Ski Design for Telemark

(Honors Capstone)

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Introduction

When observing the visitors at any given ski resort, one is most likely to see them doing one of two things: alpine skiing and snowboarding. While it may seem like that is all there is to it, there is a subsection of skiing called telemark skiing which differs by removing any heel attachment and letting it move freely, giving telemark its other name; free-heel. The detached heel allows the skier to perform lunges down the hill with every turn instead of being locked into one ski position like one would be when alpine skiing. Due to the vastly different ski positions between the two methods, forces and stresses placed on skis also vary resulting in differences in resulting ski performance.

Since alpine skiing is the more common method, modern ski design has been optimized for it which leaves telemark skiers trying different things to obtain the same performance. A common method is moving the bindings back which results in the skis being out of balance. Another issue is the different forces imparted on the skis by a telemark turn coupling with the altered binding location from design specifications resulting in an increased likelihood of the binding being torn out of the ski. This issue has reached the point that putting telemark bindings on a ski often voids the warranty provided by the company.

In order to address these issues, a new ski is being designed specifically for telemark skiers. This process starts with doing background research to better understand the nuances of ski design as well as experiments to quantify the differences in forces imparted on a ski when alpine and telemark skiing. Those results along with mechanical engineering knowledge will then be used to inform decisions on the main aspects of ski design which include strength of materials, ski shape, and distribution of core materials throughout the ski.

Background

How Skis Turn

Before any discussion can be done with regards to improving ski design for telemark, one first has to understand what makes a ski turn. While there are two ways to make a ski turn (twisting and carving), this project will be focusing on carving technique as that is where ski design has a significant impact.

To carve on skis one tilts their skis onto their edges to form a rail on which they will slide throughout the turn like is shown in **Figure 1(a)**. Being on the edges along with a skier's body weight pressing down on the middle of the ski will result in the ski's edge forming a curve (**Figure 1(b)**) which is what forces the skis to change direction.

Figure 1(a)(b): (a) shows a skier on their right edges during a right turn. The red line emphasizes the significant amount of ski tilt. (b) shows the curvature of the ski (shown in red) mid turn. [1][2]

Ski Design

<u>Shape</u>

There are two main design considerations when it comes to a ski's shape; a ski's top-down shape and its side profile. A ski's top-down shape has the greatest impact on how a ski turns and **Figure 2(a)** shows how a ski's top-down shape affects the turn radius. The more curvature the ski's sides have and the shorter the effective edge assuming the same ski width result in a shorter turn radius and consequently a tighter turn. While top-down shape is the most important factor in turn shape, it is not something relevant to force and stress distribution so it will not be a major consideration [3].

A skis side profile has more of a supporting role in ski performance by either providing stability to a ski when it is on edge or providing superior floating ability when skiing in powder. **Figure 2(b)** shows the different ski profiles used in modern skis. The technology used to stabilize a ski during a turn is camber and it works by forcing the skier's weight to compress the ski into the proper turn shape, which results in a more even force distribution throughout the ski, which helps the entire ski edge maintain contact with the snow [3]. Traditional camber (also known as full camber), however, is not very good in deep snow which resulted in the creation of rocker which lifts the tips of a ski allowing it to float on the snow's surface. A lot of all-mountain skis now use camber with front and tail rocker to get the benefits of both technologies.

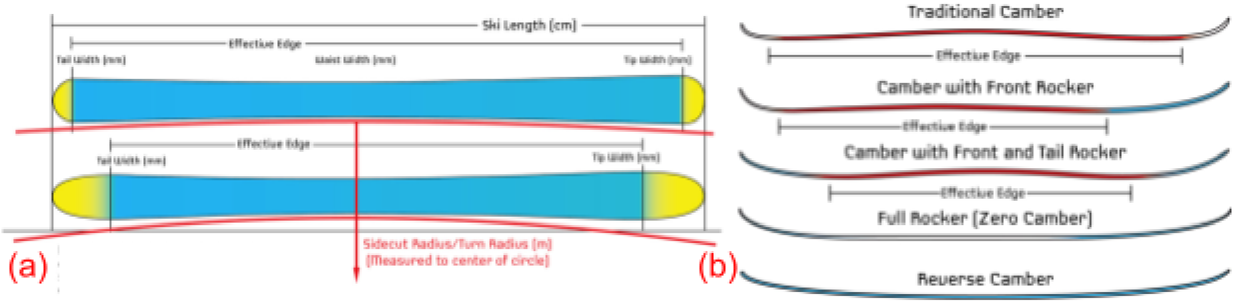

Figure 2(a)(b): (a) shows the difference in turn radius based on the top-down ski shape. A shorter effective edge and larger difference in end and middle ski widths results in a shorter turn radius. (b) shows different ski profiles used in modern skis. [3][4]

Ski Construction

Despite their simple appearance, skis are very complicated when it comes to their construction with many functional layers that allow for a wide range of customizability. They are most commonly broken down into core, structural components, top and bottom sheets, sidewall and edges. A diagram of a common ski is shown in **Figure 3**.

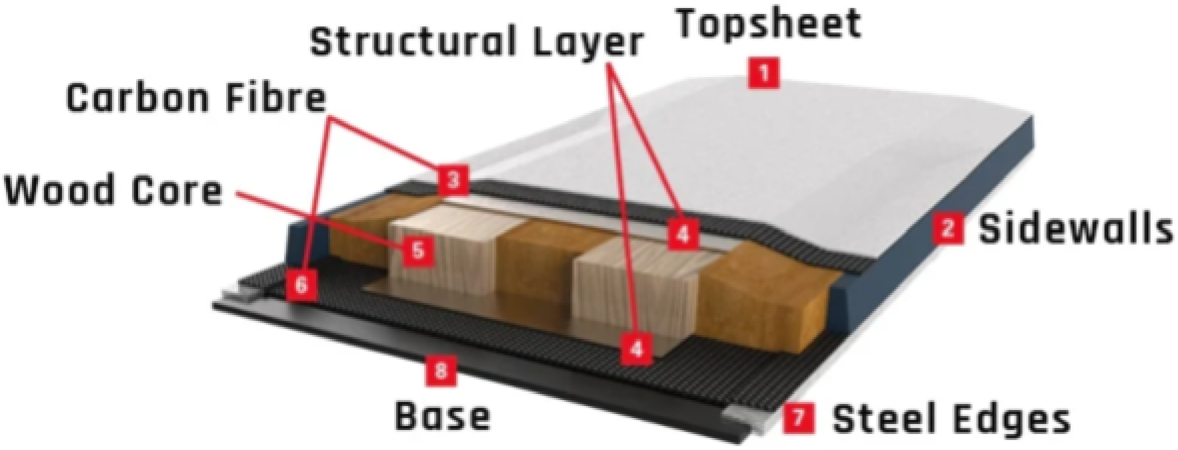

Figure 3: Cross section of a common ski construction with a wooden core, dual structural layer and ABS sidewall construction. [5]

Cores make up the bulk of the ski's construction and are often made of lightweight and flexible materials such as wood and coupled with a structural layer which will be discussed later [5]. Each possible core material has its advantages and disadvantages so most cores end up as a combination to minimize weight and maximize strength.

The structural component of the ski is what couples with the core to provide the skis torsional strength and flexibility. Materials used in these layers include fiberglass, carbon composites, titanium and aluminum. The shape and length of the structural layer coupled with the way the core is made are determining factors in ski performance. As a result, these are going to be major focuses of design towards the end of the project [5].

The top sheet of the ski is a several millimeter thick covering often made out of wood, plastic, nylon or a combination of those materials and has the purpose of protecting the internal components of the ski. The base layer is almost exclusively polyethylene plastic (P-tex) and while there is some variation in strength and speed based on how the base layer is made, it is slight and doesn’t affect the ski’s performance enough to be significant.

Finally there is the sidewall and edges. There are three main ways that sidewall is constructed, however just like with the base material, the differences are marginal at best in terms of ski performance so no research is done in that area. Edges on the other hand are something of interest because they can be optimized to provide control and stability for the ski while keeping ski weight low. An example of this would be an all mountain ski that has a steel edge built into the camber portion while leaving the rocker portions bare.

In the scope of this project, only design specifications that will have a major impact on lateral ski performance will be evaluated. These include camber/rocker designations, core material, structural material, length of structural portions and edge distribution.

Skiing Mechanics

Alpine

To best understand the problem with current ski design, it is important to be familiar with telemark skiing mechanics and how they differ from those used in alpine skiing. For this to be possible, a rudimentary understanding of alpine skiing mechanics must be established.

The side view of proper alpine skiing form is shown in **Figure 4(a)** where legs are parallel and a relatively even weight distribution is placed on each ski.

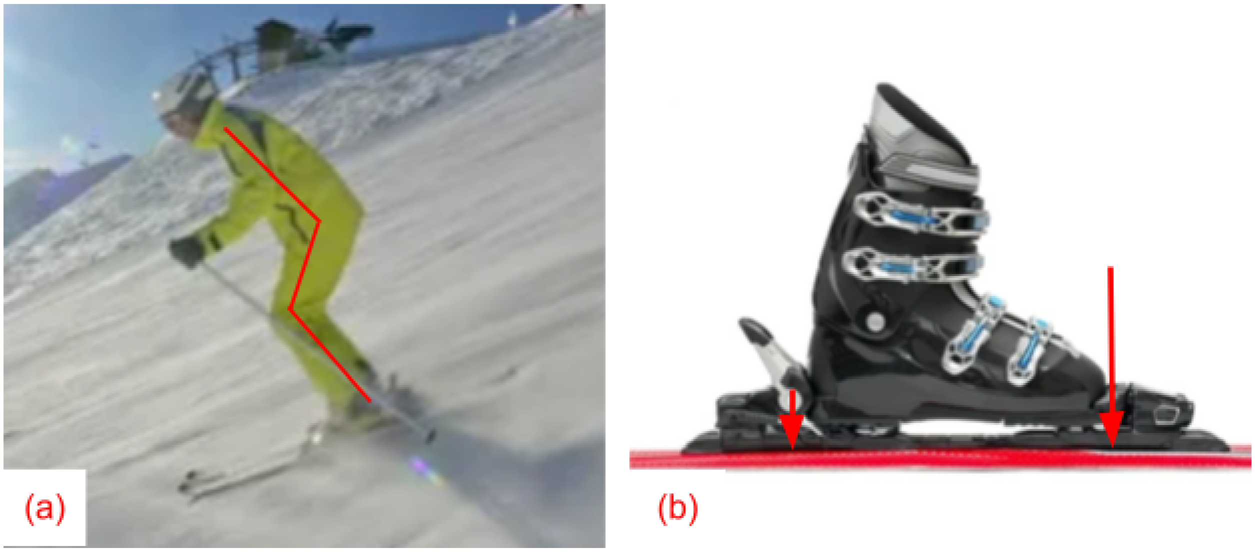

Figure 4(a)(b): (a) shows the side view of proper alpine skiing form. There is pressure placed on the front of the boot while still maintaining center of mass directly over the bindings. (b) shows forces placed on the ski by an alpine binding while in use. All forces are pushing down but more at the front. [6][7]

The goal when alpine skiing is to press one's shins into the front of the boot while maintaining center of gravity over the boot center. This position allows for the most efficient bending of the ski to create the curved rail as described in the section on how skis turn. One major aspect of alpine skiing is that a skier can control how aggressively they lean into the front of their boot; the harder they lean, the more force that transfers into the ski which further bends the ski resulting in a tighter turn. As is illustrated in **Figure 4(b)**, this results in relatively balanced down forces at the ends of the binding with the distance between them resulting in a smooth ski flex.

Telemark

The most noticeable difference between alpine and telemark skiing is the position in which the skier is during a turn which resembles a lunge demonstrated in **Figure 5(a)**.

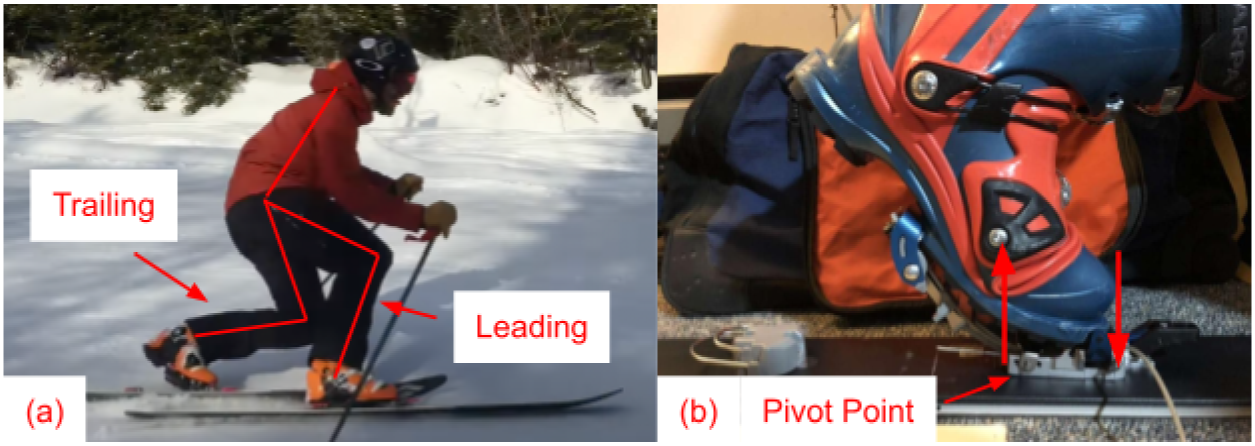

Figure 5(a)(b): (a) shows the side view of a left telemark turn. The leading leg maintains a similar position as when alpine skiing while the trailing leg drops into a lunge position. (b) shows the forces imparted on the ski by the binding with the opposing forces on opposite ends of the binding with the twisting motion creating a moment. [8]

The leading leg maintains the same position and has the same function as when performing an alpine turn. The difference is that the heel is not attached to the back of the binding and as a result, the force pushed forward by the skier is lower to ensure the heel stays on the binding and there is no pulling force at the back of the binding. Because of these differences, the forces imparted on the ski by the leading leg are lower resulting in less ski flex and consequently a larger turn radius.

The biggest difference comes from the trailing leg. Looking at **Figure 5(b)**, the contact area between the binding and the ski is much smaller than in an alpine binding. Another difference is that the heel coming up results in a bending moment around the front portion of the binding. All of this combines to create greater magnitude forces around the front binding portion of the ski which contributes to the phenomenon of telemark bindings being torn out of the ski. Another issue caused by this force distribution is that often the pulling force at the back of the front end of the binding makes the back of the ski lift off of the ground which eliminates a portion of the curving rail on which a skier carves on and creates instability. This is an issue because the trailing leg is a very important balance point when skiing but the lack of stability makes skiers not trust it and consequently push the majority of their weight on the front leg which further diminishes performance.

Methods

Research

A major component of getting the ski design underway was research into various ski parameters which included ski shape, materials, internal construction shape and length of internal components. General research included looking at informational websites, reports and patents related to current ski designs as well as studying currently available products. Using this method, information on ski shape, materials of construction and general layering was gathered.

More detailed information like internal dimensions was something that was unable to be obtained using general research. To get this information, acquaintances in the ski industry were contacted. From them, information on the thickness of ski layers and distribution of structural materials was gathered.

Force Measurements

One important set of information needed to start designing and testing any skis was gathering real-life force information. This was done using self made apparatus in combination with a high strength tension scale and a bathroom scale. While the best and most accurate measurements would be obtained using a pressure pad, this was not possible as getting one would cost a large amount of money and no department had one large enough for this purpose.

Spring Force Measurements

The first force of interest was the force from the boot needed to push the binding into a full lunge position. This was done using the high strength tension scale. Images of the force measurement set up are shown in **Figure 6**.

Figure 6: Shown is the apparatus used to find the force needed to flex the binding into the lunge position. Full lunge position has a nearly parallel to the ground shin.

The hook attachment for the scale was used and was attached to the top strap of the boot while the other end of the scale had grips screwed in. To measure the force, the scale was pushed forward and down to simulate what the shin would do while the back of the ski was not held down to simulate real life conditions. The reason the back being allowed to come up is accurate is because often when a skier compresses hard into a turn, the back of the ski lifts up, keeping the full force from being transferred into the ski. Had the back of the ski been held down, it would have caused artificially high force measurements.This was done several times to make sure that force measurements were accurate and precise.

Pressure Measurements

The second set of forces of interest was pressure forces along the length of the ski. This was done to understand what force downward the binding is causing at the front and that allows for a complete modeling using Finite Element Analysis (FEA). Without access to a pressure pad, a unique apparatus was developed and is shown in **Figure 7**.

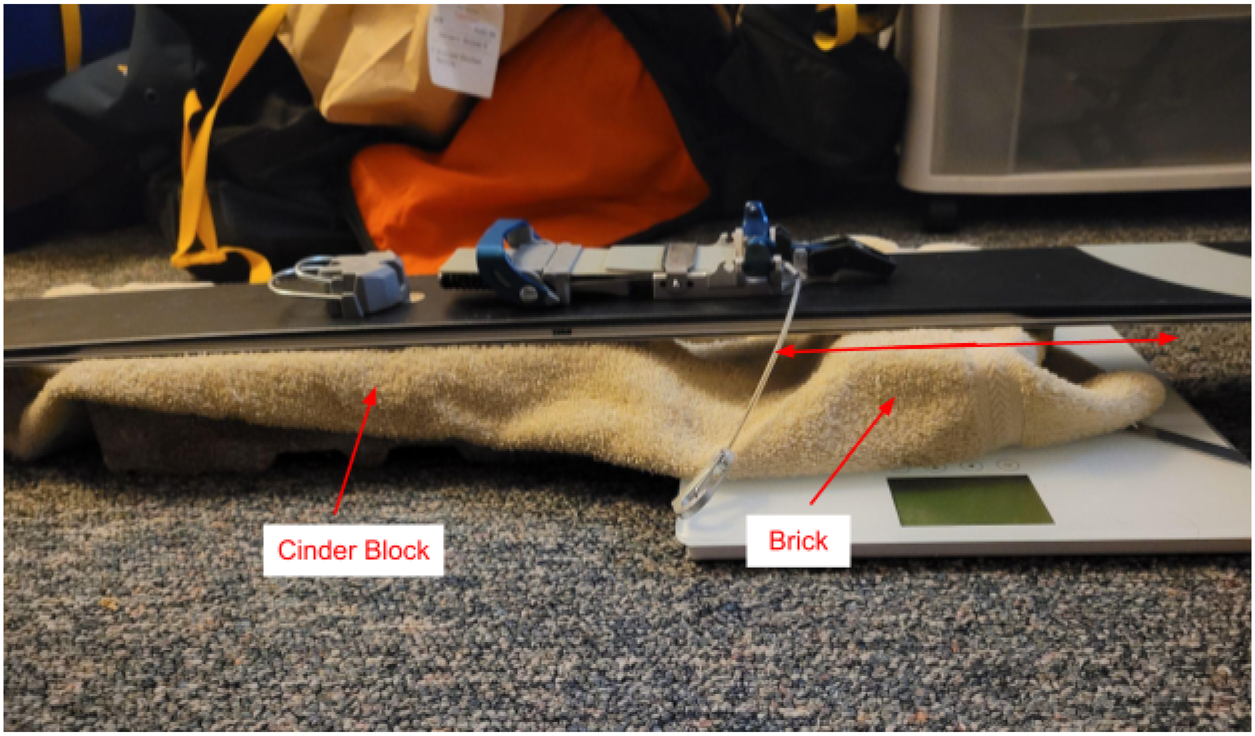

Figure 7: Apparatus used to obtain pressure measurements along the length of the ski. The front brick and scale were moved to get unique forces.

The force measuring tool was a basic bathroom scale. The original apparatus design was with the ski directly on the scale. To ensure an accurate force measurement, a board was placed behind the scale to make sure the ski was supported in front and behind the scale and was parallel to the ground which would mimic a regular skiing environment. An issue with that design, however, was that the ski pressing on the edges of the scale kept it from registering.

To account for this problem, a brick was placed between the ski and the scale. The brick was small enough that its entire surface fit within the scale perimeter so the weight on the scale was placed just as if someone was standing on it. Since the brick raised the front of the ski quite drastically, a cinder block was used behind the scale instead of the board to again make the ski parallel with the ground. A blanket was wrapped around the brick and the block to protect the scale and the ski base.

To collect the data itself, the skier would clip into the binding and get into two positions and get the forces imparted for each. The first was in an alpine position which was a relaxed but athletic standing position. To ensure an equal force distribution between feet, the skier was required to wear boots on both feet and stood on a cinder block placed right next to the measured ski. The other position was in the telemark lunge.

Specifically, the force was measured for the trailing leg as the leading leg is well modeled by the alpine position.

All of the force measurements were taken at various points of the ski, however based on discussion, only the forces at the front of the ski were measured as that was all that was needed for a complete FEA model.

CAD Modeling

All of the CAD modeling was done in SolidWorks. The first step in CAD modeling was to make a basic shape that further designs would be based off of. This was done as a single part and single material for the sake of simplicity. The general ski shape was based off of the ski that over the years has proven to be a good telemark ski; the Armada JJ. To make the CAD model accurate, various measurements were made along the length, width and thickness of the ski.

In terms of the ski's width, three points were measured; the nose, boot center and tail maximum widths. Along the length of the ski, the values measured were the distance from the tip of the ski to the front of the camber, from the front of the camber to boot center, from boot center to the back of the camber and from the back of the camber to the back tip of the ski. This would allow for a highly detailed side profile model. The ski thickness was measured at the same points mentioned above.

The initial attempt to model the ski was making rectangular sketches in consecutive planes that represented the sections measured along the length of the ski. These sketches would then be connected with a guideline and a lofted surface would be made. This plan failed, however, because the surface was unable to be filled in and the ski was hollow due to constraints in using the lofted surface function.

The next and successful attempt involved making a sketch of the ski's side profile using the gathered measurements and then making an extruded boss. This shape would then have multiple extruded cuts in the top plane to match the top/down shape of the ski along with filets to smooth the curves. Once the basic ski was modeled, several variations were made testing several parameter changes which will be discussed in *Ski Design Optimization*.

Once the ski optimization was completed, the final CAD model was made by segmenting the chosen basic model. First the edges and sidewall of the ski were removed and saved as a part using extruded cuts. The same was done for the base, top layer and structural layer leaving the ski core which was also saved. All of these parts were then transferred to an assembly, mated and materials were designated for each part. The result was the ski shape of choice along with proper measurements and materials for the ski's internals.

Finite Element Analysis

Finite element analysis was performed on several variations of ski design made in SolidWorks. In terms of defining materials, since FEA can get incredibly complicated if one introduces multiple materials and composites, each ski was modeled with self made properties. These included material parameters like the young's modulus. In an effort to be as accurate as possible, the parameters used were a weighted average of the material properties for the core and structural layer, with an emphasis on the core due to that being a majority of the ski's construction.

In order to make a FEA work, forces and boundary conditions are needed. The two forces used in the FEA analysis were the force pushing down at the front of the binding and the moment created by the pull on the pivot point. These represent the major forces imparted on the ski as there are no forces at the back of the ending like there would be in a model for an alpine turn. The boundary conditions used were a fixing at the front and back of the ski's camber. These two points were used because they are the main firm contact points with the snow and the curvature of the ski in a carve is bent around those two points. Once the scenario was run, stress and displacement profiles were collected.

Ski Design Optimization

The first thing that was optimized was the materials used in constructing the ski along with the design of the ski's internals. This optimization was based on inherent material properties along with general statics principles regarding ski cross-section shape. The other parameter that was optimized was the side profile shape of the ski to maximize the efficacy of the camber. The top-down shape was ignored for the most part as that has a smaller effect on the stress and displacement distribution in the ski.

Results

Force Values

The force values taken from all of the trials are summarized in **Table 1**.

Table 1: Table showing 4 trials of force measurements for each location and scenario.

Trial #	Spring Force Telemark (lbf)	Under Front Telemark (lbf)	Under Front Alpine (lbf)
1	106	173	79
2	105	191	84
3	103	188	86
4	108	190	81
Average	**105.5**	**185.5**	**82.5**

Compared to the unflexed front force, the flexed front force is drastically higher which matches with predictions discussed in the background section. In addition to the higher downward force at the front of the binding, there is substantial force acting on the pivot point for the binding which contributes to the ski's moment.

Materials of Choice

In terms of materials, the two ski segments that were adjusted for their inherent properties were the core and the structural layer. The top sheet and side walls were designated as nylon as it is a common topsheet material and is good at keeping moisture out of the rest of the ski. The base was the traditional choice of p-tex (a type of polyethylene) and the edges were steel to provide a firm outer layer of protection while being workable in terms of sharpening.

The core material that ended up being chosen was maple wood due to its multi directional strength and vibration dampening properties. One of the design constraints was making a ski that would not be prone to having the bindings tear out which is what kept bamboo from being the final choice despite it being the most common core material on the market. Maple wood has multidirectional strength so not only would it be strong in the skis length direction as a core but also hold in binding screws firmly. Telemark skiing is also prone to a lot of ski vibration due to some portions of the ski not having high loads so using a material with high vibration dampening was very important.

The structural material chosen was aluminum due to its flexible strength while being relatively lightweight. This differs from the carbon fiber and fiberglass structural layers that are commonly used in newer skis for the same reason as the core material; for multi directional strength. Fibers are strong in a plane but would be weak to the forces of a binding screw being torn out which is something that aluminum would be good at preventing. The additional weight of the aluminum is something that cannot be ignored and will be addressed in the ski shape.

Ski Shape

There are two main points of the ski shape that were adjusted and those were the core shape/distribution and the ski's side profile. While the core optimizations had to do with both ski turn performance and ski integrity, the side profile was optimized exclusively for deformation and stress distribution.

The cross section of the middle of the ski shows the general design of the ski core and is shown in **Figure 8**.

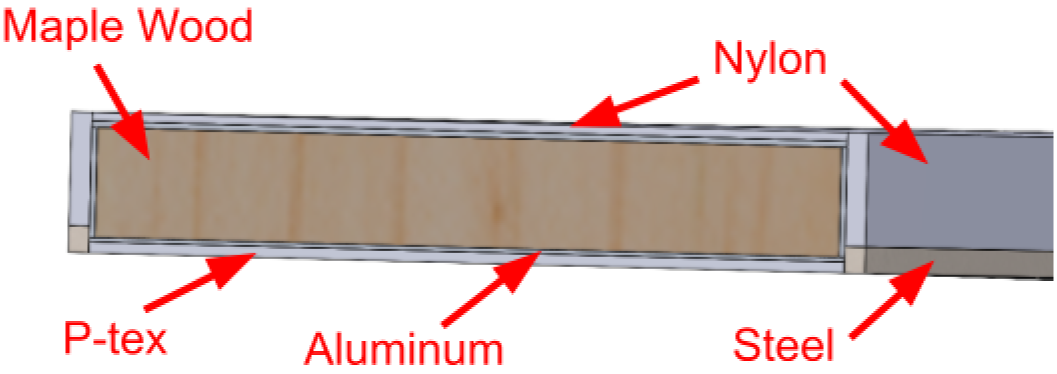

Figure 8: The ski cross section at the boot center of the ski. The topsheed and sidewall are made from nylon, the edges are steel, the base in p-tex, the core is maple wood and the structural layer is a boxed aluminum.

The big difference between a traditional ski core is the thickness of the aluminum layer and the shape of the aluminum layer. While most structural layers are approximately 1-1.5 mm thick, the aluminum above is 3 mm thick. This helps a lot with strength around the binding area and prevents the ski from over flexing and the binding from tearing out. Another difference is that while most structural layers are flat layers along the length of the ski, this layer is a rectangular tube around core material giving it additional flex resistance and strength due to the box column being stronger. All of these changes result in an increased amount of aluminum which means an increase of weight. To compensate for that, the structural layer only covers the length of the ski's camber which differs from most designs where the structural layer covers the entire length of the ski. While this might bring about concern about the stability of the tips of the skis, the steel edges were left to loop all the way around to replace that support.

The other shape consideration was the ski's side profile which is shown in **Figure 9**.

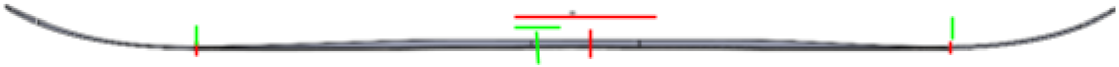

Figure 9: The red vertical lines show the camber ends and camber peak for a traditional alpine ski and the red horizontal line represents where an alpine binding would be. The green vertical lines show the camberends and camber peak for the optimized design and the green horizontal line shows where the front portion of the telemark binding would be.

What ended up being the optimal ski shape in terms of displacement distribution was a ski with the same camber end points but an adjusted camber peak point. Looking at the alpine peak with the telemark binding, the front of the binding and high force would be acting on the downward portion of the camber which reduces its efficacy at distributing stress. However, if the camber peak is moved up, the skier is now pressing down on the top of the camber and getting the best use out of it. Another benefit of moving the camber peak up while keeping the camber points at the same spot is that now the ski gets higher force tolerance at the front due to a shorter "lever" and better snow contact with the back of the ski due to a greater bend towards the snow at the back. After testing this design in FEA, the displacement distribution was shown as in **Figure 10**. The smooth and even distribution indicates success compared to condensed and aggressive distributions for previous designs.

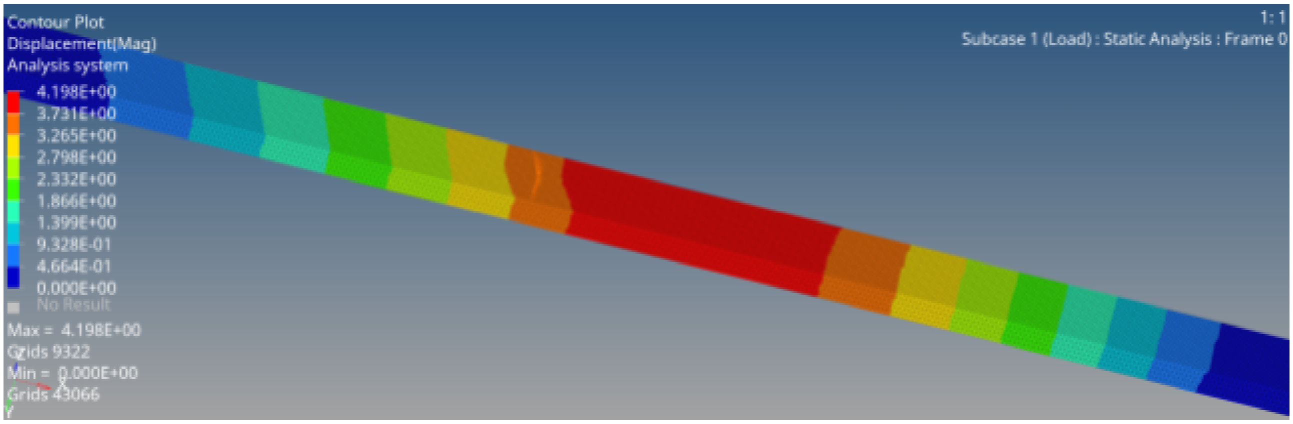

Figure 10: The displacement profile for the optimized ski. It is very even on both ends without any drastic changes. The segment shown is from the two camber endpoints.

Conclusion

At the end of the project, a lot of successful work was done in determining materials of construction and ski shape. That being said, there are several other things that would be good to look into. The first would be more variations in the structural layer's shape as the cross sectional shape of a beam has an impact on the stresses in the beam. Another spot of interest would be gaining more real life forces. Due to the lack of a pressure pad, the forces gathered were limited and gathering those additional forces would help with making more accurate models and getting a better idea of what is going on in the ski. Finally, more in depth analysis could be done in FEA. Due to limited expertise it was hard to get as much out of the software as possible but with more time, more in depth analysis could be performed on each model.

In terms of next steps, once a more flushed out ski design is made, Freeheel Life and Shaggy's ski companies would be interested in a potential prototype. With a prototype in hand, more real life measurements could be done and more work could be done to optimize the ski and if things go well, start production of the first ever telemark specific engineered ski.

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