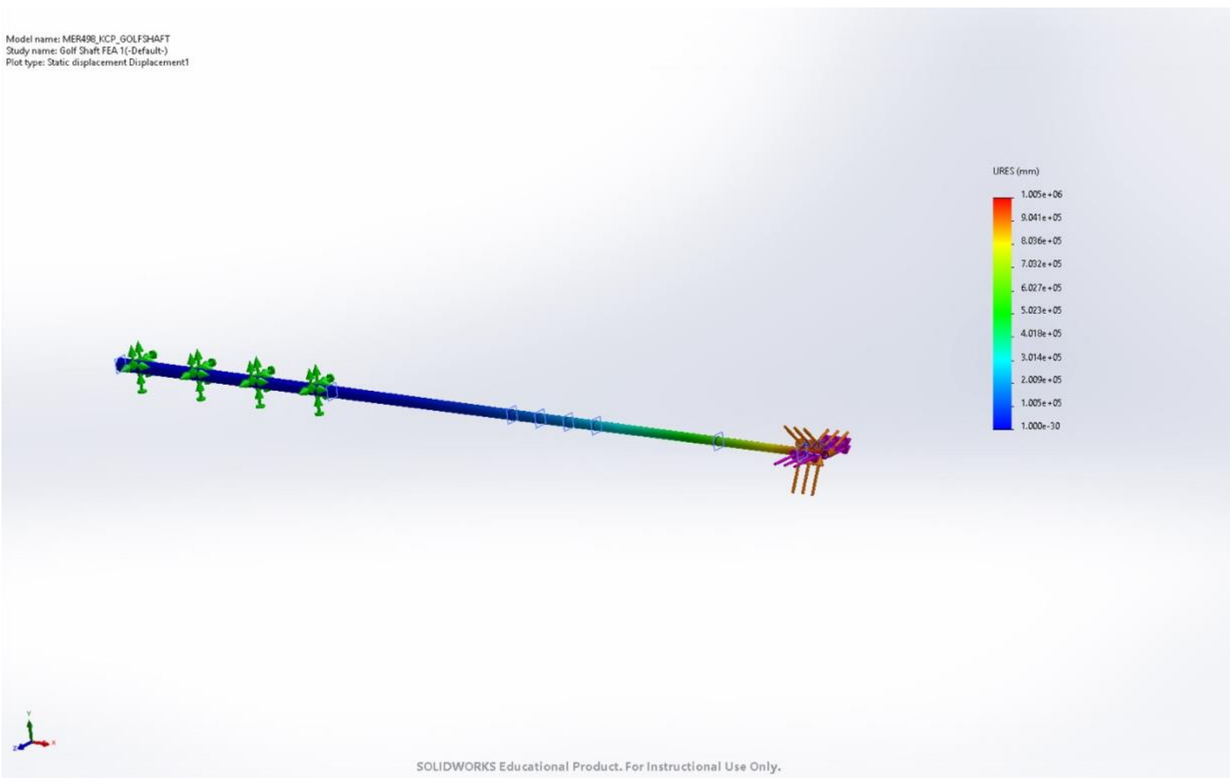

Figure B.2: Deflection plot of the golf shaft as simulated in SolidWorks from a profile viewpoint. Highest deflection is found at the tip with a total deflection of approximately 105m.

Table B.3: Tabulated material properties for the FEA analysis shown in Figure C.2.

2nd FEA				
Material: Flax Fiber	Young's Modulus, XX 25400 N/mm^2	Young's Modulus, YY 6800 N/mm^2	Young's Modulus, ZZ 6800 N/mm^2	Poisson's Ratio, XY 0.36
	Poisson's Ratio, YZ 0.382	Poisson's Ratio, ZZ 0.382	Shear Modulus, XY 2000 N/mm^2	Shear Modulus, YZ 1700 N/mm^2
	Shear Modulus, XZ 2000 N/mm^2	Mass Density 1500 kg/m^2	UTS, XX 255 N/mm^2	UTS, YY 24.8 N/mm^2
	Ultimate Comp. Strength, XX 128 N/mm^2	Ultimate Comp. Strength, YY 85.3 N/mm^2	Ultimate SS, XY 39.3 N/mm^2	Yield Strength 255 N/mm^2
	Thermal Expansion Co., XX -1.2E-6 K^{-1}	Thermal Expansion Co., YY 7.5E-5 K^{-1}	Thermal Expansion Co., ZZ 7.5E-5 K^{-1}	Thermal Conductivity, X 0.1 W/m*K
	Thermal Conductivity, Y 0.1 W/m*K	Thermal Conductivity, Z 0.1 W/m*K	Specific Heat 1386 J/kg*K	Material Damping Ratio 0.2

As shown in Figure B.2, the results from this second FEA were worse than in the first one, for what would appear to be a more robust description of the flax fiber properties. This result was puzzling, yet it emphasizes many of the same trends: approximations in the geometry are responsible for some shortcomings, and the work done to resolve issues with the material properties were still not lining up with the correct coordinate axes. Moreover, loading cases were much too high for the first two FEA analyses – the first two cases used loading of 1350lb_f, much higher than the value of 414N found later in previously published literature, leading to the need for a third study. Before this study was run, loading inputs were changed to 414N and a torque of 1.65N*m, and the material properties were fixed so that the fiber orientations were in line with their correct orientations. In this simulation, the shaft deflected 20m, as shown in Figure B.3. Material properties used for this simulation can be found in Table B.4.

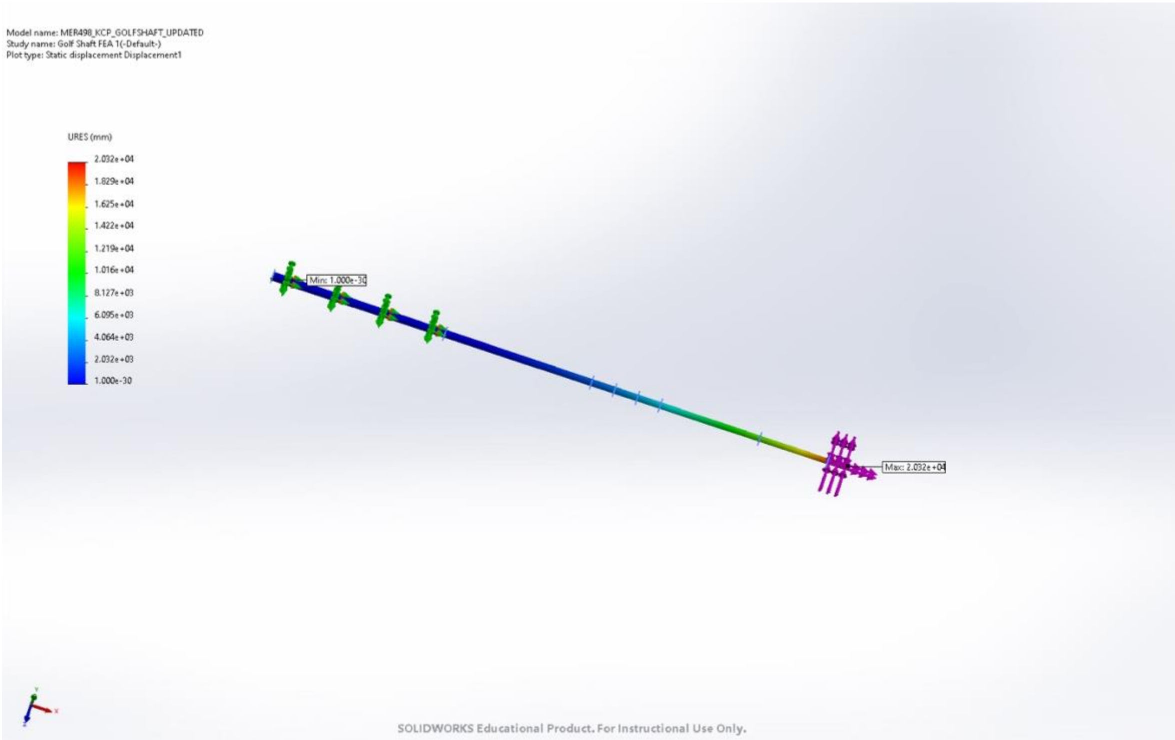

Figure B.3: Deflection plot of the golf shaft as simulated in SolidWorks from a profile viewpoint. Highest deflection is found at the tip with a total deflection of approximately 20m.

Table B.4: Tabulated material properties for the FEA analysis shown in Figure C.2.

3rd FEA	Young's Modulus, XX 6800 N/mm^2	Young's Modulus, YY 25400 N/mm^2	Young's Modulus, ZZ 6800 N/mm^2	Poisson's Ratio, XY 0.0967
Material: Flax Fiber	Poisson's Ratio, YZ 0.36	Poisson's Ratio, ZZ 0.382	Shear Modulus, XY 2000 N/mm^2	Shear Modulus, YZ 2000 N/mm^2
	Shear Modulus, XZ 1700 N/mm^2	Mass Density 1500 kg/m^2	Ultimate Tensile Strength, XX 24.5 N/mm^2	Ultimate Tensile Strength, YY 255 N/mm^2
	Ultimate Comp. Strength, XX 85.3 N/mm^2	Ultimate Comp. Strength, YY 128 N/mm^2	Ultimate Shear Strength, XY 50 N/mm^2	Yield Strength 255 N/mm^2
	Thermal Expansion Co., XX 7.5E-5 K^{-1}	Thermal Expansion Co., YY -1.2E-6 K^{-1}	Thermal Expansion Co., ZZ 7.5E-5 K^{-1}	Thermal Conductivity, X 0.1 W/m*K
	Thermal Conductivity, Y 0.1 W/m*K	Thermal Conductivity, Z 0.1 W/m*K	Specific Heat 2.3 J/kg*K	Material Damping Ratio 0.2

This FEA simulation came much closer to realistic results, which is a sign that this design is rapidly approaching feasibility. While not yet a realistic FEA simulation, as the shaft cannot physically deflect 20m, the progress through each iteration to take a shaft that was deflecting potentially as much as 1005m to one that is only deflecting 20m demonstrates significant progress with the development of the FEA. That said, this approximation is likely not enough to explain away all the deflection, down to a reasonable amount, and the simulation in its current state confirms that this shaft design is essentially exploding on impact. Unfortunately, there was not enough time to complete another design iteration or to try and better approximate the geometry in a new study; It will be impossible to tell until prototyping and testing is complete.

Appendix C: Design Iterations of the Golf Shaft

Throughout the entire design process, a total of 3 complete design iterations were completed, each building off one another to improve the overall results until a successful solution was found. From the specification sheet obtained from Fujikura, the first design was determined through a process of resizing the flags to fit the dimensions of a hybrid golf shaft, before reevaluating each individual flag based on its individual contributions to the design requirements for the hybrid golf shaft. Flags deemed not contributing enough to these design requirements, were redesigned by changing their weave type, fiber orientation, fabric weight, and flag dimensions. The initial design iteration is visually depicted in Figure C.1, and a list of each flag arranged by layering order, containing its center of mass location along the shaft and fiber orientation, can be found in Table C.1.

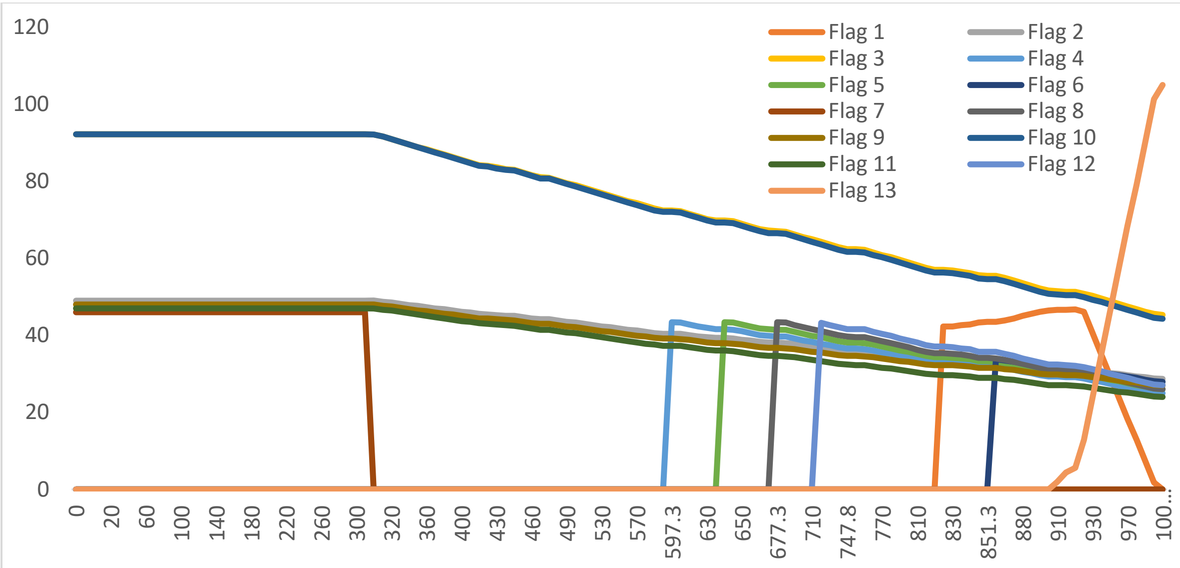

Figure C.1: Visual representation of the shape and location of individual flags in the first iteration of the shaft design.

Table C.1: Specifications of individual flags in the first golf shaft design. Flags are ordered according to their number, with Flag 1 being the outermost flag, and Flag 13 the innermost flag.

Flag #	COM (mm)	Mass (g)	Orientation
1	933.41	1.65	Uni 0º, Heavy
2	456.28	5.04	Uni 0º, Light
3	443.70	26.61	Bi-Axial
4	818.50	3.82	Uni 45º, Heavy
5	835.59	3.49	Uni -45º, Heavy
6	930.16	0.56	Uni 0º, Light
7	150.50	1.66	Uni 0º, Light
8	853.92	3.11	Uni 45º, Heavy
9	453.27	4.89	Uni 0º, Light
10	442.19	26.49	Bi-Axial
11	446.35	4.69	Uni 0º, Light
12	871.40	2.77	Uni -45º, Heavy
13	971.63	1.37	Uni 45º, Heavy

Since the swing weight calculation was the primary design requirement tuned for in this process, and swing weight is a function of the head mass, in addition to the distribution of the mass in the grip and shaft of the club, fluctuations of the club head design had a large impact on the need to try multiple design iterations to satisfy this design constraint. The second design iteration considered these changes in the head mass at the time, as well as began to resolve some of the resulting issues with swing weight and changing regions of the shaft to introduce better adhesion between the layers of fiber. The second design iteration can be found in Figure C.2, and a list of each flag arranged by layering order, containing its center of mass location along the shaft and its fiber orientation, can be found in Table C.2.

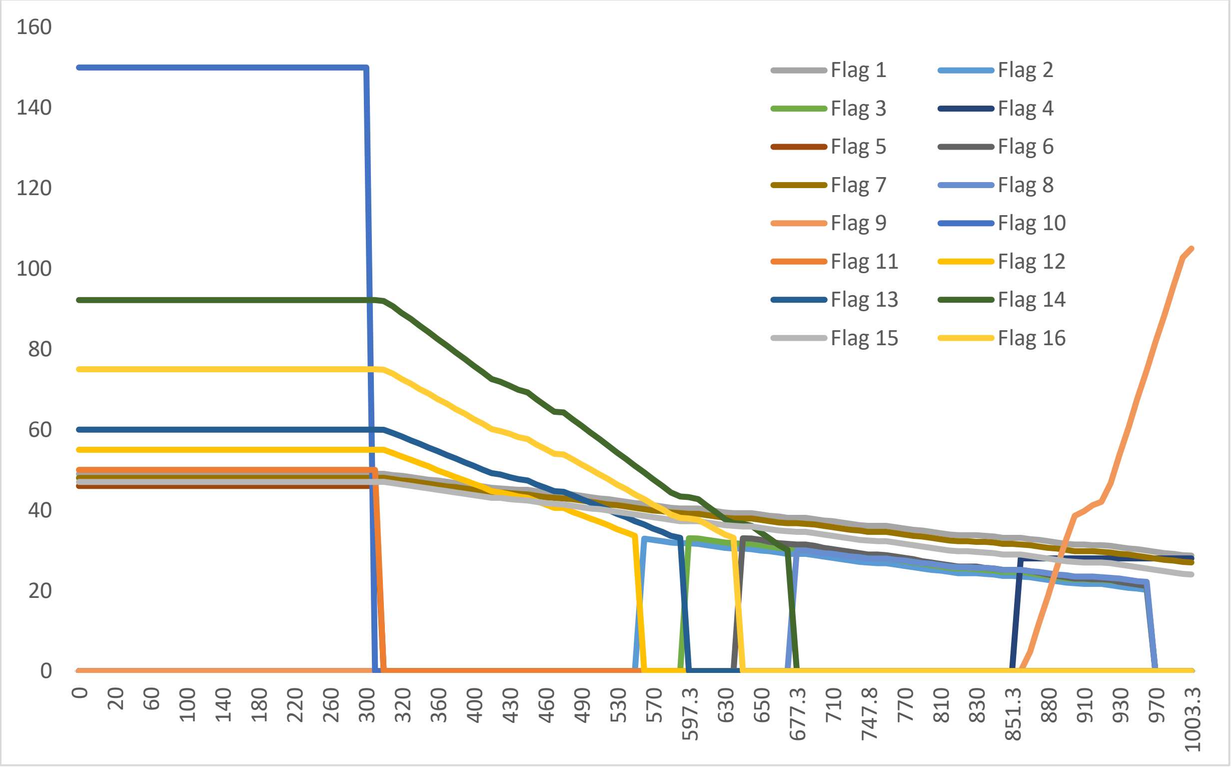

Figure C.2: Visual representation of the shape and location of individual flags in the second iteration of the shaft design.

Table C.2: Specifications of individual flags in the second golf shaft design.

Flag #	COM (mm)	Mass (g)	Orientation
1	456.28	9.25	Uni 0º, Light
2	816.90	2.37	Uni 45º, Light
3	833.86	2.17	Uni -45º, Light
4	927.80	1.48	Bi-Axial
5	150.50	4.85	Bi-Axial
6	852.37	1.94	Uni 45º, Light
7	453.27	8.97	Uni-0º, Light
8	867.63	1.64	Uni -45º, Light
9	953.30	1.73	Uni 45º, Light
10	150.50	4.97	Uni 0º, Light
11	150.50	2.63	Bi-Axial
12	278.65	9.74	Bi-Axial
13	298.65	11.14	Bi-Axial
14	289.48	17.76	Bi-Axial
15	446.35	8.60	Uni 0º, Light
16	282.84	8.96	Uni 0º, Light

Changing masses in the design for a short time forced iteration on a third design, but reversion of this mass back to values much closer to that of the head mass used in the first design iteration made completion of the design iteration unnecessary. Finally, research into commercially available flax fiber weaves revealed that the only type of fiber used would be unidirectional flax fiber sheets. To account for this discovery, each flag that was not unidirectional in the second design was evaluated and replaced with a unidirectional flag whose fiber orientations accounted for the properties of the flag it replaced. In some cases, multiple flags were added to compensate for the properties of the flag they replaced as well, particularly when replacing bi-axial fabrics. This final design iteration can be found in Figure C.3, and a list of each flag arranged by layering order, containing its center of mass location along the shaft and its fiber orientation, can be found in Table C.3.

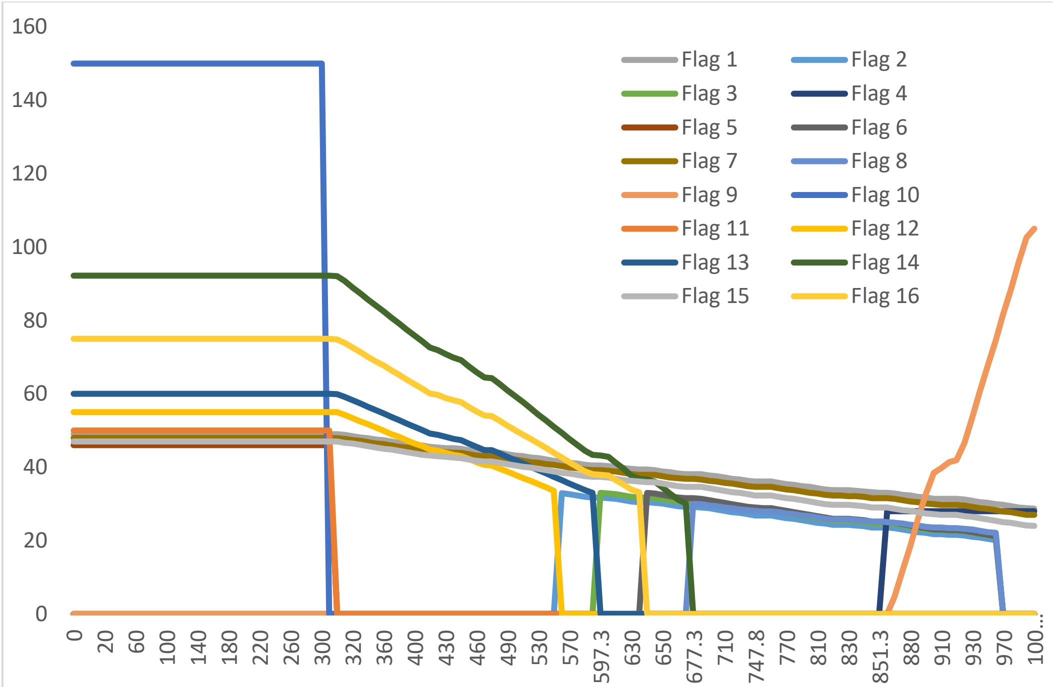

Figure C.3: Visual representation of the shape and location of individual flags in the final iteration of the shaft design.

Table C.3: Specifications of individual flags in the third golf shaft design using unidirectional flags only.

Flag #	COM (mm)	Mass (g)	Orientation
1	953.30	1.73	45º
2	927.80	0.93	90º
3	927.80	0.93	0º
4	867.63	1.64	-45º
5	289.48	11.16	0º
6	456.28	9.25	0º
7	852.37	1.94	45º
8	298.65	7.00	-45º
9	298.65	7.00	90º
10	453.27	8.97	0º
11	833.86	2.17	-45º
12	282.84	8.96	45º
13	282.84	8.96	45º
14	446.35	8.60	0º
15	816.90	2.37	45º
16	278.65	6.12	90º
17	150.50	5.79	0º
18	150.50	5.03	90º