Design of a Hybrid Ski Touring Binding System

A Major Qualifying Project
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Abstract

The goal of this project was to provide a solution to the ski binding industry that allows for the interchangeability between an alpine resort-style ski binding and an uphill touring-style ski binding. This binding system aims to satisfy two use cases: (1) the ability to ascend and descend on an uphill touring-style ski binding, and (2) the ability to ascend on an uphill touring-tyle ski binding and descend on an alpine resort-style ski binding. As a result of researching current market options and ways to create a better ski binding, our team designed a ski binding plate system which was prototyped using 3D printed PLA and manufactured from aluminum. The initial PLA prototype was lab tested to better understand how it would react under applied loads and the final aluminum model was mounted to skis and tested on snow. The result of this project was the production of a usable binding system that performed well and accurately addressed the desired use cases. This binding system showed promise and leaves the possibility for future iterations and use in the consumer market.

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Glossary

Uphill/Ascent: refers to traveling uphill via the use of ski touring bindings

Descent: refers the ski downhill via the use of touring bindings or alpine bindings

Alpine/Resort Skiing: refers to skiing downhill in resorts

Alpine Bindings: bindings that feature toe and heel pieces that have standardized release mechanisms used solely for descent

Demo Binding: A type of alpine bindings that feature adjustable plates under the heel and toe piece so bindings can be resized to different user's boots

Ski Touring: refers to uphill travel on ski as well as ski descents

Backcountry Skiing: refers to ski touring out of boundaries of ski resorts

Touring/Tech Bindings: bindings that allow for walking uphill and skiing downhill that do not have standardized release mechanisms; usually function using pins

Hybrid Bindings: ski bindings that feature the use of a tech style toe and alpine style heel piece

50/50 Bindings: ski bindings that feature uphill and downhill modes and are designed to performed equally in the resort and backcountry

Low-tech (bindings): basic bindings use for ski touring that do not have a standardized release mechanism; usually function using pins

Frame Bindings: A type of touring bindings that feature an alpine binding mounted to a plate that releases at the heel and allows for pivot from the toe so the user can walk and ascend

Telemark Skiing: a form of skiing in which the user's heel is permanently free to move about the fixed toe; allows element of alpine and ski touring to be combined

Stack height: how high a binding sits off the ski, in relation to the boot placement to the surface of the ski

Elastic Travel/Elasticity: the distance a binding can move before the boot releases

Anti-Friction Device (AFD): a pate that slides laterally via a spring, or low friction materials to control the motion of the boot relative to the ski

Suspension: how well a ski and binding absorb impacts and smooth the ride; dictated through a binding's suspension and stack height

Ramp: the angle the of a ski boot in a binding in relation of the toe position to the heel

Upward Ramp: the toe sits higher than the heel

Downward Ramp: the toe sits lower than the heel

Inadvertent Release: when a binding release prematurely when forces are not injurious

DIN (Deutsches Institut für Normung, German Institute of Standardization): an industry wide scale of release force for ski bindings

ISO (International Standards Organization): a set of standards defining ski boot and binding compatibility

I. Introduction

Backcountry ski touring is a discipline of skiing that has gained popularity in recent years. The increased interest in the sport has led to a rapidly growing gear market with constant technological advancement in the tools used for this activity. Ski bindings on the market today offer a range of features that specifically target the needs of users who ski in the resort or the backcountry. Current market options do well to address these needs in the different disciplines of the sport. Specific bindings excel for use inbounds in a resort, for short touring laps, or for long backcountry tours. As avid skiers with extensive experience with different ski bindings, our team noticed a gap in the current binding market. There is no option that can serve a skier in all disciplines of skiing without any compromise.

When assessing this gap, we started by researching and comparing the current binding options available for use today. From this assessment, we created specific functional needs for our design which helped inform our choices throughout the design process. From our research and experience, we wanted our design to prioritize a modular binding system that would offer skiers one pair of skis that could be used for all disciplines of skiing. The binding system needed to have lightweight technology for uphill and downhill access in the backcountry. The system also needed to excel for standard use in the ski resort. This project aims to create a ski binding system that successfully combines these use cases.

The overall goal of this project is to provide a solution to the ski binding industry that allows for the interchangeability between an alpine resort style ski binding and an uphill touring style ski binding. This binding will satisfy two use cases: the ability to ascend and descend on a touring binding, and second the ability to ascend on a touring binding and descend on an alpine binding.

1.0 Tech Report

1.1 Background Research

1.1.1 Disciplines of Skiing

The sport of skiing has three main divisions: alpine, Nordic, and ski touring. The two divisions of skiing that form the crossroads for this project are alpine (resort) and ski touring (backcountry skiing).

1.1.1.1 Alpine

Today, alpine skiing is characterized by releasable ski bindings, which differ from the original leather boots and bindings used in the early days of modern skiing. These bindings were first introduced in 1952 by Cubco and have since seen immense improvement and modernization. Today, we are left with a handful of market leaders and some smaller companies rounding out the industry. The sport has been further developed with introductions of skis made with metals, plastics, fiberglass, and composites, in addition to wood. These materials have been coupled with creative shaping of ski side cut and rocker profile to reach the level of ski performance that is seen in today's market. Furthermore, the sport has been made more accessible to a broader range of people through development of a greater number of ski resorts and the introduction of chair lifts. These improvements have allowed for greater uphill lift capacity to get more skiers on the mountain at once (Fry, 2017).

1.1.1.2 Ski Touring

The origins of ski touring can be traced back to the development of telemark skiing in Telemark, Norway when Sondre Norheim innovated on the binding of his boot to his ski through winding material over his toe and around the heel of his boot. This binding design allowed for the ability to climb uphill with the skis attached to the user's foot due to the free heel and pivot point at the toe. In 1890, one of the earliest ski touring expeditions was undertaken in the Swiss Alps and similar ski explorations grew in popularity throughout the early 1900s (Martinescu-Bădălan & Stănciulescu, 2019). The act of ski touring or backcountry skiing began to take its form as an alternative to lift and mechanized access downhill skiing. The goal of backcountry skiing developed to encompass accessing more distant terrain through human power. The progression in the sport of backcountry skiing would not be possible without the continued and rapid development of ski touring equipment. The skiing industry began to see the first development of touring specific bindings in the late 1950s with continued development throughout the remainder of the 20th century and now into the 21st century. The development has ranged from cable bindings with a hinge at the toe that resembled telemark bindings to "low-tech" bindings that use pins to secure the skier's boot to the ski. Touring bindings have been further developed and now there is a host of hybrid bindings available that allow for superior downhill performance and acceptable uphill performance (Wild Snow, 2020).

There are a significant number of skiers that find themselves at the intersection of these two sects of the sport and enjoy both skiing laps at the resort and touring up magnificent mountains in the backcountry. To understand the reasoning for this project, it is also important to understand the history and differences of these two divisions as well as the technical differences between the equipment. While significant steps have been made to improve upon the safety of alpine ski bindings, the touring industry still lags in its adherence to modern day safety standards. Although in recent years, steps have been made to improve the safety performance, there is still headway to be made.

1.1.2 General Safety Standards

The first modern heel-and-toe binding for alpine skiing was the Cubco binding, first introduced in 1952, but not popularized until the 1960s (Wolfgang, 2002). With the Cubco binding, the toe of the skier's boot could release in all directions including up; and the heel could release in a forward fall. This binding revolutionized the industry. Bindings released in the 1960s had challenges because boots were not standardized so a binding that worked well on one boot might be dangerous on another (Masia, 2003).

A binding's ability to release at the proper moment is imperative to minimizing injury. General safety standards are followed by manufacturers and ski technicians to ensure a binding's safety and consistency in the field. The International Organization for Standardization (ISO) provides the requirements, specifications, and guidelines that ensure international consistency of goods and products (Dawson, 2014). Deutsches Institut für Normung (German Institute for Standardization, DIN) develops norms and standards for rationalization, quality assurance, and safety. DIN standards provide a universal set of numbers that serve as release values for bindings. Ski technicians set the DIN for individual skiers to provide a safer performing binding. DIN values are found in both the toe and heel portions of the binding and a higher DIN value means that more force needs to be applied to the binding before it releases. A lower setting, meanwhile, will release at a much lighter pressure.

1.1.3 Parts of an Alpine Ski Binding and Basic Binding Functionality

Bindings play an important role for skiers because they provide the user control over their movement due through the transfers of inputs into the skis. Bindings are designed to detach from the skier's boots before injury occurs but stay on during non-injurious events. Figure 1 shows the components of a modern ski binding.

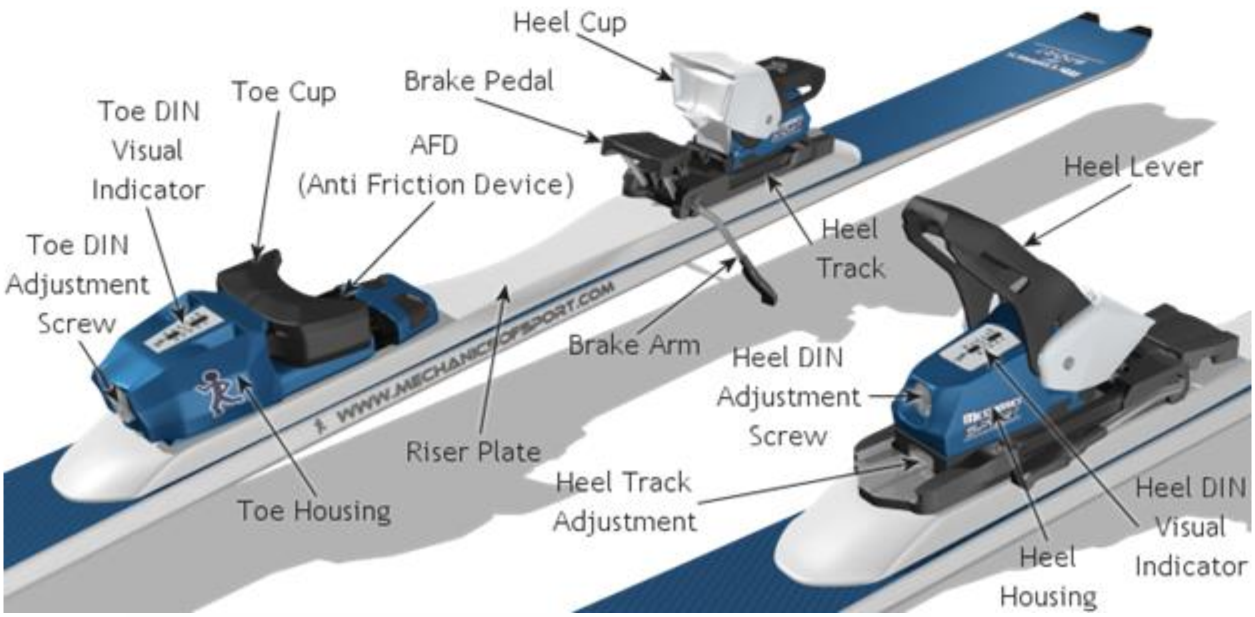


Figure 1: Components and Features of an Alpine Ski Binding (Guisado, 2016)

Bindings are designed to let the toe and heel of the boot move within them to an extent before they release. This provides a certain amount of shock absorption and minimizes inadvertent release (Guisado, 2016). Ski bindings are built to dampen vibrations through the materials they are constructed out of, but some use more elaborate damping systems often contained in the riser plate.

1.1.3.1 Alpine Bindings

The global market for alpine ski bindings is competitive and features regional and global companies that have created a strong market competition. These companies significantly bolster market growth with their strategic collaborations, new product launches, and technological innovations. The bindings that these manufacturers sell range in ability and function. Modern bindings keep the skier locked in even when skiing fast and aggressively through rough snow (Guisado, 2016). These bindings properly function to release smoothly in the event of a crash, protecting skiers from the twisting forces that can lead to injuries (Guisado, 2016).

1.1.3.2 Touring Bindings

Touring bindings have two different modes, one for walking up and one for skiing down. When ascending, the heel of the boot is not attached to the ski and the binding pivots at the toe. When skiing down, the toe and heel are held as normal. There are several different systems that touring bindings can use, some of which work with normal ski boots. As touring bindings are intended for going uphill, they are often made to be as light as possible, which makes them less strong and durable than alpine bindings.

1.1.3.2.1 Frame Bindings

A frame ski touring binding is the closest type of touring binding to an alpine binding. They consist of a front stop and an alpine ski heel retainer mounted on a plate. The system works by having a plate that locks during the downhill skiing phase and unlocks during the touring phase.

This allows the skier's movements to follow the natural movement of the foot and allow for comfortable ascent. Frame bindings are visually like regular alpine bindings as the toe and heel pieces are very much the same as their alpine counterparts. The user steps into frame bindings in the exact same way as an alpine binding. The 'frame' that connects the toe and heel releases so the skier can 'walk' while clipped into the binding. On the downhill, frame bindings ski very similarly to normal alpine bindings. Frame bindings only have one heel riser, limiting what terrain is accessible on the ascent. The heavy weight of frame bindings and alpine boots make this option unideal in the backcountry. Figure 2 shows how a frame binding is used.

Figure 2: Functionality of Frame Bindings (*REI*, 2019)

1.1.3.2.2 Tech (Full Pin) Bindings

Full pin (tech) bindings are a lightweight and effective option for backcountry skiers. They have two steel pins on the toe that snap into special receptacles in the tip of the shoe, the so-called pin inserts. Pin toes are available in combination with different heel mechanisms: downhill-oriented alpine heels (e.g. Marker Kingpin) with better power transmission, or lighter pin heels (e.g. Marker Alpinist). In pin bindings, the toes are close to the point of rotation and the boot tilts forward more directly, allowing the skier to walk much more naturally uphill. An example of a full pin binding, the Marker Alpinist 12 is shown in figure 3.

Figure 3: Marker Alpinist 12 (Backcountry Skiing Canada, 2020)

Many experienced skiers want a binding that allows for aggressive skiing while maintaining the low weight of a tech binding (Cripple Creek, 2019). Companies like Marker and Fritschi spearheaded the hybrid movement by developing bindings with a pin toe and alpine heel. The pin toe allows for the same walkability that a tech binding offers, while the frame heel keeps the ski boot locked in more effectively.

New binding technology has evolved in recent years to offer skiers options that are marketed to be used reliably in the resort and backcountry. These bindings advertise “the security and power of an alpine binding with the touring capability of a backcountry set-up” (Salomon, 2020). Figure 4 shows the Salomon Shift, a 50/50 binding, and figure 5, shows the variety of touring compatible bindings on the market today.

Figure 4: Salomon Shift in Use (*Outdoor Gear Lab,* 2020*)*

Figure 5: Ski Bindings for Uphill Travel (Outdoor Gear Exchange, 2020)

1.1.4 Physics of Skiing

Ski bindings must withstand a variety of different forces while providing optimal performance. Downhill performance can be improved with greater power transmission, elastic travel, suspension, and safety release mechanisms. The purpose of this project is to optimize the performance of 50/50 ski bindings, which requires an understanding of the forces acting on a skier when skiing downhill, specifically the forces that cause a binding to release. The two categories of forces experienced when skiing are internal forces and external forces. Internal forces are the forces created by the skier from internal movements. External forces consist of gravity, friction, and reaction forces from the snow; these forces act upon a skier and must be managed by the ski, binding system, and the skier.

1.1.4.1 Forces on a Binding

Internal forces are generated by the skier and are applied through different movements. These forces are generated and controlled by the legs, core, and shoulders. As skiers turn and carve their way down the mountain centripetal forces, centrifugal forces, drag (wind resistance), and friction act against them. When skiing, the skier's center of gravity must be inside the base of support so the skier can balance against these forces to maintain control.

The external forces acting when skiing are gravity, friction, and reaction forces. Gravity acts downwards and accelerates the skier, while friction, drag, and reaction forces act against the skier. Figure 6 below displays these forces and a free-body diagram.

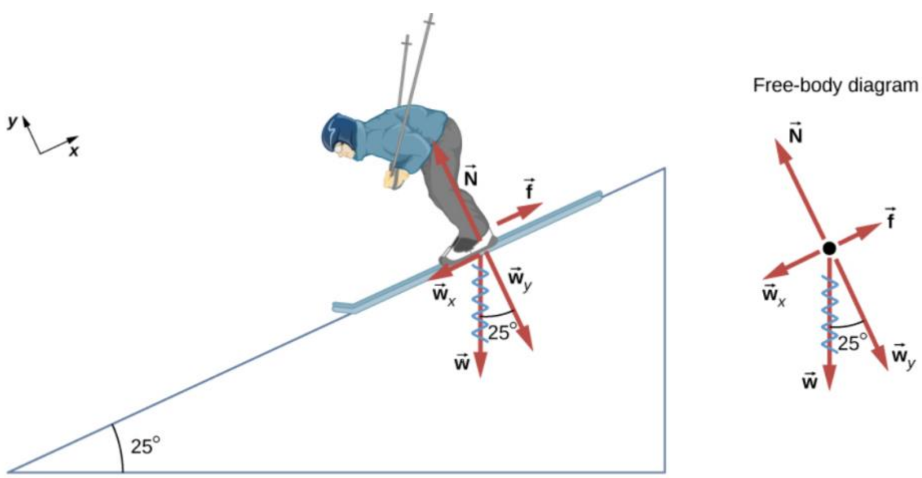


Figure 6: Forces Acting on a Skier Along the Slope (*The Physics of Downhill Skiing Group Activity*, n.d.)

There are two components of gravity acting on a skier due to the angle of the slope. One component is parallel to the slope that pulls the skier into motion, the other is perpendicular to the slope that keeps the skier in contact with the slope.

As a skier accelerates downhill from gravity, friction from the surface and air (wind resistance, drag) act against the skier. Skiers must balance the force of gravity, surface friction, wind resistance, and deflection from the terrain or other bodies and obstacles.

Since many binding releases are caused from lateral forces, the forces acting on a skier in a turn must be understood. To initiate a turn, the skier must interact with the snow and use the snow to push oneself into a turn; if the direction of an external force is to the right, the skier will turn to the right. The force the skier puts into the snow is equal and opposite to the force the snow returns to the skier. Snow conditions greatly impact how well a ski holds in the snow and the forces returned to the ski and skier. Freshly groomed hardpack grips and responds very well, while powder and ice offer much less hold and response. The ability for a ski to hold in the snow will influence the balance of forces and therefore influence the force and tension on a binding, dictating when it will release.

Additionally, when a ski is pushed into a turn and onto its edge, the ski bends from the forces acting on it. The force from the skier pushing into the center of the ski and the force from the snow pushing against the tip and tail of the ski cause the ski to flex and bow upwards. Bindings must be able to withstand this flex both structurally and functionally. This also puts a great forward force on the binding. The binding must not be uprooted or loosened from its mount during flexion, and the flexion and forward force must not cause the binding to inadvertently release.

1.1.5 Mechanics of Bindings

When a binding releases, it is due to lateral or forward force applied against the ski that overcomes the tension of the binding holding the boot in place. When a skier is maneuvering and turning down the mountain, and their center of gravity falls too far inside or outside the base of support, balance is lost, and the skier can lose control. If all control is lost and the force of the skier falling opposes the forces against the ski, a lateral release will occur from the large twisting force put on the ski and binding system. Similarly, if the center of gravity of the skier moves too far forwards and leans over the front of the ski in a harsh manner, the force applied to the binding can cause an upward release. There are a multitude of different falling mechanisms and force interactions that can cause binding releases in different situations and circumstances, but they are often caused by large lateral forces and/or large forward forces. Figures 7 and 8 show the forces that cause an alpine binding and tech binding to release, respectively.

Figure 7: Different Perspectives of Forces that Cause an Alpine Binding to Release

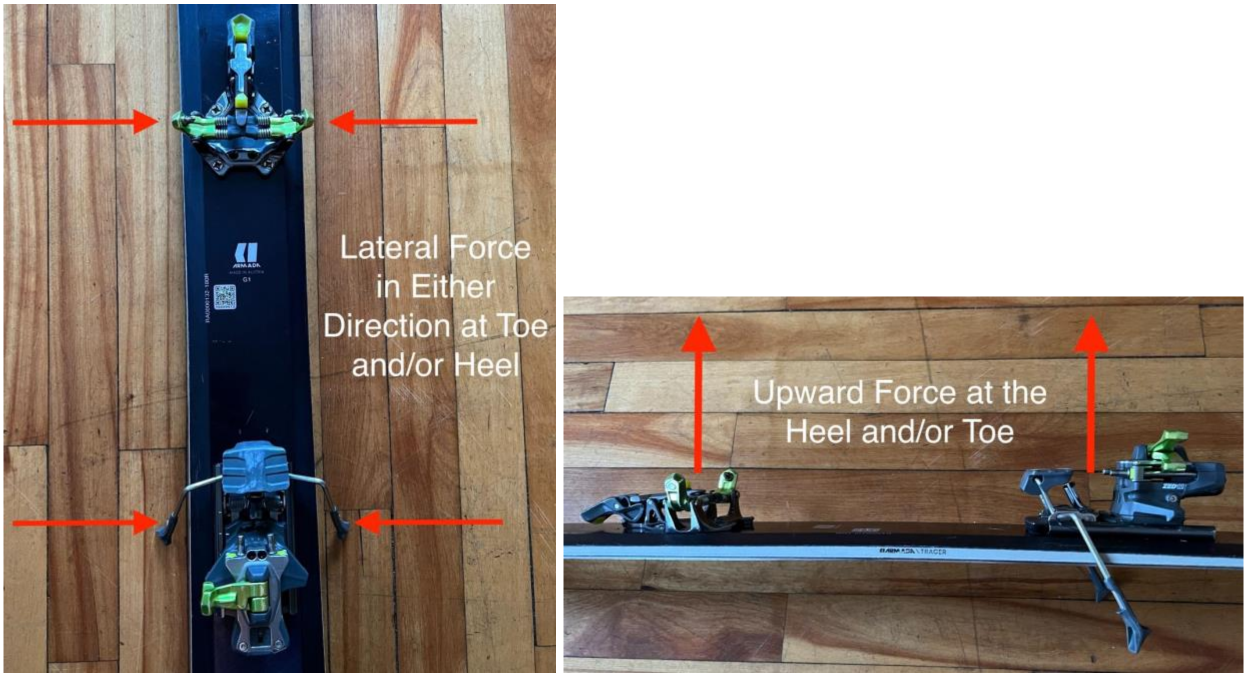


Figure 8: Different Perspectives of Forces that Cause a Tech Binding to Release

1.1.5.1 Binding Retention Systems

The retention system in alpine bindings functions via forward pressure, while the retention system in touring bindings functions via clamping the toe and heel with pins. The toe and heel piece work together to safely secure the boot to the ski and transfer and filter the appropriate loads.

The most important aspect of a binding is elastic travel. Elastic travel, which defines the binding ability to retain or release the skier, is the distance a binding can move before the boot releases from the binding (Olson, 2014). The higher the elastic travel, the more a binding can move before releasing. Elastic travel is coupled with a binding spring to determine the force it takes to displace the binding (Olson, 2014). Another component of bindings is release value, which is the measurement of the amount of spring preload, which is the amount of force required to initially move the binding. Release value is measured in different ways, most commonly using a DIN certification. (Olson, 2014).

Binding retention is determined by finding the proper balance of elasticity and release value (aka spring preload). A binding with low elasticity will require a higher release value to account for lower travel and prevent inadvertent release. The compromise with this combination is a greater chance of injury. On the other hand, a binding with high elasticity will allow the binding to be set to a lower release value; The increased travel allows the skier more time to recover from an awkward situation before the binding releases, and therefore the spring preload does not need to be set to a higher value (Olson, 2014). The latter combination is preferred because it allows the skier more time to recover but does not require a high load to release from the binding is an unrecoverable situation.

1.1.5.2 Alpine Binding Mechanics

The toe and heel pieces of alpine bindings are designed and built to maximize downhill performance and prevent injuries. The main purpose of the toe piece is to provide suspension and allow the boot to release, while the main purpose of the heel piece is to secure the boot in the binding. The toe piece features an anti-friction device (AFD) that slides laterally via a spring, or low friction materials. The AFD plate controls the motion of the boot relative to the ski and allows the boot to smoothly move laterally during a release (Olson, 2014). This piece helps to increase the "suspension" of the binding and offers a smoother ride, without compromising on control. The heel piece of an alpine binding exerts both forward and downward force into the heel of the boot to secure it. The forward pressure dictates the pressure of the boot into the toe piece and allows the heel piece to clear during a twisting fall. The downward pressure controls the release of the boot during a forward fall (Olson, 2014). The combination of these forces, shown in figure 9, exerted by the heel piece work to remove free play in the boot and manage releasability.

Figure 9: Clamping Mechanism of an Alpine Binding

1.1.5.3 Tech Binding Mechanics

Most tech bindings rigidly connect the toe of the boot to the toe piece of the binding to allow for uphill use. Due to this rigid connection, tech bindings typically feature only a few millimeters of elastic travel. The connection is often a metal-to-metal connection, meaning the binding transmits feedback to the skier and the ride is less smooth than an alpine binding (Olson, 2014). Due to the low elasticity in these bindings, a high release value is often used to combat minimal travel and prevent inadvertent releases. Unlike alpine heels, there is no downward or forward pressure in a tech heel; it only provides upward resistance (Olson, 2014). Therefore, for the binding to release, the upward force must exceed the retention spring enough for the heel insert to clear and release. The reason there is no forward pressure from a tech heel is because there is a ~5.5mm gap between the heel of a boot and the binding itself. The components are not under spring tension, and the pins and heel inserts can move freely relative to one another (Olson, 2014). The forces present in a full tech binding are shown in figure 10. The power transfer of a tech binding lacks considerably when compared to an alpine binding, although this can often be forgiven as they serve two functions and are usually skied less aggressively.

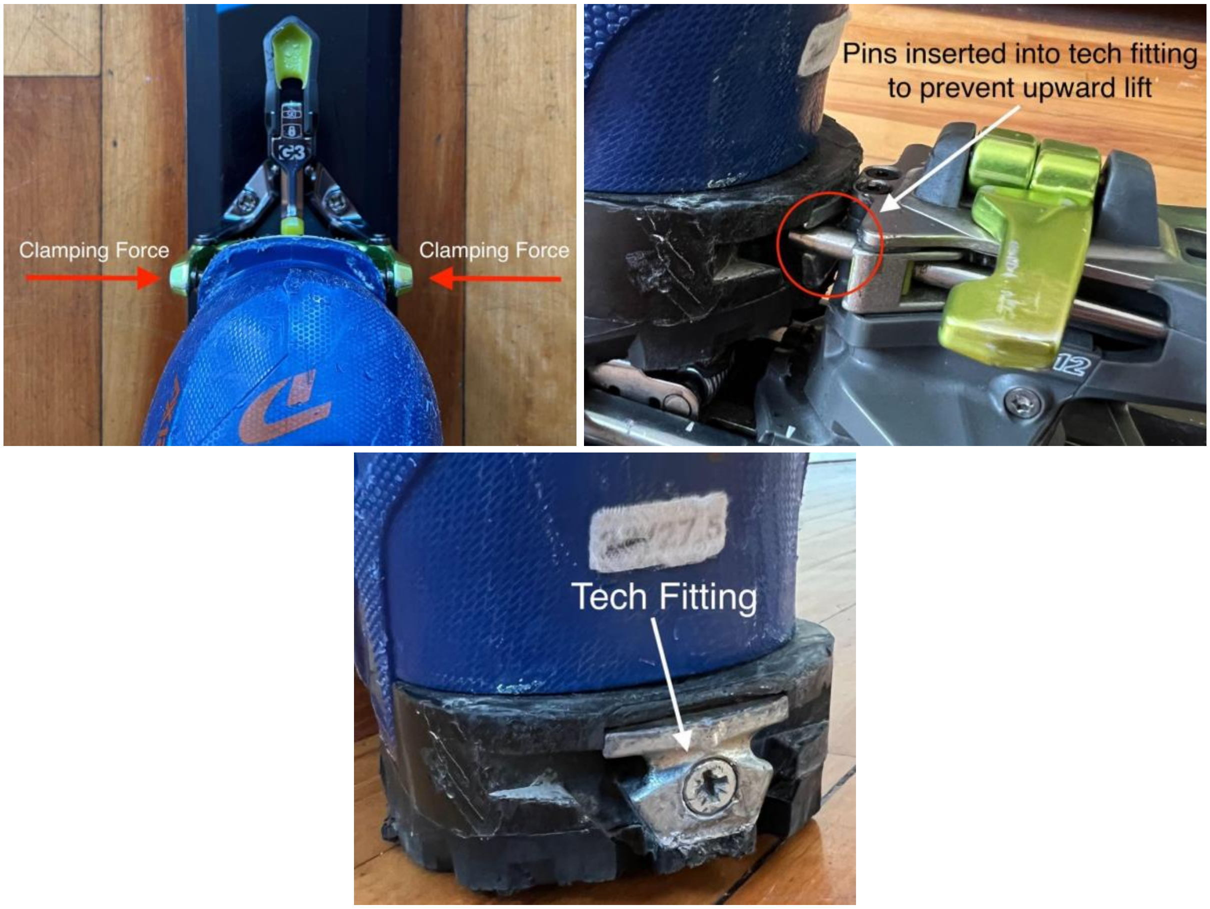


Figure 10: Different Views of Clamping Mechanism of a Tech Binding

It is unfair to compare the downhill performance of a tech binding to an alpine binding; although it serves as a good marker as most skiers understand the feel and performance of an alpine binding. Technology has advanced to a point where many tech bindings offer good downhill performance in a variety of conditions, but still require concentration and a more active ski style. Additionally, conditions tech bindings are optimized for snow that often provide a natural damper and suspension to the skier. However, once you cross inbounds into firm, wind-scathed, refrozen snow, an alpine binding is the best option because of the built-in suspension.

1.1.6 State-of-the-Art

The current options on the market cover a wide range of desired usage styles, but there are deficiencies in performance and safety with these options. For the purpose of this project, there are five touring bindings currently at the top of the hybrid ski touring binding market that form the basis of features that our binding system will seek to synthesize.

1. Fritschi Tecton 12
2. Marker Kingpin 13
3. Salomon Shift 13
4. Marker Duke PT 16
5. C.A.S.T. Freetour System

The below sections offer a summary of the performance and safety characteristics of the above bindings.

1.1.6.1 Fritschi Tecton 12

The first binding that we seek to analyze is the Fritschi Tecton 12, which can be seen below in figure 11. The Tecton features an alpine style heel piece and a tech toe. The toe piece of the Tecton provides a lateral release function, lateral elasticity of 13 mm, and a DIN setting ability. The heel piece also provides lateral and vertical release along with 9 mm of vertical elasticity and a DIN setting. Furthermore, the alpine style heel provides a larger contact patch with the skier's boot. This allows for much better power transfer than tech heel pieces that only contact the skier's boot through pins. The Tecton allows for a maximum DIN setting of 12 and a minimum of 5 at the toe and heel. For uphill use, the Tecton features climbing risers of 9° and 13° and an on-ski weight of 680 grams (g) per binding with brakes attached (Fritschi Swiss Bindings, n.d.). These characteristics depict a binding that performs well on long uphill climbs due to its versatile climbing risers and light weight when compared to other competitors. The binding also provides the user with ample downhill performance for backcountry skiing due to its toe and heel elasticities and DIN setting along with the alpine style heel. Despite this, due to the tech toe, it is still an unideal option for resort skiing due to the wide variety of snow conditions found in the resort and the propensity to get ridden harder and with more frequency (Blister Review, 2017).

Figure 11: Fritschi Tecton 12 (Fritschi Swiss Bindings, n.d.)

1.1.6.2 Marker Kingpin 13

In addition to the Tecton, Marker has its own hybrid binding known as the Kingpin. The two bindings perform similarly and offer the consumer competing options (Marker, n.d.). Like the Tetcon, the Kingpin features an Alpine style heel piece and a tech toe. Unlike the Tecton, the Kingpin does not provide a lateral release function at the toe, nor does it have lateral elasticity at the toe. It also does not have a DIN setting at the toe, only at the heel. Due to the relatively wide mounting pattern of the toe piece, it provides better power transfer than other touring bindings on the market. The Kingpin heel piece does provide vertical elasticity, although numbers were not available from the manufacturer. The heel piece, like the Tecton provides ample power transfer due to the large contact patch and allows a maximum DIN setting of 13. For uphill purposes, the Kingpin provides risers of 7° and 13°, and the binding comes in at a weight of 775 g per binding with brake attached (Marker, n.d.). As seen from the similarities in specifications, the Kingpin and Tecton both remain good options for high performance ski touring but would not hold up well to resort use.

1.1.6.3 Salomon Shift 13

The Salomon Shift 13 was the first binding to reach the market that sought to combine alpine touring ability with true downhill performance and ISO/DIN certifications at the heel and the toe. Since then, the Marker Duke PT 16 has emerged as a direct competitor. The Duke seeks to solve the same problem, but through a mechanism that features an interchangeable toe piece (Blister Review, 2021). The Shift works through a mechanism that transforms the toe piece from a toe piece with pins and the ability to provide uphill functionality to an alpine style toe that functions similarly to a traditional alpine binding. The toe piece of the Shift provides lateral release, DIN setting, and an ample 47 mm of lateral elasticity. This elasticity far exceeds that of the Tecton or Kingpin and exceeds that of many alpine bindings on the market. The heel piece of the shift is a lightened version of what is seen on most alpine bindings. It features a larger contact patch, which improves performance over tech bindings, DIN setting, vertical release, and vertical elasticity of 9 mm, which meets that of the Tecton. The Shift allows a maximum DIN setting of 13. During uphill use, the Shift features a single 10° climbing riser and a weight of 886g per binding (Salomon, n.d.). From personal experience and word of mouth in the ski community, there is consensus that the Shift performs very closely to most alpine bindings when skiing downhill and climbs comparatively to bindings such as the Tecton and Kingpin. On longer and more technical backcountry tours, the heavier weight and single climbing riser can affect a skier's experience negatively in the backcountry. Furthermore, some skiers have had issues with inadvertent releases when skiing with the Shift.

1.1.6.4 Marker Duke PT 16

The Marker Duke PT 16 falls under the same category of bindings as the Shift in that they both attempt to provide the skier with alpine-level performance on the downhill and ample touring ability. The Duke came as Marker's response to the Shift, but it differs largely in its functionality. The Duke has a removable toe piece, which means that during uphill use, the alpine style toe cover is removed and stowed in a backpack and what is left is a tech toe. The heel piece of the bindings always remains on the ski. The user cannot ski down on the tech toe, so the alpine toe piece must always be kept with the user. This functionality provides downhill use on par with top-of-the-line alpine bindings. Unfortunately, its complications, due to the necessity to always carry and use the alpine toe piece, may not be appealing to backcountry skiers who prioritize simple and light weight equipment for longer tours. The Duke toe and heel each provide a maximum DIN setting of 16 and lateral and vertical elasticities and release functions respectively. Unfortunately, elasticity values are not available although it can be assumed that they are comparable to the Marker Jester 16 values of 30mm and 16mm at the toe and heel respectively. The Duke provides better downhill performance than any of the above bindings due to the lack of compromise that was achievable due to its interchangeable toe piece design. During uphill use, the Duke features a single 10° climbing riser and an uphill weight of 1050g. This puts the weight far above that of the Tecton or Kingpin and the single riser means that it is limited in its uphill performance (Blister Review, 2021).

1.1.6.5 C.A.S.T. Freetour System

The C.A.S.T. Freetour System seeks to combine true alpine performance with touring ability much like the Shift and the Duke. Below, an image (Figure 12) of the C.A.S.T. system can be seen. The C.A.S.T. seeks to solve the problem in a similar fashion to the Duke with a modular toe piece and subsequently suffers from many of the same deficiencies. The C.AS.T. combines a Look Pivot 18 with an in-house made tech toe and riser system. The toe and heel pieces of the C.A.S.T. feature a DIN setting to 18, respective lateral and vertical elasticities of 40mm and 28mm, and lateral and vertical release functions. During uphill use, the C.A.S.T. has risers of 8° and 12.5° and an uphill weight of about 1000 g. In summary, the C.A.S.T. provides great downhill performance due to the alpine toe and heel pieces while also allowing for uphill use that is serviceable. The risers improve the performance, but the heavy weight of 1000 g still acts as an anchor during uphill usage (Blister Review, 2021).

Figure 12: C.A.S.T. Freetour System with Tech Toe in Back and Alpine Toe in Front (Mikko Rapeli, 2021)

A summary of this comparison can be seen below in table 1.

Table 1: State of the Art Comparison Matrix

	Marker Kingpin 13	Fritschi Tecton 12	Salomon Shift 13	Marker Duke 16	C.A.S.T. Freetour
Features					
Tech Toe	X	X	X	X	X
Multiple Touring Risers	X	X			X
ISO/DIN Certified Toe		X	X	X	X
Transformable Toe			X	X	
Interchangeable Toe					X
Uphill Weight	775 g	680 g	886 g	1050 g	995 g
Use Cases					
Downhill Tech Toe Use	X	X			
Downhill Alpine Toe Use			X	X	X
Score	3/8	4/8	4/8	4/8	5/8

1.1.7 Rationale

The extreme technological evolution of ski bindings over the past 70 years has allowed skiers to push the boundaries of the sport. We believe that our design has the capacity to continue this advancement and offer the industry a binding system that currently does not exist. To understand why this design is an invaluable product for the market, it is important to recognize the mindset that skiers bring to the binding selection process. Resort skiing and backcountry skiing differ considerably. The amount of exercise and effort is different, exposure to elements is often different, the access to help in the case of serious injury in consequential terrain differs, and for these reasons the performance of a ski and binding vary in the backcountry versus in the resort.

1.1.7.1 Ethos of Alpine and Ski Touring

In the resort, the weight of a binding has a minimal effect on the skier's performance. This fact can be the opposite in the backcountry. Backcountry skiers often spend long days ascending through wilderness for miles just to reach the base of the line they aim to ski. A 1984 study from the U.S. Army Research Institute states that it takes 4.7 to 6.4 times as much energy to move at a given pace when weight is carried on the shoe versus on the torso (Shaul, 2015). This sentiment holds true in backcountry skiing and is the reason why backcountry skiers prioritize lightweight gear. Many factors of backcountry skiing make it very physically challenging, the weight of one's skis and safety gear, weather and snow conditions, the gradient of incline, etc. Current lightweight touring bindings on the market today are less robust than resort bindings and therefore have a higher likelihood for inadvertent release. Backcountry skiers will prioritize weight thereby forgoing some safety and performance factors.

When shopping for gear, skiers have many options to fit their individual needs and styles. The desire for lightweight bindings is a main factor that backcountry skiers bring into the purchasing process. It is understood that for most backcountry tours, it is safe and viable to use a lightweight full pin binding to cut weight on the ascent. For the other portion of backcountry skiing, users do want a safer and more robust binding for challenging terrain. It is difficult to justify spending more money and additional weight on a new ski and binding setup for these circumstances. For these reasons, the hole in the consumer market has left space for new innovations to serve dual purposes to address these challenges.

1.1.7.2 Target Customer and Consumer Benefits

Our target customer is an avid skier equally interested in skiing in the resort and backcountry and looking to make an initial investment or reduce their collection of skis. This customer wants to be able to climb and ski technical terrain in the backcountry and ski laps in the resort on big, committing lines, all without paying thousands of dollars for several sets of equipment. Our target customer is one who may not have the funds to build a multi-ski quiver or the time or schedule to be able to ski more than several times a year, thus not needing several pairs of skis, but still wants to be able to tour and ride resorts. However, this product will also benefit skiers who do have a large ski quiver who are aiming to either consolidate or want to be able to ride their favorite ski both inbounds and in the backcountry.

Skiing is an expensive sport and hobby that has become more costly in recent years. While some people have both the time and money to acquire a large quiver of skis for different scenarios, many people do not have that luxury. Historically, those interested in both resort skiing and ski touring would have to purchase two pairs of skis, two pairs of bindings, and potentially two pairs of boots. New skis can cost upwards of $750 or more, new boots $600 or more, and new bindings $500 or more. This does not even include the additional equipment costs such as ski passes, outerwear, helmets, poles, climbing skins and safety equipment and classes such as avalanche training, beacons, probes, shovels, and packs. These costs add up quickly and pose huge barriers to many people.

Recently, some ski binding manufacturers have begun producing hybrid and 50/50 alpine-touring bindings that aim to serve as an option for backcountry and resort use. However, these products have shortcomings that either limit their ability in the backcountry or limit their ability in the resort. Our product would better serve as a true 50/50 option by improving on technical touring features, interchangeability, user-interface, and providing a certified alpine toe.

1.2 Design and Modeling

The goal of this project is to provide a solution to the ski binding industry that allows for the interchangeability between an alpine resort style and uphill touring ski binding. The system will utilize a single alpine style heel piece and allow for two interchangeable toe pieces that are both compatible with the heel piece. One toe piece will allow for backcountry ascents and descents, and the other will offer a certified alpine toe piece solely for descending.

1.2.1 Preliminary Design and Ideation

This design was conceived to fill holes in the current market and provide more use cases for backcountry and resort skiing equipment. The design aims to create a modular ski binding system that operates safely and efficiently during backcountry and resort use. Current binding designs do not offer a system that allows a skier to use a tech toe piece on the ascent and descent, as well as offer an interchangeable alpine toe piece for descending in the resort or backcountry. Our system is tailored to skiers who do not have the funds to build a multi-ski quiver or do not ski consistently; it allows the consumer the opportunity to ski on one pair of skis in all situations.

Current market options offer a multitude of features shown in table 1. Our design integrates features from these market leaders while using an innovative plate system that allows skiers to interchange the binding's toe pieces for their desired use case. The comparison of our binding with the state of the art can be seen below in table 2.

Table 2: Design Comparison Matrix

	Our Design	Marker Kingpin 13	Fritschi Tecton 12	Salomon Shift 13	Marker Duke 16	C.A.S.T Freetour
Features						
Tech Toe (30%)	**X**	X	X	X	X	X
Multiple Touring Risers (25%)	**X**	X	X			X
ISO/DIN Certified Toe (25%)	**X**		X	X	X	X
Transformable Toe (7.5%)				X	X	
Interchangeable Toe (7.5%)	**X**					X
Removable Heel Piece (5%)	**X**					
Score	**9.25**	**5.5**	**8.0**	**6.25**	**6.25**	**8.75**
Use Cases						
Downhill Tech Toe Use (50%)	**X**	X	X			
Downhill Alpine Toe Use (50%)	**X**			X	X	X
Score	**10**	**5**	**5**	**5**	**5**	**5**

The features and use cases shown in table 2 highlight the core components of binding usability. These are the factors a buyer considers when purchasing a new binding. The scoring matrix was based on how important each feature is to binding usability and function. Binding features such as a tech toe, multiple risers, and a DIN/ISO certification were deemed most important while a removable heel piece, transformable toe, and interchangeable toe remain less significant to the user. As shown in table 2, our binding design offers more features and use cases than other bindings currently on the market. This new binding design scores 9.25 out of 10 for technical features and allows for both use cases, rather than one like the competitors.

To develop an initial idea of how to satisfy the features in table 2, we used a design ideation process that facilitated the process to develop design solutions from customer needs. The first step in this process was to formulate our customer needs (CN). This process led to the following criteria.

1. Tech toe for backcountry use
2. Alpine toe for resort use
3. Interchangeable toe pieces
4. Both toe pieces can be used with heel piece for descent
5. Multiple touring risers
6. Transition process is quick and easy
7. Keep uphill weight to a minimum

After the CNs were developed, they were translated into engineering terms and designated as functional requirements (FR) to allow a more systematic approach to finding solutions. From this point, the design requirements (DR) to fulfill each FR were developed. This step provided us with a more appropriate statement to develop design solutions (DS) from. The DSs guide the design and creation of the first prototype of the system. The results of this ideation process can be seen in table 3.

Table 3: Design Ideation Process

Functional Requirements	Design Requirements	Design Solutions
FR1: Transmit skiing loads **FR1.1:** Transmit uphill skiing loads **FR1.2:** Transmit descending skiing loads	**DR1:** System for transmitting skiing loads **DR1.1:** System that allows for free movement of heel about secure pivot point at toe **DR1.2:** System that firmly holds heel in place	**DS1:** Binding to secure toe and heel **DS1.1:** Tech toe with pins and locking mechanism **DS1.2:** Alpine heel to firmly hold skier's heel
FR2: Filter injurious loads during descent	**DR2:** System that releases skier's boot during injurious loading	**DS2:** Alpine style components with ISO/DIN certification and elasticity at the toe and heel
FR3: Interchange between uphill function and descending function **FR3.1:** Full interfacing between binding components	**DR3:** System that provides interchangeability for uphill use and descent **DR3.1:** All components are compatible with each other	**DS3:** Alpine and tech toe compatible with demo binding track **DS3.1:** Both alpine and tech toes interface properly with heel piece for descent
FR4: Provide improved climbing performance for various slope angles	**DR4:** System to improve climbing position on steep slope angles	**DS4:** Touring risers to elevate heel during ascent of steeper slopes
FR5: Allow for lightweight options during uphill use	**DR5:** Removable components during uphill use	**DS5:** Removable heel piece on demo track

In addition to the above CNs, the project team also worked with the following constraints during the design process: an uphill weight < 680 g and a cost < \$600. These numbers are based on the leader in each category of uphill weight and cost of our design's competitors as shown above in table 1. The Fritschi Tecton 12 has the lowest weight of 680 g with brakes attached and the Salomon Shift 13 has the lowest price at \$600 (Fritschi Swiss Bindings, n.d.; Salomon, n.d.).

The designed component is a custom-built plate that interfaces with a demo binding rail. The design will use existing components including the Tyrolia Attack 13 Demo Binding, a simple technical toe piece, and Voile Climbing risers to complete the full binding system. The custom modeled plate interfaces with the Tyrolia mounting rail that is permanently fastened to the ski. A pin-style tech toe piece will be permanently mounted to the custom plate to allow for quick and easy mounting and removal from the demo rail. The plate combined with the tech toe will allow for ascending and descending in the backcountry. The Tyrolia Attack 13 alpine-style toe piece is interchangeable via the demo rail and offers safety and confidence for resort descents. Voile STS 20 climbing risers will be mounted to the skis to allow for increased terrain accessibility in the backcountry. Section 1.2.2.1 below describes our design and the methods in which the different components interact with one another.

1.2.2 Design Strategy

Given the uphill and downhill use cases and features the product sets to fulfill, an interchangeable plate system that interfaces with current market options was chosen for the design. The Tyrolia Attack 13 Demo Binding was chosen for its simple and proprietary rail locking mechanism that allows the user to quickly adjust and remove both the toe and heel piece. It also provides a very reliable option for resort use.

Our custom tech toe plate was designed to interface with the Tyrolia rail in the same manner as the Tyrolia toe. The geometry of the plate was based on the Tyrolia rail, stack height, ramp, and the tech toe piece that will be mounted to the rail. Measurements were taken of the Tyrolia rail, Tyrolia toe and heel pieces, the tech toes, and ski boots. These measurements drive the design parameters for our tech toe plate including overall height, length, width, the mounting pattern, and several cutouts for the rail interface, key handle, and locking key.

The second component of our design is the key handle and rod used to turn the locking key. The handle was designed using some reference measurements such as overall length and shape but was tailored to our custom tech toe plate.

The final component of our system is the locking key, which mimicked the overall shape of the locking key used in the Tyrolia design but was modeled with more simple geometry. The teeth to interface with the rail were measured on both the Tyrolia rail and key to ensure the fitment between our locking key and the Tyrolia rail was correct.

All these components were modeled in Creo Parametric and were manufactured for testing and use. The initial prototype was completely 3D printed, but the final product was manufactured from aluminum. The manufacturing process is documented in section 2.0 of the report.

Based on research and discussion with lab assistants we chose to use polylactic acid plastic (PLA) for initial prototyping due to its dimensional accuracy and low cost. PLA has good strength, but it is a brittle material that would struggle with durability in low temperatures. Given the system will need to support high loads over a long period of time in a demanding environment, metal was chosen as the best option for our final product, specifically Aluminum (Al) 6061. This alloy was chosen for its machinability and strength. The Tyrolia key is cast from aluminum, so we chose to machine our system from aluminum stock. Metal was also chosen because of the connection to the steel rail. If a weaker or softer material was chosen the steel rail would eat into the system over time, reducing its ability to hold in place. The material choices are validated with hand calculations and Creo simulations that mimic forces that will act on the system when in use.

1.2.2.1 CAD Model

Creo Parametric was used to model all the components in our system. The tech toe plate, key handle, and locking key, in addition to the Tyrolia rail and key stock rod were modeled and assembled to verify the whole system interfaced properly. Figure 13 shows the assembly of the entire system, and figure 14 shows an exploded view, and figure 15, the assembly of our custom components.

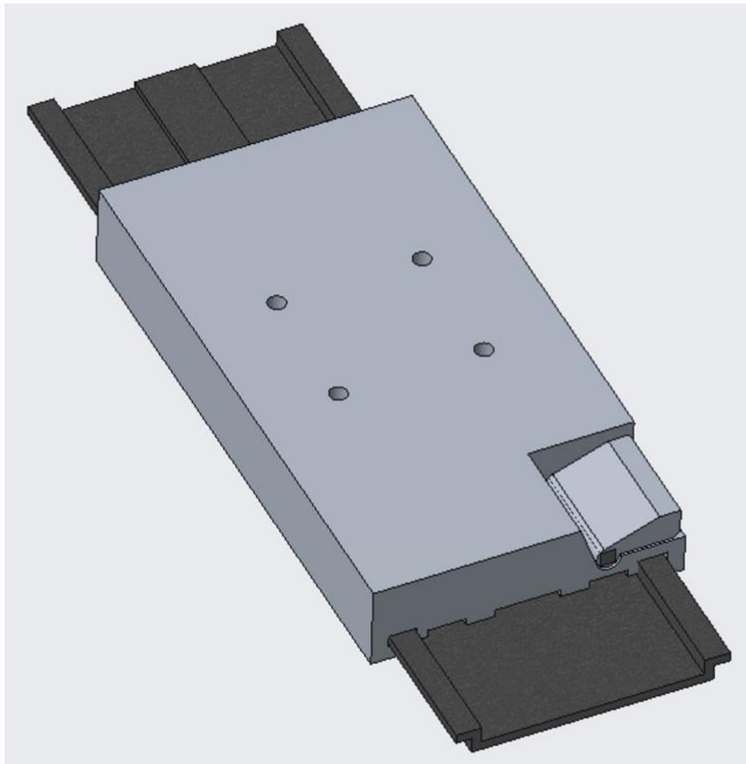


Figure 13: Assembly of Binding System with Tyrolia Rail

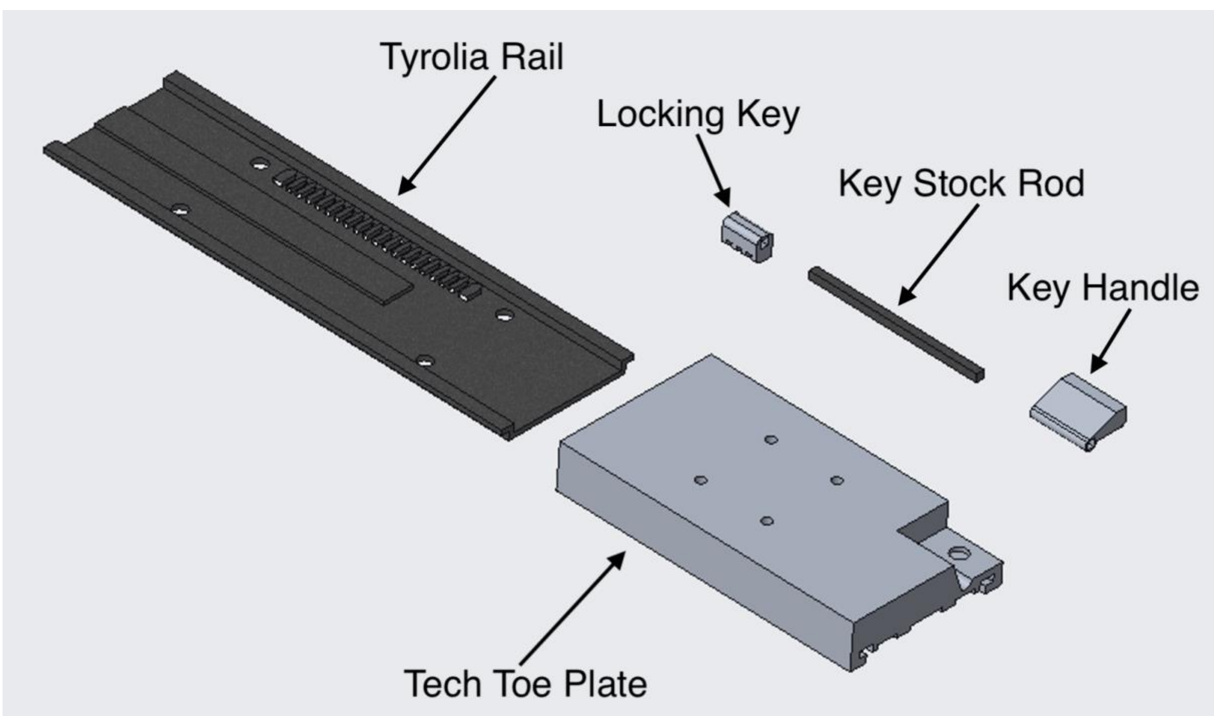


Figure 14: Exploded View of Full Binding System Assembly

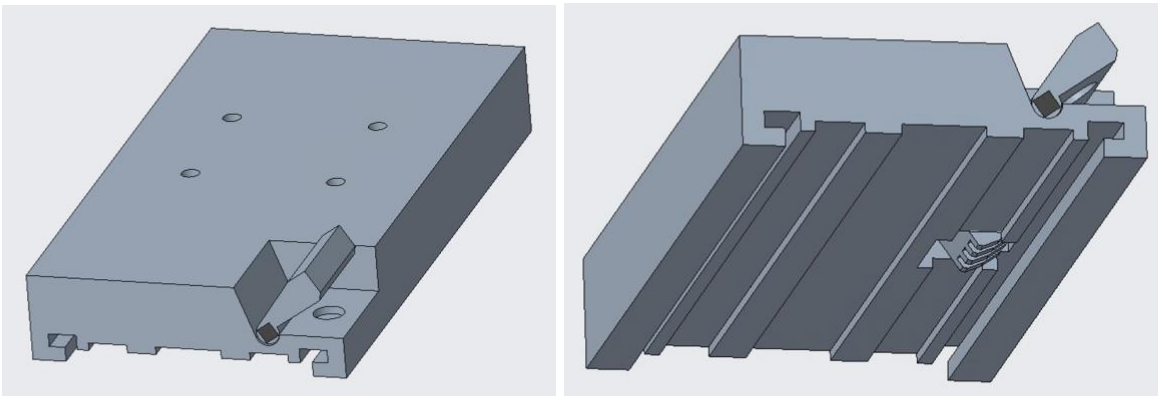


Figure 15: Top and Bottom View of Tech Toe Plate System Assembly

1.2.1.1.1 Tech Toe Plate

The tech toe plate was modeled first because it serves as the base for our system. The purpose of the plate is to slide along and lock onto the demo rail and hold the tech toe in place. Figure 16 displays an isometric view of our custom tech toe plate. The plate consists of cutouts for the rail, key handle, rod, locking key, magnet, and mounting holes for the tech toe piece.

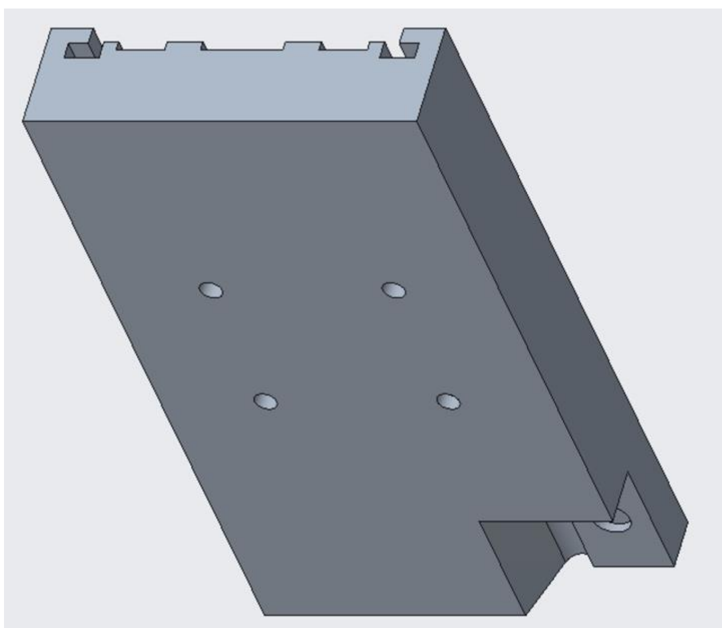


Figure 16: Isometric View of Tech Toe Plate

The tech toe plate was designed by first extruding a rectangular shape, with the origin placed in the center, to model the overall shape of the plate. Then the cutout for the demo rail was modeled by removing material from the plate. Next, the cutout for the key handle was modeled and material was removed from the plate to allow the handle to properly sit in place. Figure 17 shows these two features.

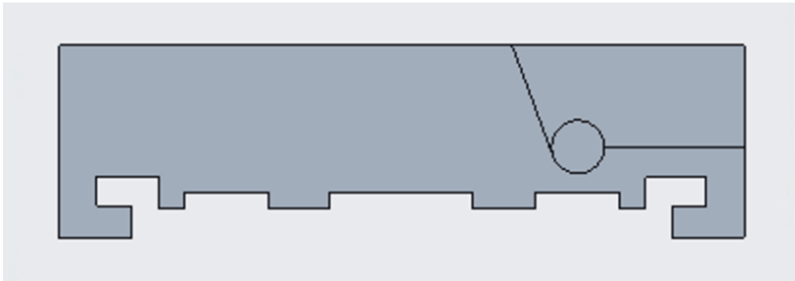


Figure 17: Cutouts for the Rail and Key Handle

The next features modeled were the cutouts for the rod through the plate and for the locking key on the underside. A cutout for a magnet was also modeled on the surface where the handle will sit. A magnet is also placed in the key handle and these magnets hold the handle in the closed position in the final assembly. These features are shown in figures 18 and 19.

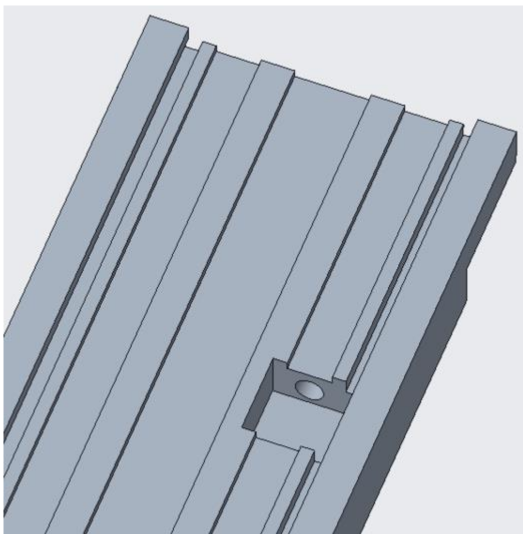


Figure 18: Cutouts for the Rod and Locking Key

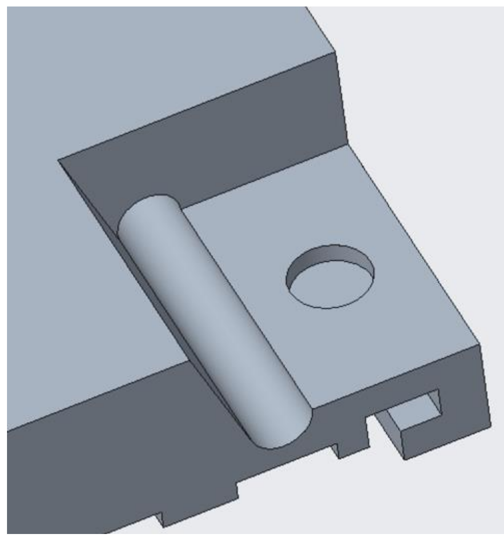


Figure 19: Cutout for a Magnet

The final feature that was modeled were the mounting holes for the tech toe piece that will mount to the top of the plate. One 10-32 threaded hole was modeled, and the hole was patterned across the top of the plate to align with the mounting pattern of the tech toes. The mounting pattern is shown in figure 20.

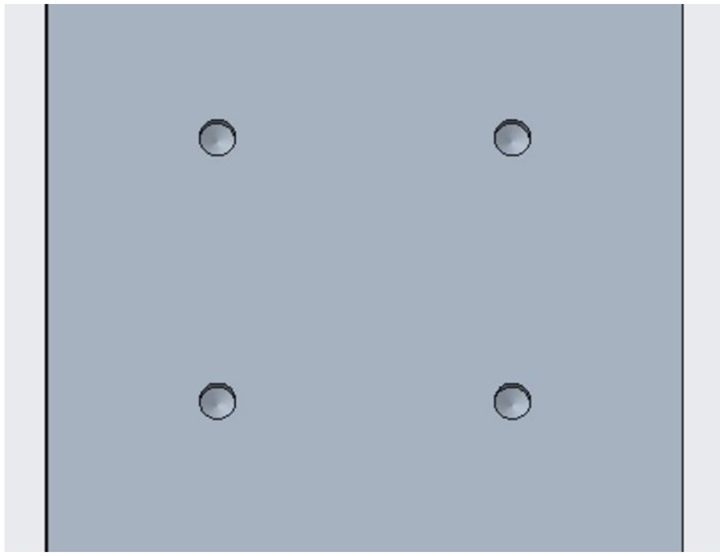


Figure 20: Tech Toe Mounting Pattern

All the dimensions used for the tech toe plate were driven by existing Tyrolia components and the tech toes used in our system. The plate was modeled to mimic the function of the Tyrolia alpine binding and fit properly with all the components. Figure 21 provides the machinist drawing of the tech toe plate.

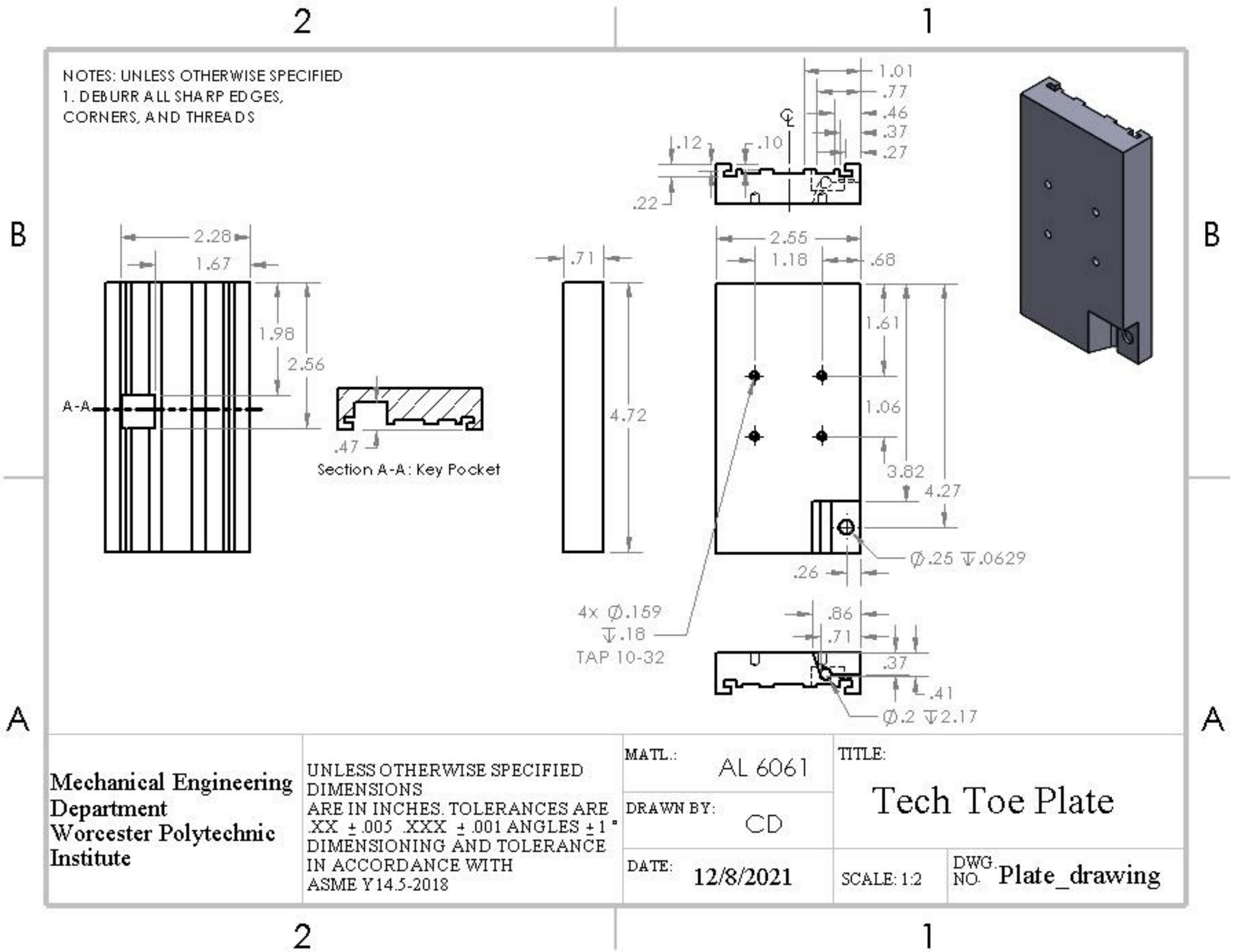


Figure 21: Machinist Drawing of the Tech Toe Plate

1.2.1.1.2 Key Handle

The next component modeled was the key handle. The handle was modeled to interface with the tech toe plate and locking key, and the dimensions were driven by dimensions taken from the Tyrolia alpine toe. Figure 22 shows an isometric view of the handle. It consists of the base extrusion to create the handle, an extruded cut for the rod, a cutout for a magnet, and a chamfered edge to increase usability and aid in dexterity. The rod extruding from the handle originally designed for the 3D printed prototype was replaced with a thru cut for the separate rod component.

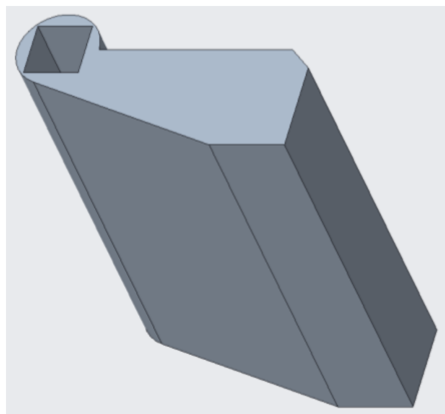


Figure 22: Isometric View of the Key Handle

The base extrusion of the component is the handle shown in figure 23. The handle was modeled to fit in the cutout on the tech toe plate and hold the rod which connects to the locking key. A chamfer was added along the outer bottom edge to help the user pull the handle during use.

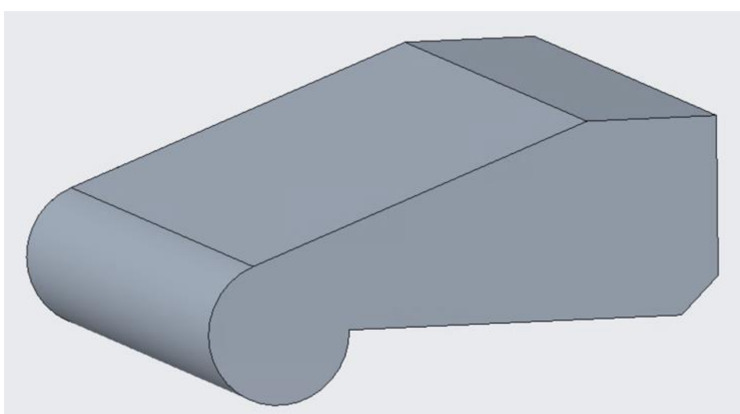


Figure 23: Key Handle Base Extrusion

Next, the square through-all extruded cut was added to the handle. The cut was modeled as a square that fits within the circular component of the handle. The cut is through the entire length of the handle, so the rod fits tightly in the handle when assembled. The placement of the square cut ensures the alignment with the locking key is always consistent throughout the use of this system. Figure 24 shows this feature.

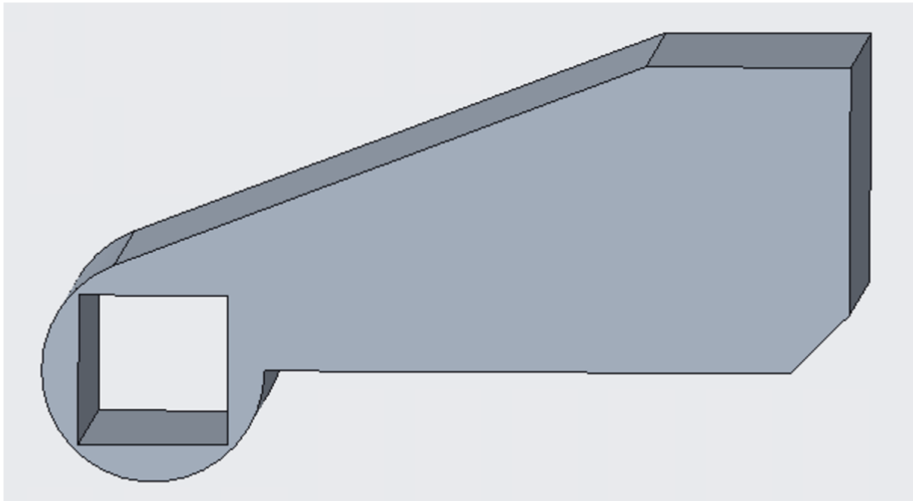


Figure 24: Square Through-All Extruded Cut on the Key Handle

The final feature was an extruded cut for the magnet that will be placed in the handle. Again, the magnet is used in the system to create opposite poles in the key handle and tech toe plate, so the handle is held in the closed position while in use. This cut is shown in figure 25 and figure 26 provides the machinist drawing of the key handle.

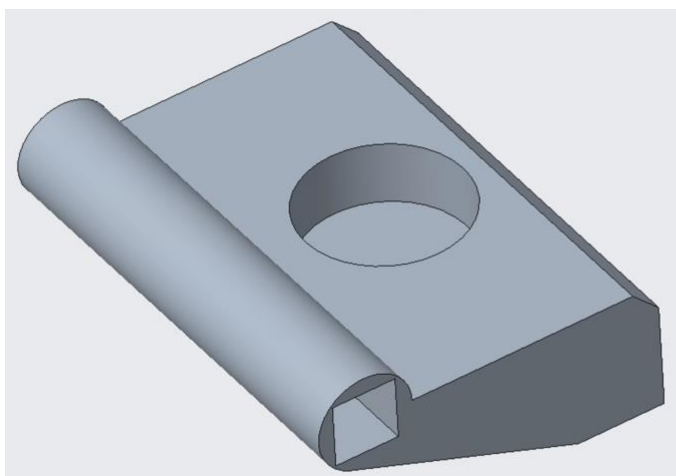


Figure 25: Magnet Cutout on Underside of Key Handle

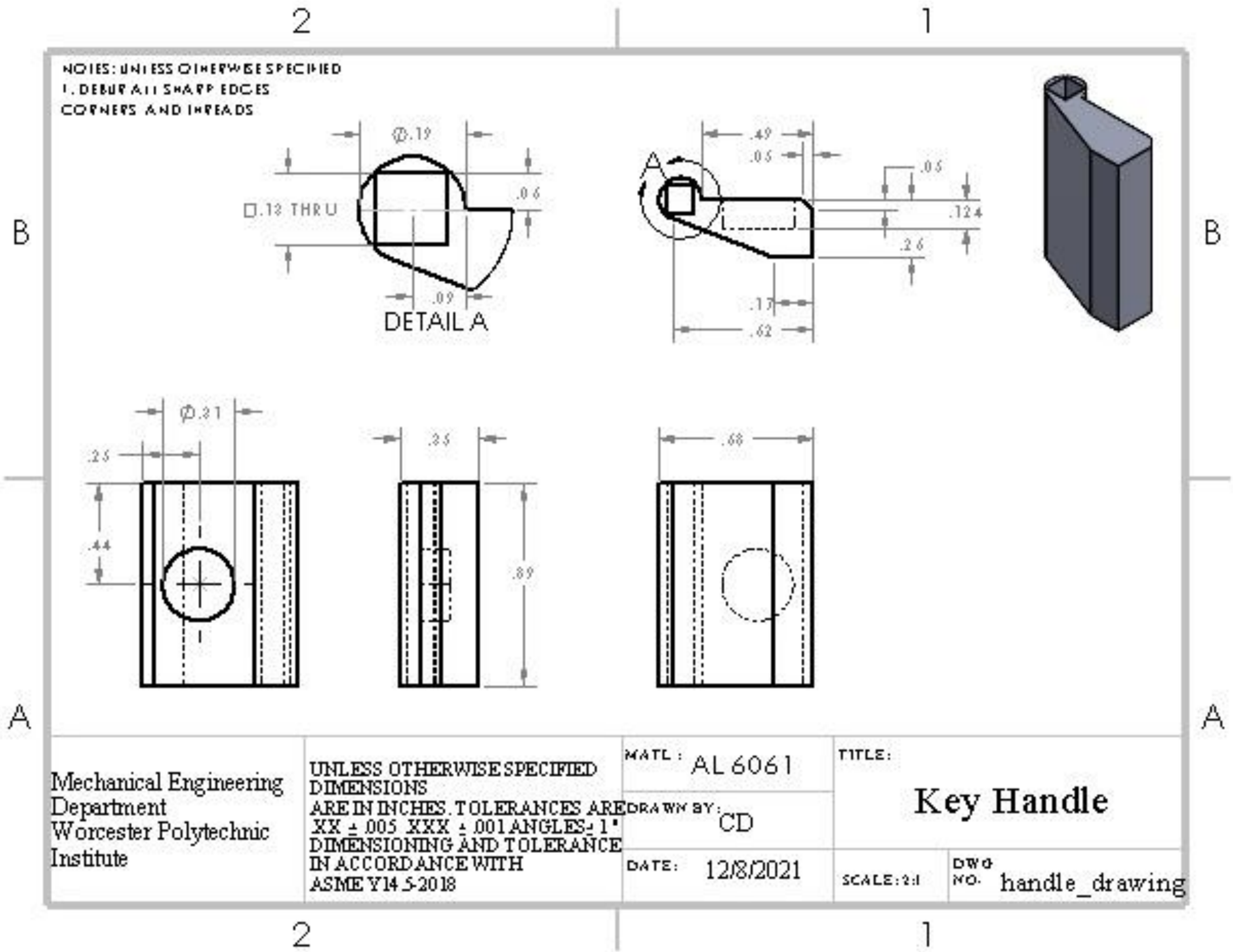


Figure 26: Machinist Drawing of the Key Handle

1.2.1.1.3 Locking Key

The locking key was the last component modeled. The dimensions were driven by the key used in the Tyrolia alpine toe and the model of our key handle and rod. The isometric view of the key (shown in figure 27) displays the base extrusion, which is a rectangular prism, cutouts to allow the key to interface with the locking ridges on the demo rail, an extruded cut square for the rod, and several chamfers and rounds that allow the key to turn in the plate and along the demo rail.

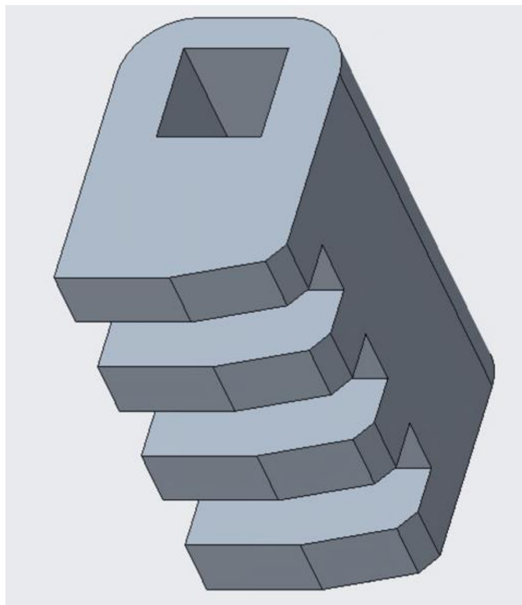


Figure 27: Isometric View of the Locking Key

The first feature modeled after the base extrusion was a cutout for the locking ridges on the demo rail. The dimensions of the cuts were modeled based on the dimensions of the cuts and ridges on the Tyrolia key and the ridges and spaces on the Tyrolia rail. Once the dimensions were determined, the cut was made and patterned across the locking key to mimic the function and fit of the Tyrolia key, which is shown in figure 28.

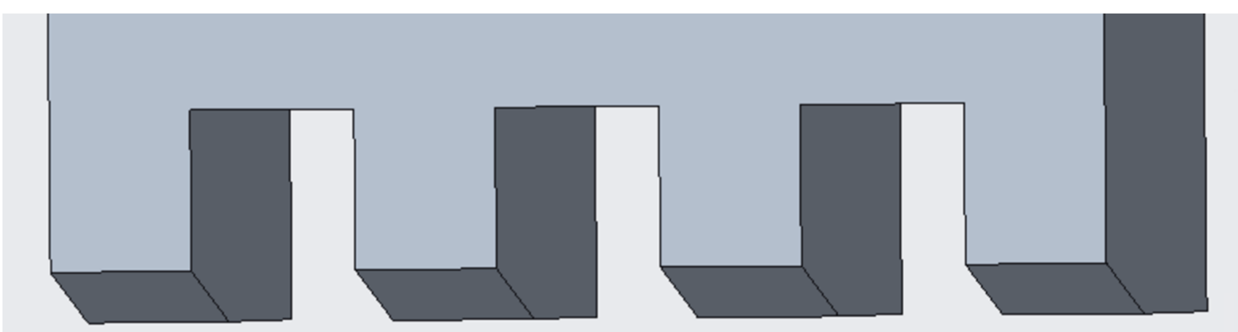


Figure 28: Cutouts for the Locking Ridges

The last feature modeled on the locking key was a square cutout for the rod to be inserted. A press fit was chosen for this fitment since the connection does not bear a high load and the square shape will help with the rotation of the locking key and key handle. The rod was modeled to use a press fit into the cutout. The cut extrudes through the whole length of the key to ensure the rod is fully secured to the locking key and ensure there is not enough play for the rod to slip out. The cutout is shown in figure 29 and figure 30 below shows the machinist drawing of the locking key.

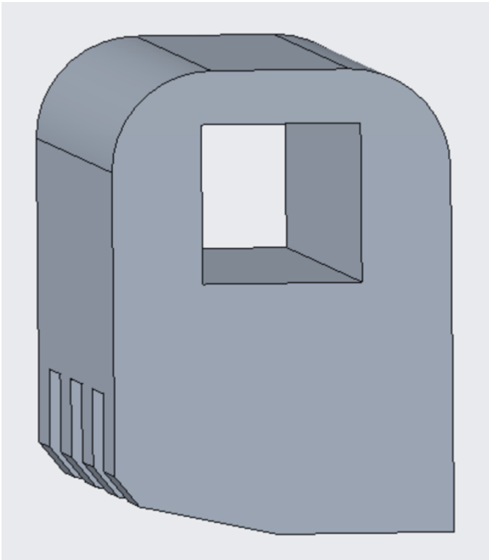


Figure 29: Cutout for Rod in Locking Key

The Creo model is a dynamic tool that is the core of the design process. It allows for the system to be assembled and tested for fitment, analyzed under different circumstances, and modified for any changes before manufacturing. It also provides further documentation of the design process.

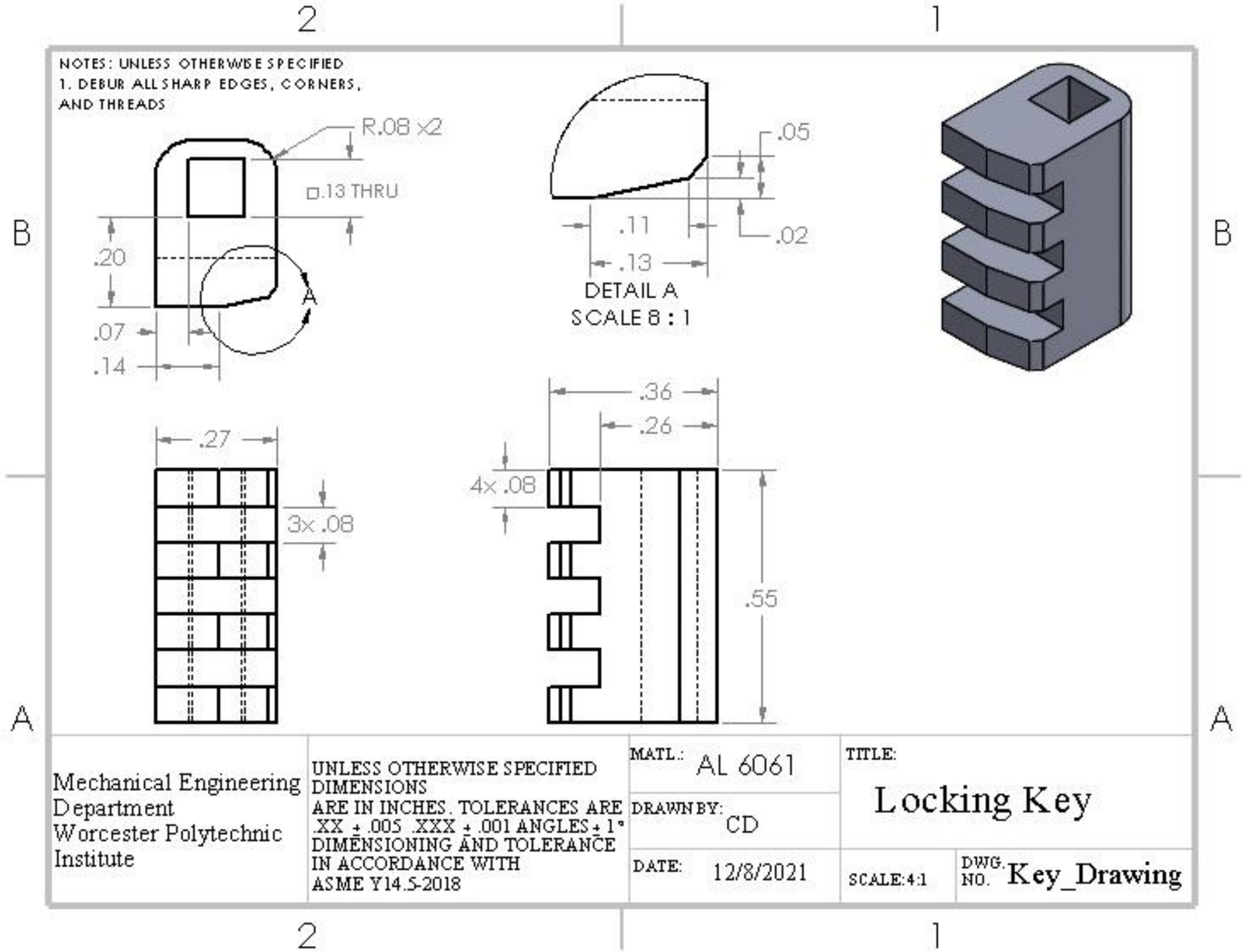


Figure 30: Machinist Drawing of the Locking Key

1.2.3 Calculations and Simulations

As a preliminary evaluation of the structural integrity of our part as it is subjected to forces during skiing, we performed hand calculations to evaluate the applied stresses in various axes. The hand calculations offered a simplified version of what would be evaluated using simulation software in Creo Parametric, so that comparisons could be made to the results generated using the software. The three simulation cases that were performed (shown in figure 31) were:

1. failure of the tech toe plate in the vertical direction,
2. failure of the tech toe plate in the lateral direction,
3. and failure of the locking key in the longitudinal direction.

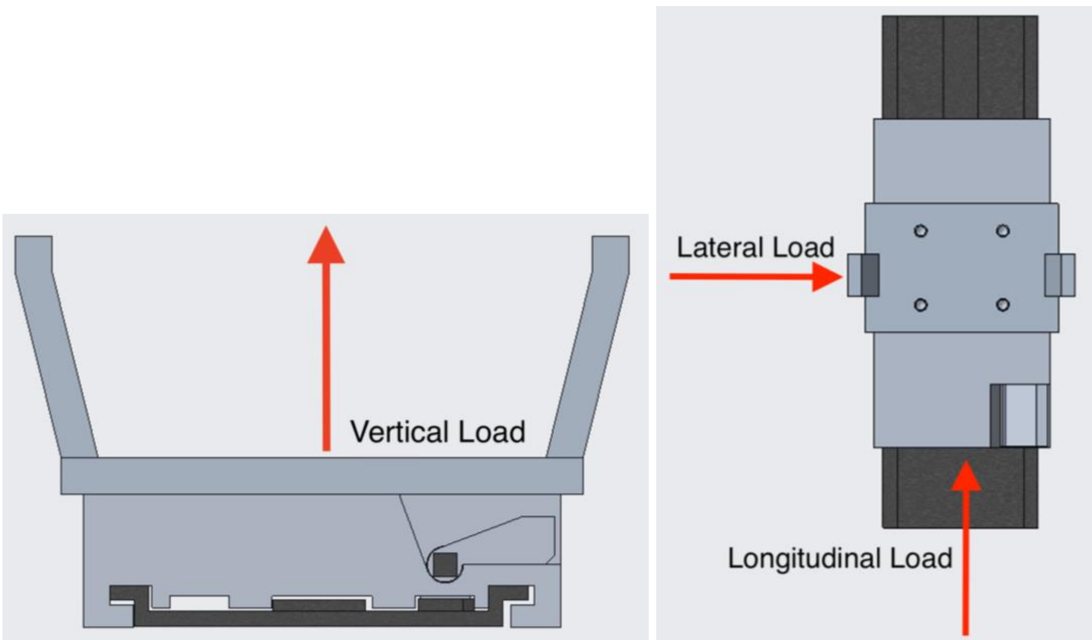


Figure 31: Simulation Cases

For the calculations, it is necessary to have a theoretical applied force to calculate the applied stress and compare it to the yield stress of the material. The theoretical applied forces were based on the clamping force of the Plum Yak 12 tech toe binding, which featured the highest clamping force of 26 different tech toes tested by Wild Snow (Dawson, 2020). The Plum Yak 12 generated a 304.4 N clamping force, which means that the pins input 304.4 N on the pin inserts located in the toe of the skier's boot. We rounded this value up to 310 N and assumed that the toe would release in the vertical or lateral direction if this force was exceeded.

The longitudinal case required a bit more thought as due to the geometry of a tech toe, a purely longitudinal force could not cause the tech toe to release. For this case, we estimated that 500 N could be applied in this direction during skiing activity and used this value in our calculations and simulations.

To rationalize the magnitude of these seemingly relatively low forces, it is important to consider that 304.4 N marks the clamping force of a single tech toe piece. The skier will be connected to the skis with two toe pieces in addition to two heel pieces. A skier's weight distributed among these four clamping points can justify a 310 N clamping force at a single toe piece.

These values would be used to determine a baseline applied stress to the components and this stress would be compared to the failure point of the components or the yield strength to determine the factor of safety (*F.S.*) of the components. As Aluminum (Al) 6061 is being used for all the components, the yield stress is equal to $2.76 \times 10^8 \frac{N}{m^2}$ or 276 MPa.

1.2.3.1 Vertical Force Calculations

The first case studies the strength of the tech toe plate with a force applied vertically. The plate will continuously experience vertical forces while in use and the plate will fail via a tensile load if the material's ultimate strength is reached. Although the plate will not physically fail until the yield strength is reached, we want to avoid deformation which occurs when the material's yield strength is reached. The tech toe plate will likely experience maximum stresses while in the apex of a downhill turn or during a fall. The vertical failure of the plate was calculated considering the yield strength of the material and using the vertical stress formula. The hand calculations were simplified to analyze one rectangular section of the plate which is shown in the figures below.

To determine the structural integrity of our custom designed tech toe plate it was necessary to analyze the stresses on the component with an upward force. The force was evenly distributed across the mounting pattern and applied to the top of the plate, while the plate was fixed along the shaded portion of the rail cutouts shown in figure 32. This fixture face was chosen because when a vertical force is applied to the plate, this portion of the rail cutouts will be in contact with the Tyrolia demo rail and thus generate the reaction force to hold the plate in place. Figure 32 below, also depicts the region of the tech toe plate that was analyzed in the hand calculation.

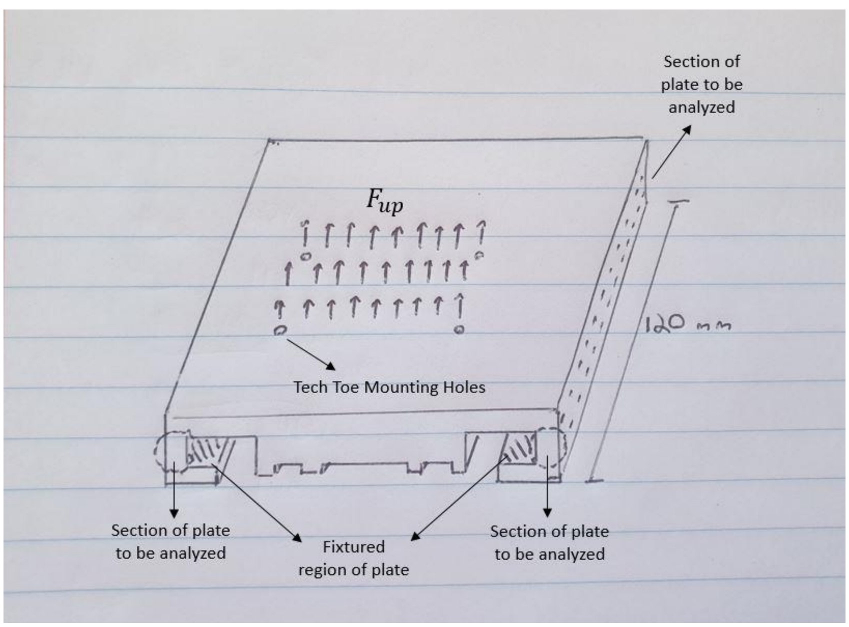


Figure 32: Tech Toe Plate Depicting Applied Force, Relevant Dimensions, and Analyzed Sections

The sections that were analyzed for this case are outlined with a dashed line. As can be seen they run along the side of the tech toe plate for the entire length and are symmetrical across each side. Below in figure 33, the upward force (F_{up}) is simplified across the tech toe mounting pattern and is located in the middle of the mounting holes at a distance of 82 mm from one end.

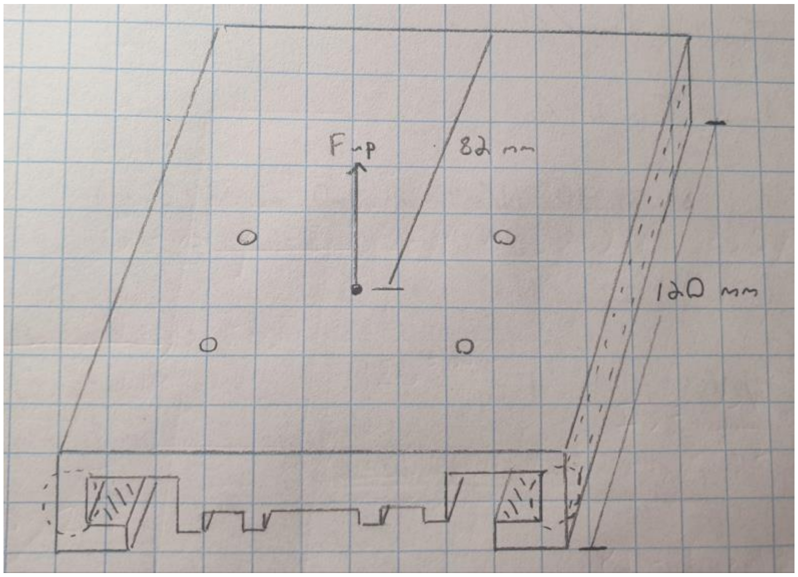


Figure 33: Simulation Conditions for Tech Toe Plater Under Vertical Load

Figure 34 below shows the isolated beam that makes up this section with the applied upward force and the distributed reaction force along the bottom of the section.

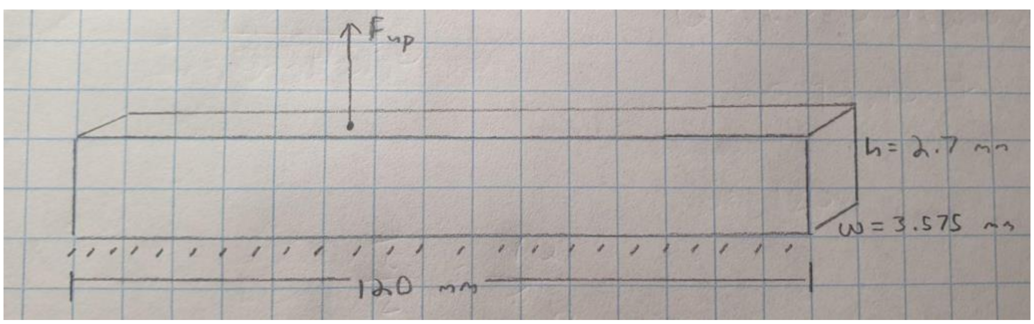


Figure 34: Isolated Beam to be Analyzed for the Vertical Case

As can be seen, the dimensions of the beam are length = 120 mm, width = 3.575 mm, and height = 2.7 mm. F_{up} is counteracted by a distributed reaction force along the bottom of the beam. For the purposes of this hand calculation, we are going to assume that the reaction is evenly distributed, so that the force can be simplified to a single point in the middle of the beam. This simplification can be seen below in figure 35.

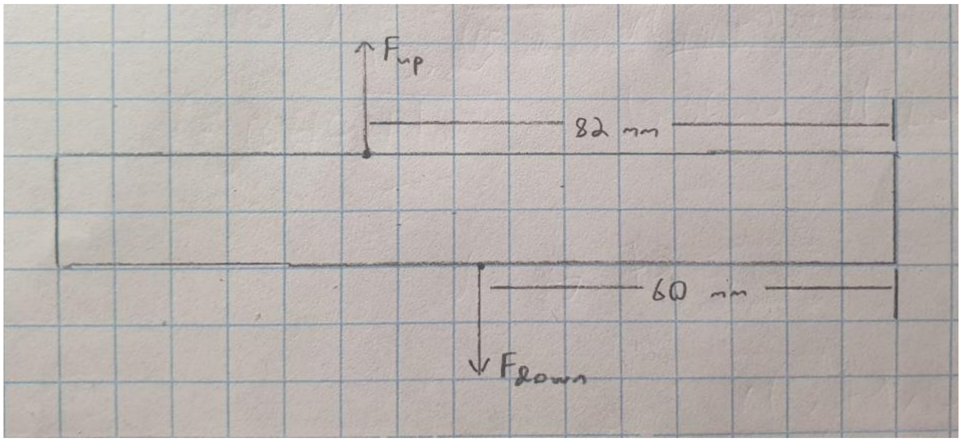


Figure 35: Beam with Simplified Reaction Force

In the above image, the beam is shown with the simplified reaction force along the bottom. Next, we need to move F_{up} to act in the same vertical line as F_{down}. This must be done to use the tensile stress equation, $\sigma = \frac{P}{A_0}$, where σ is the tensile stress (Pa), P is the applied load (N), and A_0 is the cross-sectional area of the beam (m^2). When moving the force, a moment is induced on the beam that we must acknowledge. This moment will be solved for with the following equation: $M = F_{up}\,\Delta x$, where M is the moment (Nm), F_{up} is the upward force (N), and Δx is the distance that the force is moved (m). The calculation for this induced moment is as follows. In our case, the upward force will be the 310 N force discussed in section 1.2.3.

$$M = F_{up}\,\Delta x$$
$$M = 310\,N\,(0.082\,m - 0.06\,m)$$
$$M = 6.82\,Nm$$

This induced moment is extremely small relative to the yield strength of our material Al 6061, and thus it can be ignored in the subsequent calculations as it will have little effect on the behavior of the tech toe plate under the applied load. Figure 36 below depicts the beam with the simplified forces.

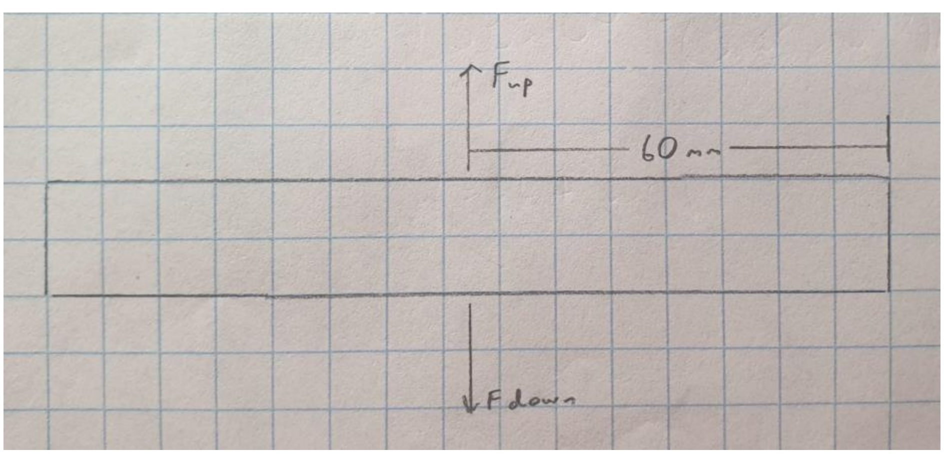


Figure 36: Beam with Simplified Forces

Now that the forces have been simplified and the induced moment properly addressed, the stress when the 310 N force is applied can be determined and compared to the tensile strength for the tech toe plate. The process to solve this stress is as follows.

$$\sigma = \frac{P}{A_0}$$

$$\sigma = \frac{310\ N}{2(0.120\ m \times 0.003575\ m)}$$

$$\sigma = 361{,}305.4\ Pa = 0.361\ MPa$$

Now that we have solved for the stress within the beam by hand, we can verify the results using Creo. Below in figure 37, the results of this simulation can be seen.

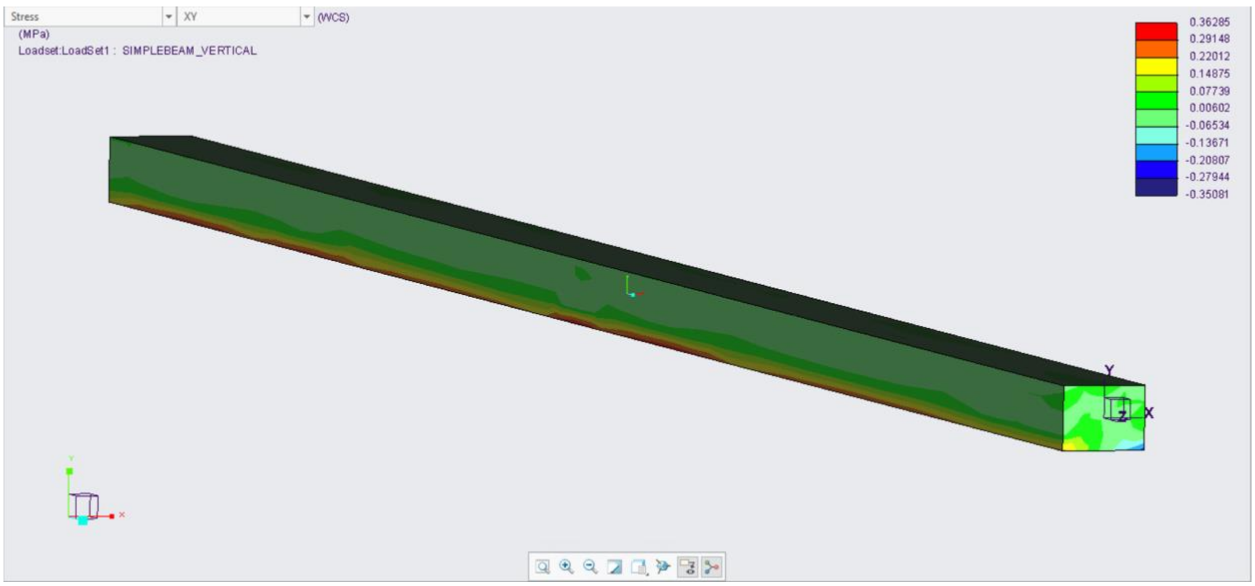


Figure 37: Results of Simplified Case Simulation Results

As seen above, the maximum stress in the beam was 0.363 MPa along the lower left edge of the beam. This value is slightly larger than the hand calculated value of 0.361 MPa. This is due to a discrepancy between the method used in our hand calculation to find the average stress across the cross section and the integral method used by the software to find the average stress across the stress curve.

The above hand calculation and simulation are a simplification of the actual forces and stresses the tech toe plate will experience from a vertical load and give credence to the more realistic simulation. In reality, the plate will experience multi-direction distributed forces while in use, rather than the point load used in the hand calculations. It is also likely that in addition to the tensile stress, there is a shear stress component. Subsequently, we performed a simulation of the entire tech toe plate with the applied forces and fixtures. The results of this simulation are shown below in figure 38.

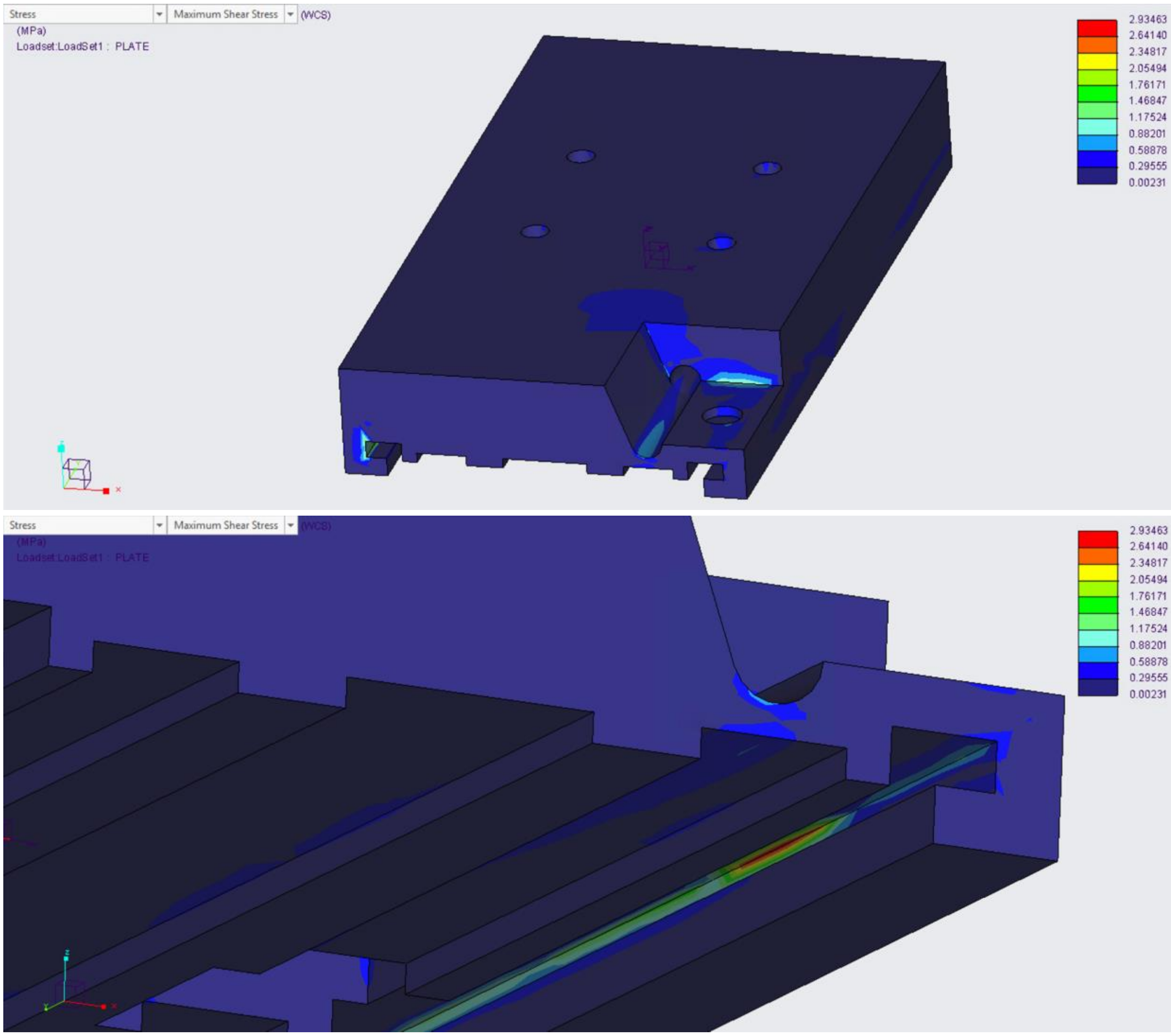


Figure 38: Two Views of Shear Stress in Plate Under Vertical Load

The color-coded key in the top right of each image depicts the minimum and maximum stresses seen in the simulation. In this simulation, the maximum stress is 2.935 MPa and is experienced in the inside edge of the rail cutout. This value is far below the tensile strength of Al 6061 and thus will exhibit a very high factor of safety, which will be solved using the following equation: $Minimum\ Factor\ of\ Safety\ (F.S.) = \frac{Yield\ Strength}{Maximum\ Stress}$.

$$F.S. = \frac{Yield\ Strength}{Maximum\ Stress}$$
$$F.S. = \frac{276\ MPa}{2.935\ MPa}$$
$$F.S. = 94.04$$

This factor of safety gives immense confidence in the strength of our tech toe plate, under vertical load, as it compares to the point of failure of Al 6061.

1.2.3.2 Lateral Force Calculations

The second case studies the strength of the tech toe plate with a force applied laterally. The plate will continuously experience lateral forces while in use and will need to withstand these forces for safe and reliable use. For this scenario the plate was fixed along two surfaces shown in figure 39, and for the hand calculations the case was simplified to a simple cantilever beam to examine the stress and verify the software for the more realistic scenario. A lateral force was applied to the left side of the plate from the view in figure 39.

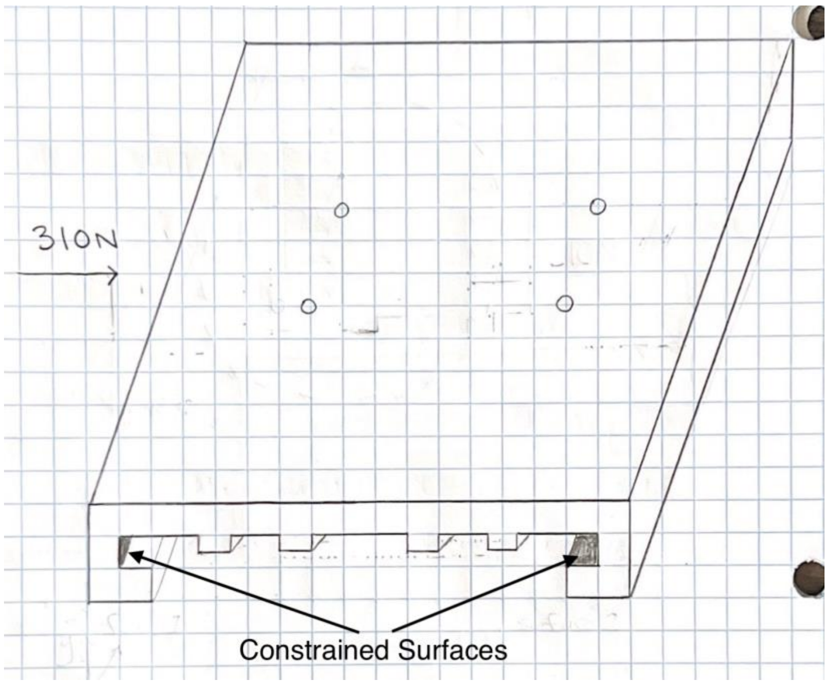


Figure 39: Constrained Surfaces of the Tech Toe Plate Under Lateral Load

The left side surface of the rail cutout was constrained in all directions to prevent the tech toe plate from translating in the x-direction, and the right upwards facing surface was constrained in all directions to prevent the tech toe plate from rotating about the z-axis due to the load applied. These surfaces were chosen as these are the surfaces that will be in contact with the rail to prevent the plate from translating or rotating. Figure 40 shows a view looking down the length of the plate with the 310 N force applied and the reaction forces on the plate.

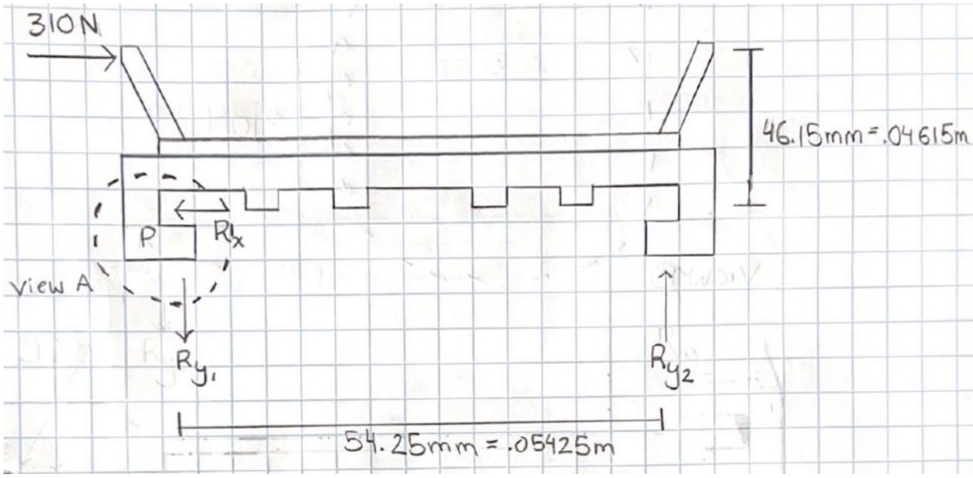


Figure 40: Lateral Load and Reaction Forces on Tech Toe Plate

To determine the reaction forces, simple force and moment equilibrium equations were used.

$\Sigma F_x = 0 = 310\ N - R_x$
$R_x = 310\ N$

$\Sigma F_y = 0 = -R_{y_1} + R_{y_2}$
$R_{y_1} = R_{y_2}$

$\Sigma M_P = 0 = (-310\ N)(0.04615\ m) + (R_{y_2})(0.05425\ m)$
$14.3065\ Nm = (0.05425\ m)(R_{y_2})$
$R_{y_2} = 263.71\ N = R_{y_1}$

With these reaction forces, the shear in the tech toe plate can be calculated. View A on figure 40 shows the portion of the plate where R_x acts, and where the tech toe plate will be simplified and analyzed for shear stress. Figure 41 shows View A and the reaction forces on that portion of the plate.

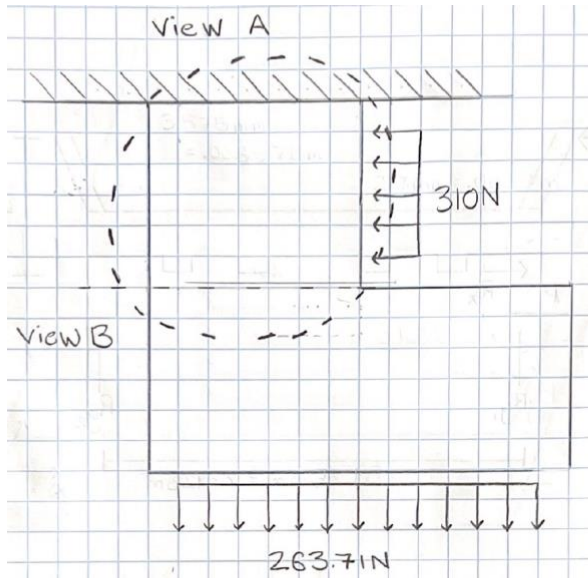


Figure 41: Reaction Forces on Tech Toe Plate Under Lateral Load

Figure 41 is view A from figure 40 and shows the 310 N horizontal reaction force and the 263.71 N vertical reaction force on the plate. Both forces are uniformly distributed across the surfaces they act on. The tech toe plate can be further simplified to a simple cantilever beam by only analyzing the section of the plate in view B on figure 41. View B is shown in figure 42; this simplification can be made because the vertical reaction force has no bearing on the lateral shear in the beam.

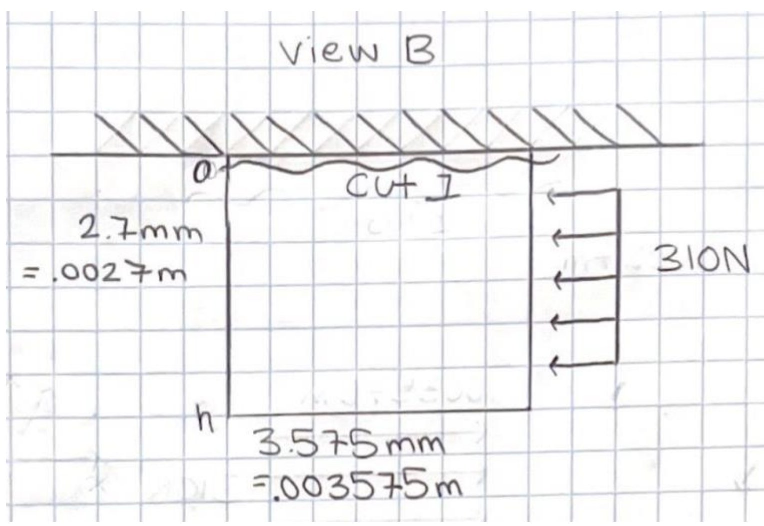


Figure 42: Simplified Cantilever Beam of Lateral Load Case

View B shows the tech toe plate reduced to a simple beam that is fixed along one surface, with one distributed load acting on it. This is the case that will be used for the hand calculations to determine the maximum shear stress in the beam and verify the simulation results. At any point along the height, the beam can be cut across the x-axis and the shear force, normal force, and moment can be calculated. The distributed force can be simplified to a single 310 N force acting at half the height of the beam and the shear force can be calculated. The shear force will be at its maximum where the beam is fixed and it will be at a minimum at the end of the beam, in the y-direction. Figure 43 shows the breakdown of these forces.

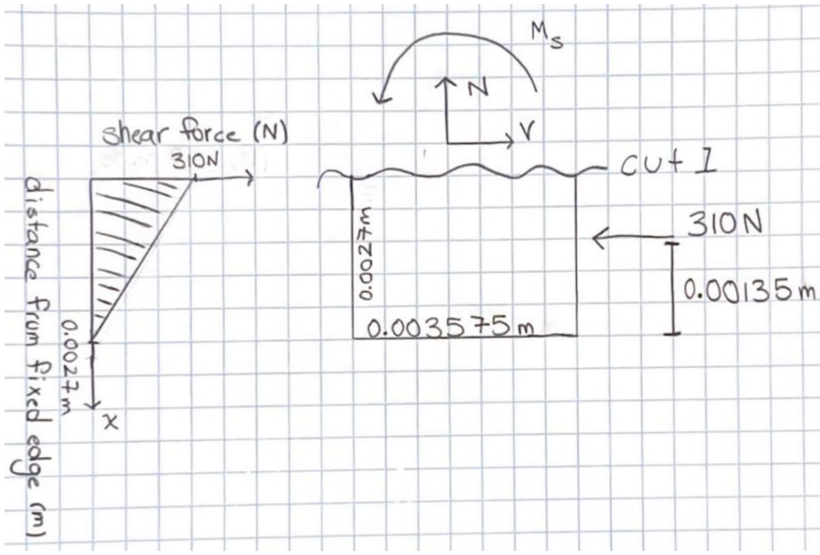


Figure 43: Shear Force in Simplified Beam Under Lateral Load

To confirm the structural integrity of the tech toe plate, it was analyzed under worst-case conditions, when the shear force is at its maximum of 310 N. The 3D beam is shown in figure 44 and the maximum shear force was calculated using the following equation: $\tau = \frac{3V}{2A}$, where $\tau$is shear stress (N/m^2), V is shear force (N), and A is area (m^2).

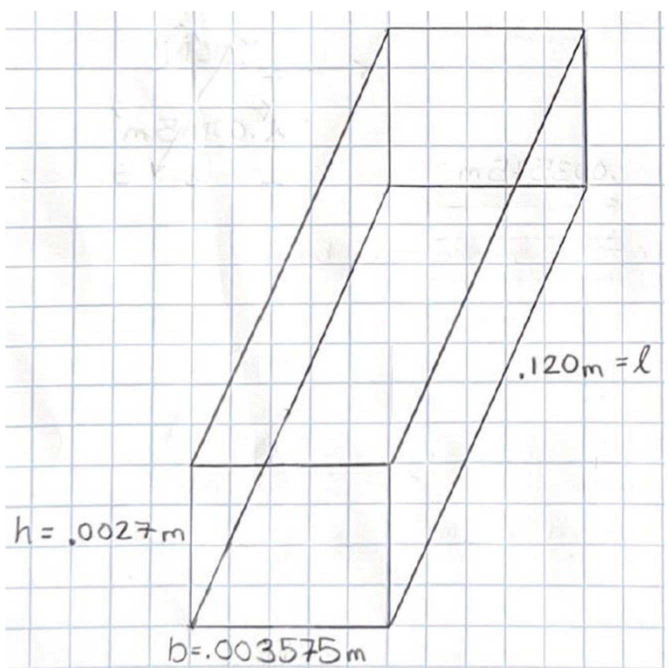


Figure 44: Simplified 3D Beam under Lateral Load

The shear stress was calculated for the YZ plane since the beam will shear across the x-axis. The area was calculated as follows:

$$A = b \times l = 0.003575\ m \times 0.120\ m$$
$$A = 4.29 \times 10^{-4}\ m^2$$

The shear force in this case is 310 N so the maximum shear stress in YZ was calculated and then converted to megapascals (MPa).

$$\tau_{YZ} = \frac{3V}{2A} = \frac{3(310\ N)}{2(4.29 \times 10^{-4}\ m^2)}$$
$$\tau_{YZ} = 1{,}083{,}916.084\ \frac{N}{m^2} \times \left(\frac{1\ MPa}{10^6\ \frac{N}{m^2}}\right) = 1.0839\ MPa$$
$$\tau_{YZ} = 1.0839\ MPa$$

The hand calculations yield a maximum shear stress in YZ of 1.0839 MPa, which should act at the right upper corner of the beam where the shear force is maximum. This simplified beam was modeled in Creo, fixed along the upper surface, and a 310 N distributed load was applied to the bottom surface, opposite to the fixed surface to properly create a cantilever beam within Creo. Figure 45 shows these conditions and figure 46 shows the results of the simulation.

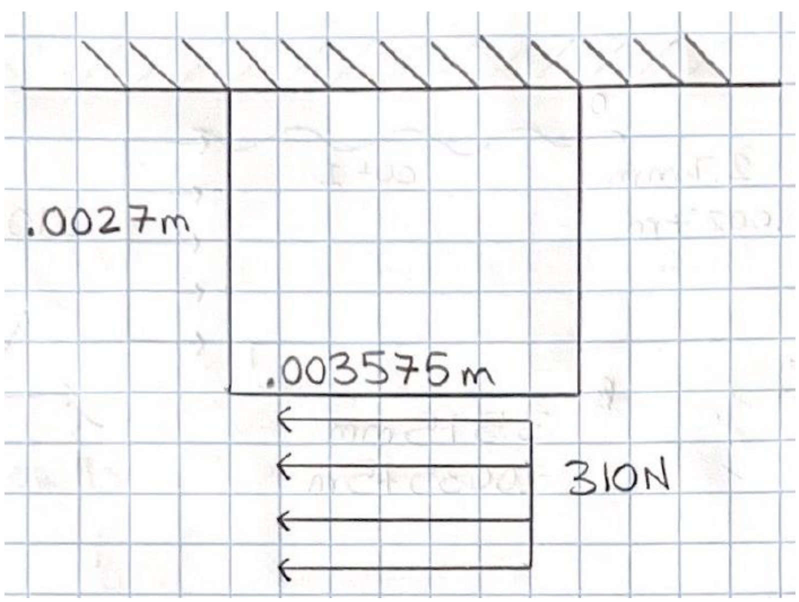


Figure 45: Fixture and Load Conditions for Creo Simulation

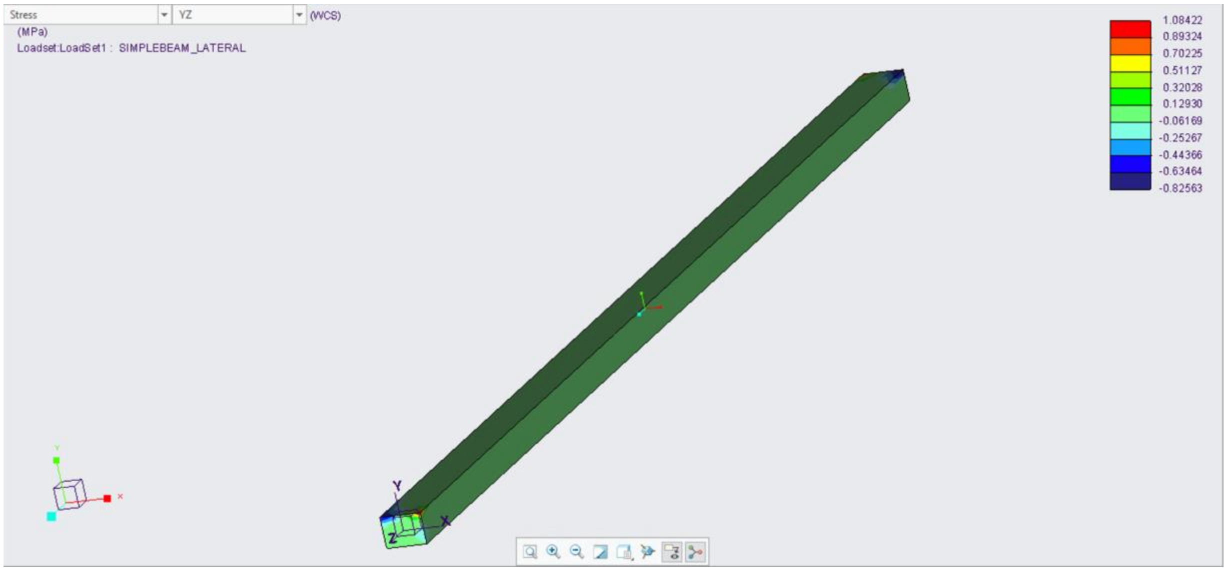


Figure 46: Creo Simulations of Simple Cantilever Beam under Lateral Load

As shown, the maximum shear stress on the beam in YX is 1.084 MPa and it acts along the upper right corner of the beam where the shear force is maximum. The simulation yielded the same results as the hand calculations which means the simulation results are valid and can be trusted for more complicated cases. The results also show that the stress the beam experiences, and thus the tech toe plate, is much lower than the yield strength of Al 6061 and gives confidence that the plate is structurally sound.

The hand calculations are a simplification of the actual forces and stresses the tech toe plate will experience from a lateral load but lend credibility for the more realistic cases below. In reality, the plate will experience multi-direction distributed forces while in use, rather than the point load used in the hand calculations. A more realistic case is shown above in figure 40, where the 310 N load is applied at the pins and transferred through the tech toe plate.

This scenario was modeled in Creo with the constraints shown in figure 39. The simulation was performed with the two surfaces constrained in all directions, and the 310 N load applied laterally at the outer side of one of the pins. The results are shown in figure 47.

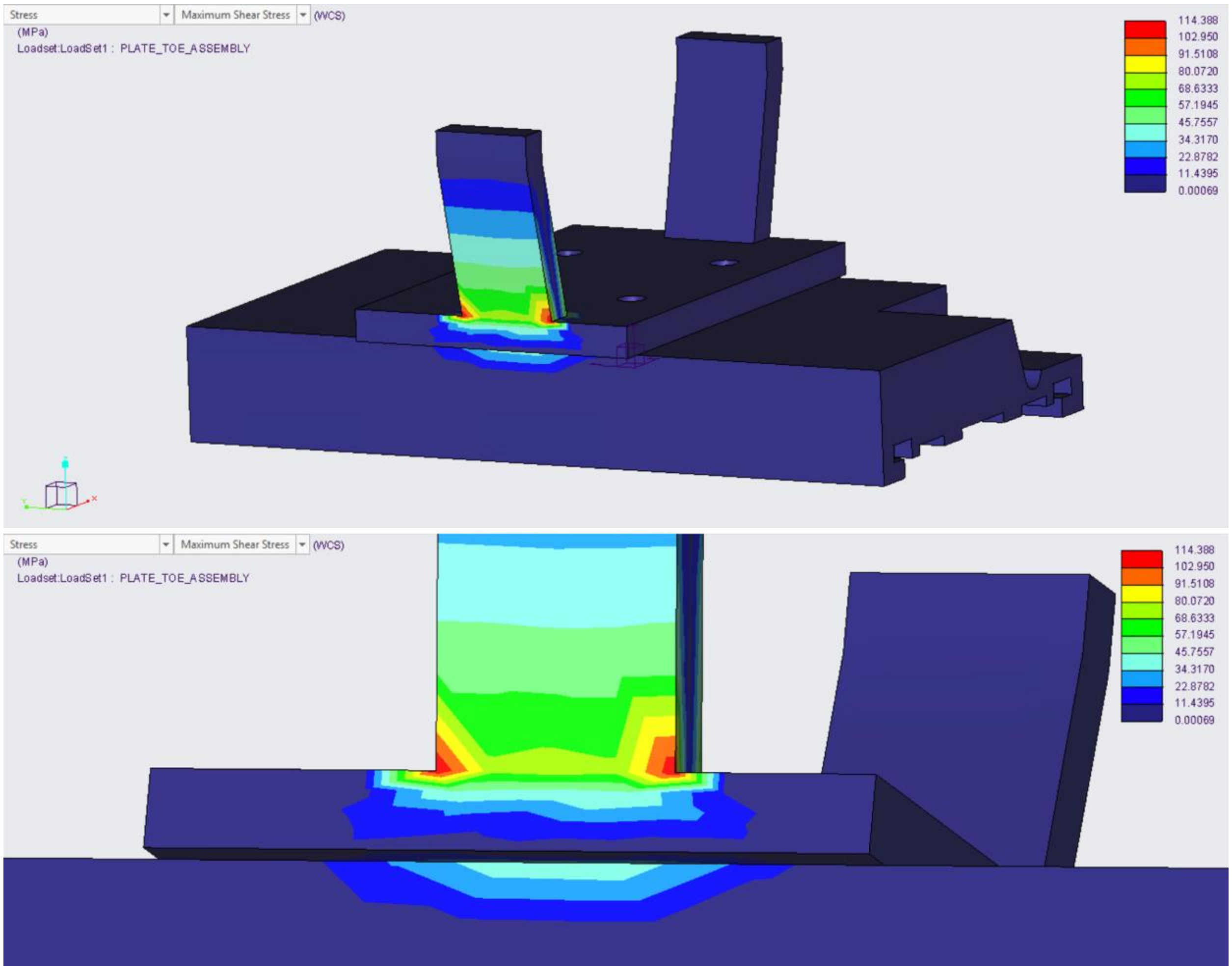


Figure 47: Tech Toe Plate and Tech Toe Simulation Under Lateral Load

As seen in the figures above, the maximum shear stress occurs in the tech toe due to the geometry of the toe and the location of the force application. However, since we did not design the tech toe and those components have already been tested and proved to be structural, we are not concerned with that shear stress. The shear stress in the tech toe plate is our only point of analysis, and figure 47 shows the maximum shear stress occurs right below the tech toe. The plate has a maximum shear stress of 40.2414 MPa, which is well below the yield strength of the plate. Additionally, the overall shear stress in the rest of the plate, including the rail cutouts was under 5 MPa.

The factor of safety was calculated to determine the risk of failure for the tech toe plate and to relate the maximum shear stress to the material's yield strength. The *F.S.* was first calculated for the maximum shear stress in the plate.

$$F.S. = \frac{Yield\ Strength}{Actual\ Stress} = \frac{276\ MPa}{40.2414\ MPa}$$

$$F.S. = 6.85$$

A factor of safety of 6.85 is very high and gives confidence that this tech toe plate will not fail under normal circumstances. These results tell us that under the worst-case scenario, the binding will release before the plate reaches its yield strength.

1.2.3.3 Longitudinal Force Calculations

The final calculations looked at the longitudinal failure of the locking key. To determine if the key would withstand heavy loads during use, the longitudinal failure of the locking key was calculated. The team determined that a maximum longitudinal force of 500 N would be applied to the key into the face where the rod is inserted. This force would distribute evenly across the four teeth of the key. In the maximum force scenario, each tooth would have a 125 N distributed load applied. Figure 48 shows the full locking key and highlights the single tooth that was used for the simplified calculation for maximum shear.

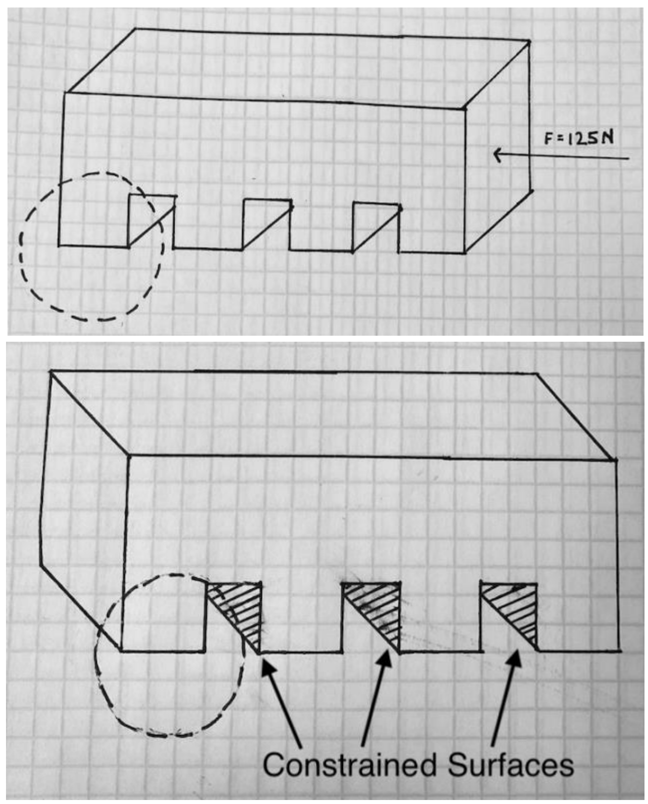


Figure 48: Opposite Isometric Views of the Locking Key Showing Simulation Conditions

When looking at the forces applied to a single tooth, the system was assessed as a simple cantilever beam. The height of the beam is 0.00275 m, the base is 0.002 m, and the length is 0.00657 m. This simplification and free body diagram can be seen in the following figure.

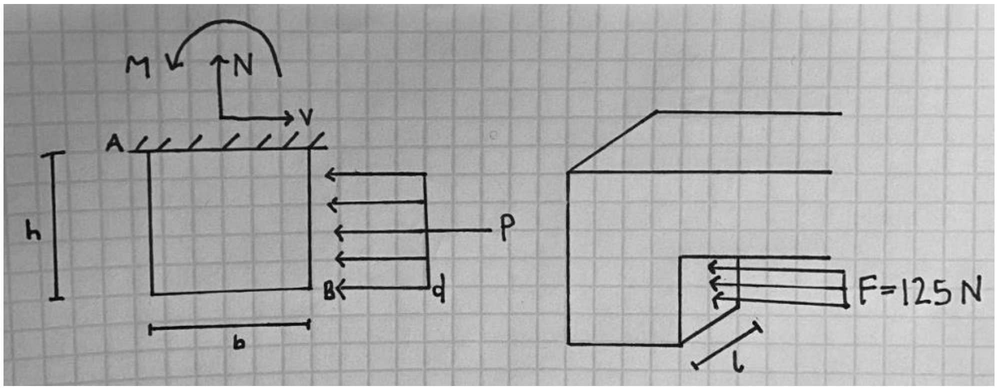


Figure 49: Free Body Diagram and Tooth of Locking Key

As seen in figure 49, the longitudinal force (*F*) is applied as a distributed force of 125 N into the beam. The part will shear in the plane shown in the sketch. At any point along the height, the beam can be cut across the x-axis to calculate the shear force, normal force, and moment. The distributed force of 125 N can be simplified to a point load at half the height of the beam. The shear force will be the largest where the beam is fixed and it will be the smallest at the end of the beam, in the y-direction.

To calculate the maximum shear on this system, we used the equation: $\tau = \frac{3V}{2A}$. First, to determine the reaction forces, simple force and moment equilibrium equations were used.

$$\Sigma F_y = 0 = N$$

$$\Sigma F_x = 0 = V - 125\ N$$
$$V = 125\ N$$

$$\Sigma M_A = 0 = (-125\ N)(0.001\ m) + M$$
$$M = .125\ Nm$$

The shear stress was calculated for the YZ plane since the beam will shear across the x-axis. The area was calculated as follows:

$$A = b \times l = 0.002\ m \times 0.00675\ m$$
$$A = 0.0000135\ m^2$$

The shear force (*V*) in this case is 125 N so the maximum shear stress in YZ was calculated and then converted to megapascals (MPa).

$$\tau_{YZ} = \frac{3V}{2A} = \frac{3(125\ N)}{2(0.0000135\ m^2)}$$
$$\tau_{YZ} = 138{,}888{,}888.89\ \frac{N}{m^2} \times \left(\frac{1\ MPa}{10^6\ \frac{N}{m^2}}\right) = 13.89\ MPa$$
$$\tau_{YZ} = 13.89\ MPa$$

The hand calculations yield a maximum shear stress in YZ of 13.89 MPa. This beam was modeled in Creo, fixed along the upper surface, and a 125 N distributed load was applied to the bottom surface, opposite to the fixed surface to properly create a cantilever beam. Figure 50 shows the simulated results of these conditions.

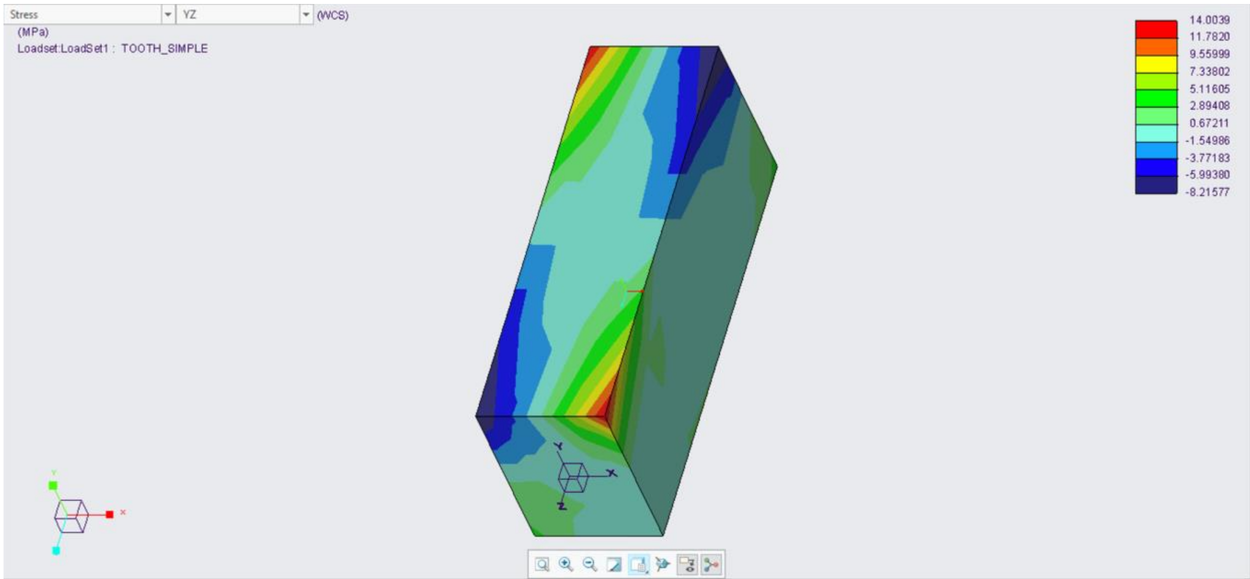


Figure 50: Creo Simulation of Tooth of Locking Key Under Longitudinal Load

As shown in figure 50, the maximum shear stress on the beam in YX is 14.0039 MPa. The hand calculations gave a very similar result, with a difference of only 0.7%, which means the simulation results are valid. This determines that the Creo simulation can be trusted for more complicated cases. These results also show that the stress on the locking key system is much lower than the yield strength of Al 6061 which gives assurance that the design will remain structurally sound.

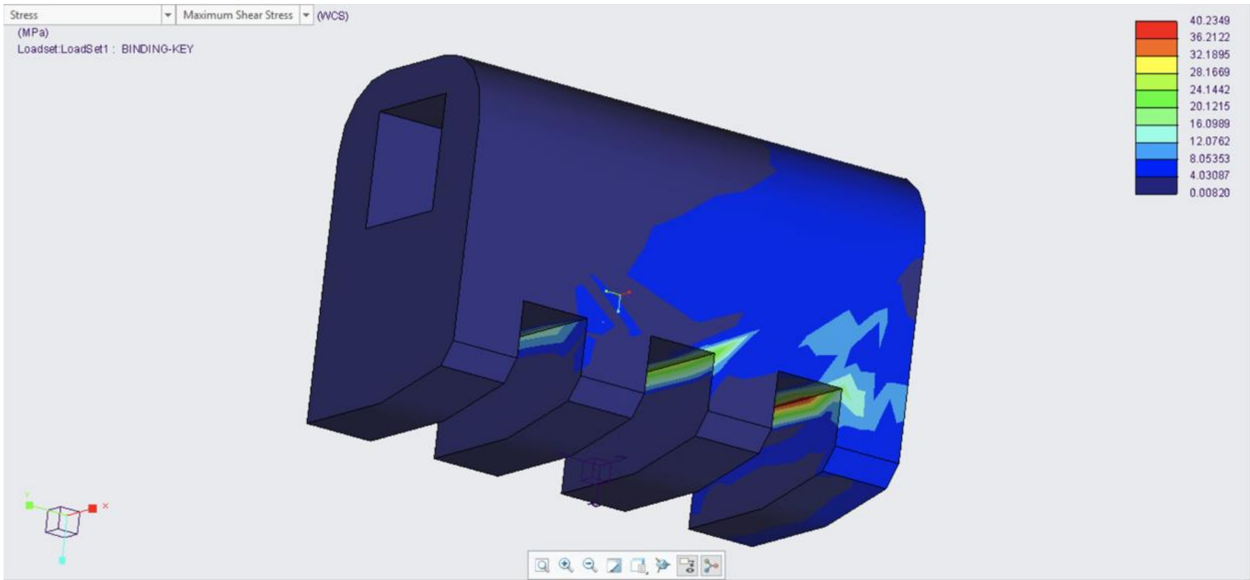


Figure 51: Maximum Shear Stress in Locking Key Unger Longitudinal Force

For the simulation of the full locking key system, the part was constrained on the left facing surfaces of the three rightmost teeth (the surfaces that will oppose translation from the external force). Figure 51 shows that the maximum shear stress occurs on the interior corner of the rightmost tooth. This simulation shows that the key has a maximum shear stress of 40.2349 MPa.

Finally, the factor of safety was calculated to ascertain the possibility of failure. The factor of safety also relates the maximum shear stress to the material's yield strength. The *F.S.* was first calculated for the maximum shear stress in the locking key.

$$F.S. = \frac{Yield\ Strength}{Actual\ Stress} = \frac{276\ MPa}{40.2349\ MPa}$$

$$F.S. = 6.86$$

With the factor of safety of 6.86 we have very high confidence that the locking will not fail under the normal or extreme circumstances that the system will experience.

1.2.3.4 Summary of Hand Calculations and Creo Simulation

The simulations and results show that under intended use our system will provide skiers with a safe and reliable experience. Table 4 shows the factors of safety for each analysis case.

Table 4: Factors of Safety for System

Analysis Case	Factor of Safety
Vertical Force on Tech Toe Plate	94.04
Lateral Force on Tech Toe Plate	6.85
Longitudinal Force on Locking Key	6.86

The vertical case has an extremely high factor of safety and there is no fear that the tech toe plate will fail under these circumstances. The factors of safety for the lateral and longitudinal case are considerably lower than the vertical case, but still very high.

For reference, structural steel in buildings is typically designed to a factor of safety of 4.0-6.0, automobiles to 3.0, and aircrafts range from 1.5-2.5 (*Factors of Safety*, 2010). All the factors of safety for our system are above these values. Under proper use and performance, the tech toe and heel piece will release well before the shear stress in the plate nears the yield strength of the plate, thus releasing the loads from the system and preventing deformation or failure. These calculations and simulations give confidence that our system is properly designed to withstand the forces and environments it will experience and is ready for further prototyping and manufacturing.

2.0 Manufacturing Report

To take our design from a computer model to a physical, manufactured prototype, we needed to ensure our system was designed for manufacturability. This entailed making an initial prototype of the design out of 3D printed PLA and testing the fitment and function of the prototype with the Tyrolia parts. This process is highlighted below. Once initial prototyping was complete, the manufacturing process for the final prototype could be started.

2.1 Initial 3D Print Prototyping

After the initial CAD model was completed, the team 3D printed multiple PLA prototypes. When printing, the team chose to use specific fill properties to create a consistent and effectively printed product. For the tech toe plate, the layer height was defined as 0.2 mm, the wall thickness was 2 mm, and the infill density was 20%. For the key handle and locking key, the layer height was 0.15 mm, the wall thickness was 1 mm, and the infill density was 15%. These values remained the same across all 3D printed prototypes to ensure consistency in tolerances and dimensional accuracy. Once the components finished printing, the team post processed and assembled them. To post process the parts, the structural filament used as supports during the printing process were removed. Parts were then assembled into the completed prototype. Figures 52, 53, and 54 show different angles of the final 3D Printed Prototype.

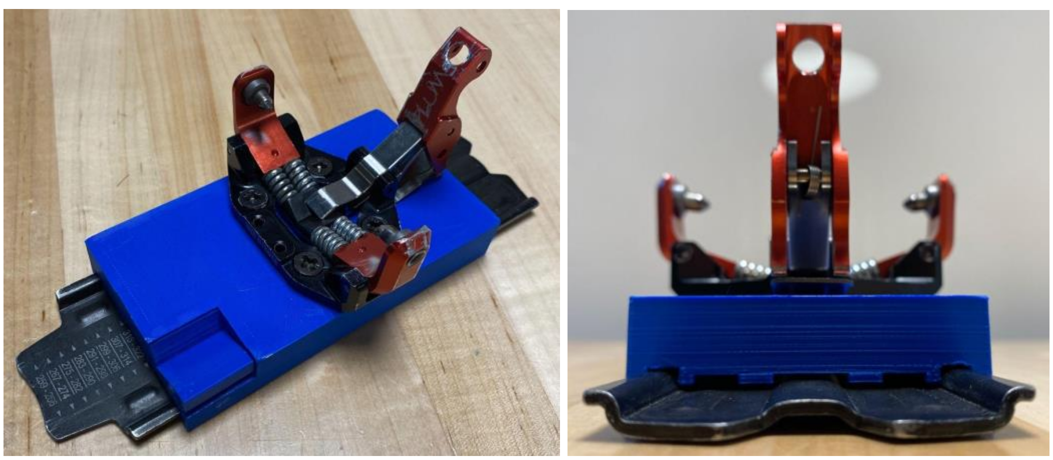


Figure 52: Two Views of the Completed 3D Printed Prototype Mounted to Demo Rail

Figure 53: Underside of Tech Toe Plate with Rail Cutouts and Locking Key Mechanism

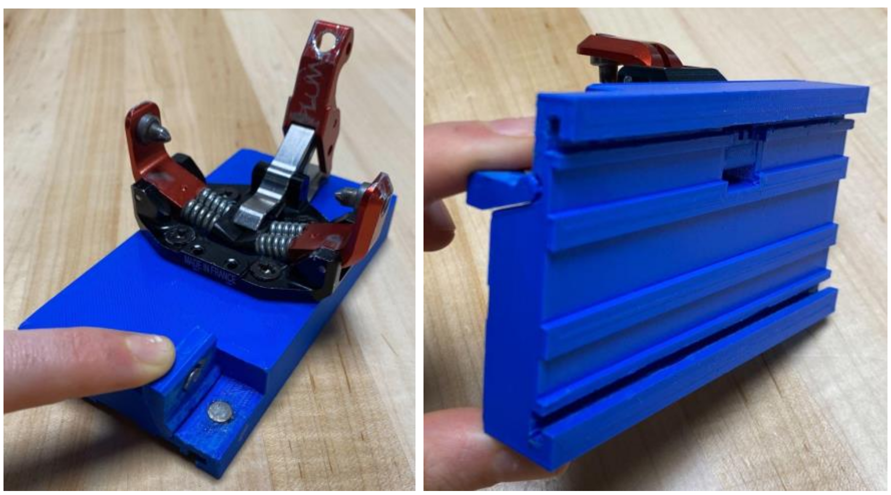


Figure 54: Top and Bottom View of Function of Key Handle, Rod, and Locking Key

The team printed four different iterations of the initial design to adjust for tolerancing and design changes. The above figures display how the system interfaces with the demo rail. As can be seen in figure 52, the tech toe plate slides smoothly and tightly onto the rail. The locking key, shown in figure 53, interfaces properly with the metal locking ridges on the plate. Overall, the 3D printing process was a success that allowed for model modifications and design optimization.

2.1.1 3D Print Prototype Equipment Interface Testing

Once our design components were 3D printed, it was necessary to perform interface testing to determine if adjustments needed to be made. The interface testing entailed assembling the components in the correct orientation and determining if they properly interfaced with one another. This process was necessary to ensure our parts were dimensionally inaccurate. The main areas of concern when determining the accuracy of our components were the demo rail fitting within the rail cutout, the rod and key handle fitting into the hole within the tech toe plate and rotating properly, the rod fitting within the hole in the locking key, and the key interfacing with the locking ridges on the demo rail.

After our first print, the tech toe plate slid onto the demo rail with ease but left a slight wobble when the two components were manipulated. To address this, we decreased the gap for the edges of the rail. The rod and key handle fit within the hole in the plate and after some sanding, the rod was able to be pushed into the locking key, but the tolerances were very tight, and it was difficult for the key to be turned. We determined that it was necessary to reduce the side length of the square rod slightly as well as the diameter of the circular part of the handle. When the locking key was tested, we found that it interfaced with the locking ridges on the rail very poorly. It appeared that the 3D printed teeth on the key were quite inaccurate from the given dimensions. To account for this, the gap between the teeth was increased and the width of the teeth was decreased. In addition, it appeared that the key was slightly too large for the cutout within the plate. The adjustments made to the teeth on the locking key fortunately accounted for the fitment issues between the cutout and the key, so the size of the cutout did not need to be addressed. After making these adjustments, the components fit together properly, and the prototype demonstrated a working function.

2.1.2 Lessons Learned and Next Steps

The 3D printed components provided a lot of information with regards to our design and the manufacturing process. Initially, the intent was to 3D print the final component rather than manufacture it out of metal, but the 3D printing process revealed that this would not be possible.

After determining that nylon would likely be the best material to print the components out of as a final product, we attempted to make a set of the components in nylon. Once finished, the components exhibited poor characteristics and were extremely dimensionally inaccurate. The pieces could be physically deformed and easily broken by hand and the dimensions were extremely poor compared to the 3D model. As we initially had luck with the PLA printed components, we briefly discussed manufacturing the final product out of PLA as we discovered that it has the same strength characteristics, but after further research it was evident that the material was too brittle and would likely be unreliable in field testing.

These discoveries lead us to reconsider manufacturing the components out of metal for the final product. Initially, we were wary of manufacturing the parts out of aluminum as we thought the complex geometries would prove very difficult to machine. After meeting with the machining experts in the Washburn Shops we determined that we could indeed manufacture all our components, and it would likely be necessary to produce parts that exhibited ample strength characteristics. Based on all this information, we determined that it would be best to proceed into the next step with the intent to manufacture all our components out of aluminum and steel.

2.2 Manufacturing Process

The process began by importing our Creo files into Esprit, which is a CAM software that creates toolpaths and simulations, allowing a piece of stock to be turned into the machined part. We used Haas Mini Mills and the AccuteX Wire EDM (electrical discharge machining) to machine the designed parts. The Mini Mills are used for creating simple geometry and features such as facing, drilling, and milling pockets, while the Wire EDM is used to cut more complex geometrical features that milling tools would not be able to reach or replicate. The use of Esprit allowed for trial and error and provided the program for the machines, which then brought our design to life in the form of a fully functional prototype ready for testing.

2.2.1 Tech Toe Plate

The tech toe plate was the first component that was programmed and machined. We chose to machine the plate from stock aluminum that had a width of 3.5 inches, a length of 5 inches, and a height of 1.5 inches. Our material selection process allowed us to conclude that aluminum would be the lightest, most sourceable material option that would also withstand the assumed applied stresses on the system. Our stock material was sourced from the WPI Washburn Laboratories Machine Shop. The tech toe plate was machined using both the Haas Mini Mill and the AccuteX Wire EDM.

The process to complete the tech toe plate took many steps. Figure 55 shows the modeled plate with assigned reference numbers for the six different faces.

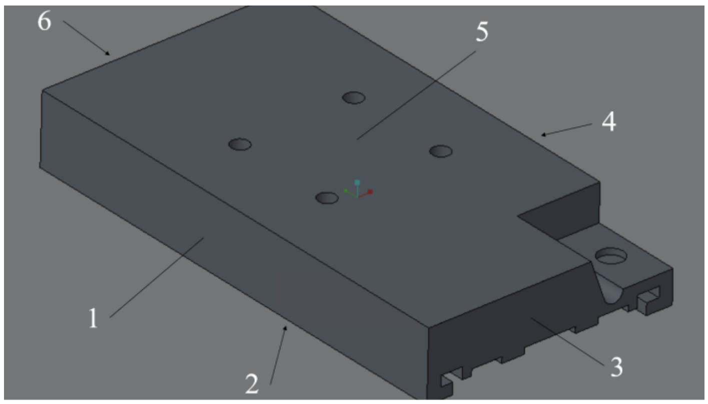


Figure 55: Final Tech Toe Plate with Face References

We began by exporting the Creo model to a STEP file which was imported into Esprit. Then we wrote the Esprit program that would guide the following steps of machining on the Mini Mill. Figure 56 shows the tools used to create the features of the tech toe plate.

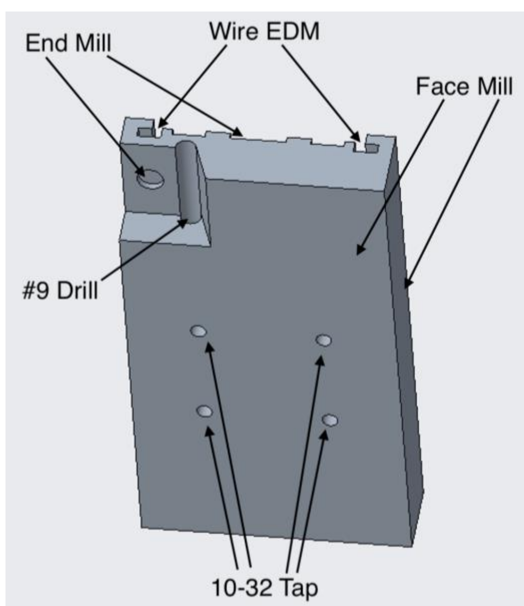


Figure 56: Tools Used to Create Each Feature of the Tech Toe Plate

The first two operations dimensioned the plate down to the proper width. A 3-inch end mill was used to face side 1 of the stock material to eliminate any roughness and create a clean finish. The part was then flipped in the vice jaws and the origin of the part was probed at the top of the parallels. Figure 57 shows the part after these initial steps.

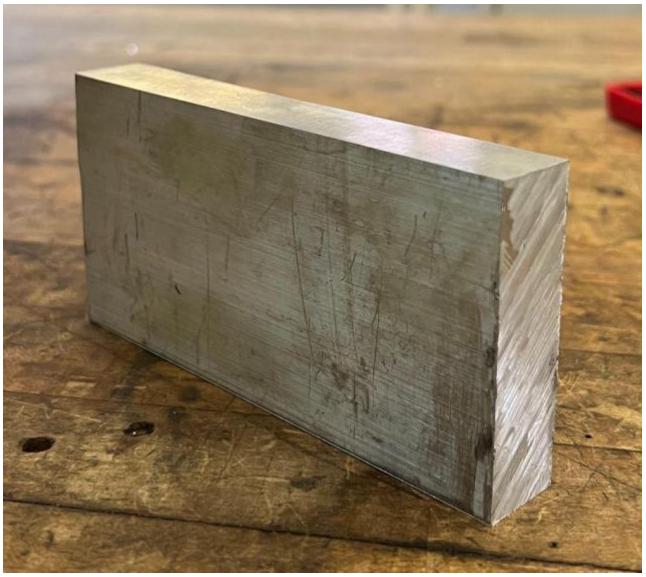


Figure 57: Progress After Initial Milling Operation

The unfinished side, face 4, was then faced down with the 3-inch face mill, creating an accurate width. The next two operations faced the part down to the proper length. First, the ⅜-inch end mill faced a level surface on face 6. The opposite side of the part, face 3 was then milled down to the necessary length dimension. The final stage of this operation consisted of facing side 5 of the stock material, creating spot holes, drilling four mounting holes, drilling a pocketing hole, and cutting an even chamfer around the edge of the part with a ⅜-inch chamfer mill. The four mounting holes were then threaded with a 10-32 manual drill tap to create threads to mount the toe piece to the plate with 10-32 screws on face 5.

At this point in the machining process, five out of the six faces of the part had undergone cutting operations. For face 2, a 3-inch face mill started by bringing the part down to the correct height. Next a ¼-inch end mill created grooves along the rail interfacing surface by cutting away excess material. Using an ⅛-inch end mill, a square pocket was made for the locking key component of the system to sit in. Finally, a chamfer was made around the edge of the part with a ⅜-inch chamfer mill. This operation finalized the base shape for the part. Figure 58 shows the simulated machining process for this operation in Esprit.

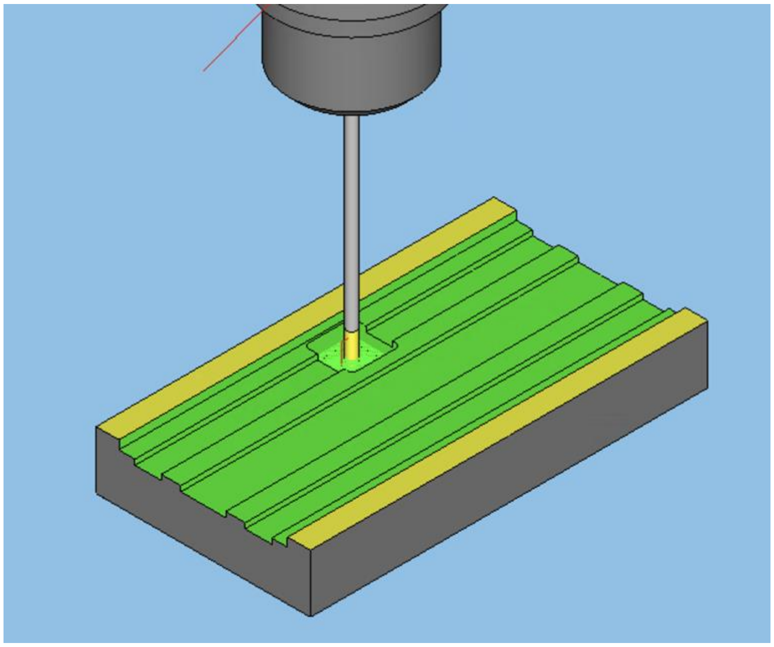


Figure 58: Pocketing Operation Simulation in Esprit

The final milling operation on the tech toe plate created a pocket to fit the dimensions of the key handle component. The part was oriented in the vice so that a #9 drill with a 0.196 inch diameter could create a hole from the top of the part on face 3 through to the pocket for the locking key. This hole serves to later connect the handle to the locking key with ⅛ inch key stock. A ¼-inch end mill was then used to cut away material from face 5 to create the exact space for the handle to sit in. This operation completed the steps that were achievable on the Haas Mini Mill. The part during this stage can be seen in figure 59 below.

Figure 59: Key Handle Pocket Operation

For the final step to complete the tech toe plate component, the wire EDM was used. This tool allowed us to cut away the final sections of material that were limiting the plate from sliding onto the mounting rail. The operation was programmed in Esprit and the plate was placed upright in the vice jaws as seen in figure 60. Finally, the machine used electric discharges to generate sparks to cut away the necessary material. This was the final operation performed to create the tech toe plate for the system. The results of these steps can be seen in figure 61.

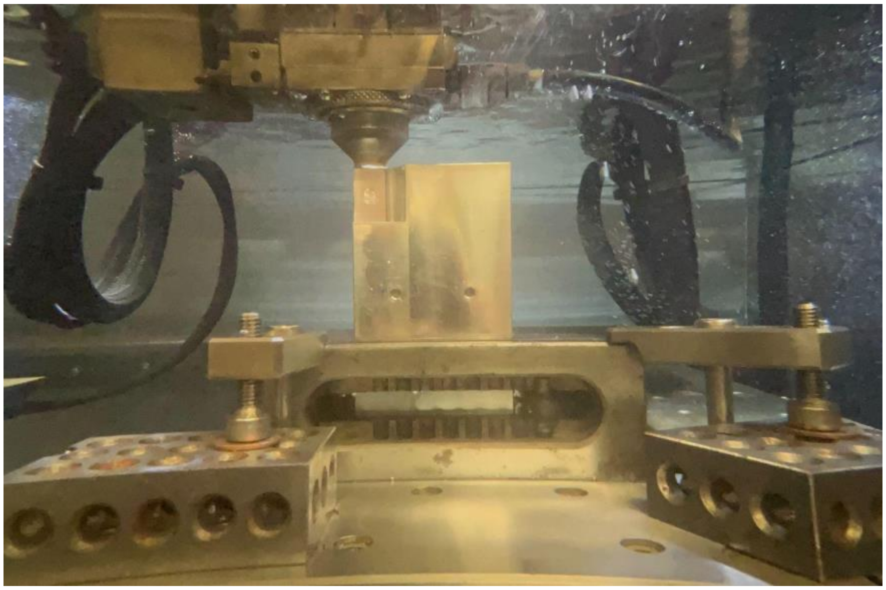


Figure 60: Tech Toe Plate Operation in Wire EDM

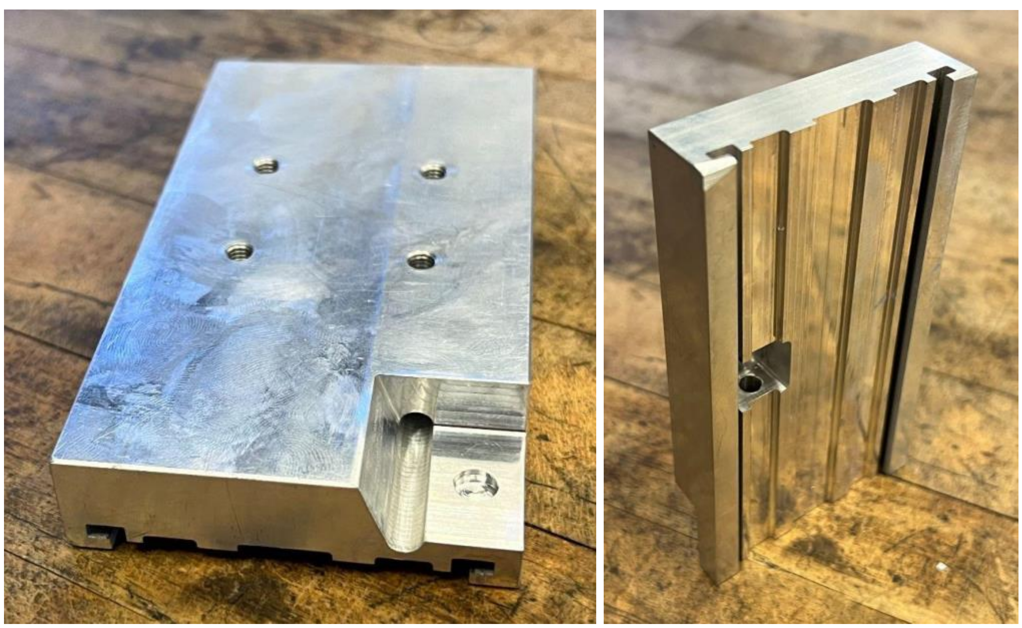


Figure 61: Top and Bottom View of Completed Tech Toe Plate Component

2.2.2 Locking Key

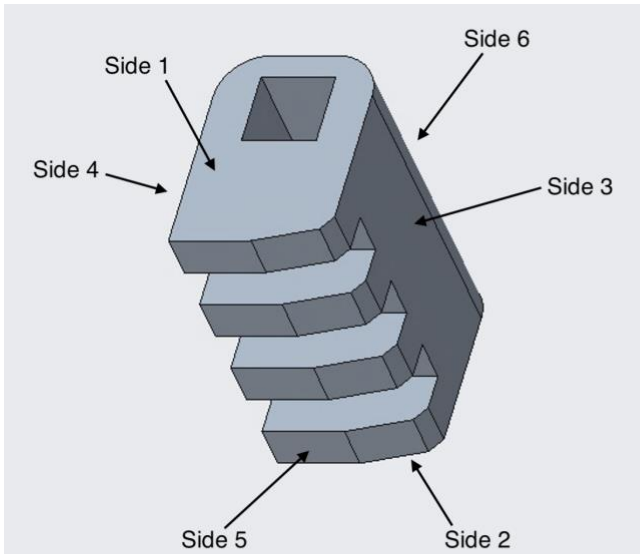


Figure 62: Isometric View of Locking Key Designating Each Side

The locking key, shown in figure 62, was the second part to be prototyped. Since the system was changed for locking key, key handle, and rod assembly to be three separate pieces, the design of the key was changed slightly. The square pocket in the locking key was changed to a through-all pocket and the dimensions of the square pocket were adjusted for a "loose" press fit with the ⅛ inch key stock. Once these changes were made the Creo model was exported to a STEP file that was imported into Esprit.

The locking key was machined using the Mini Mill, Wire EDM, and Super Mini Mill. The Mini Mill was used for simple operations such as facing and drilling, the Wire EDM was used for complex profiles, and the Super Mini Mill was used for precise features. To create the key, several machining stages, and a piece of stock greater than the length, width, and height of the key was necessary. The stock was cut to the height of the key and pilot holes were drilled on the mill in the first stage. In the second stage, the Wire EDM was used to cut the square through-all pocket and cut the vertical profile of the key. In the last stage, the key was brought to the Super Mini Mill for the teeth to be milled out.

The Esprit program began by orienting the locking key in the program and defining a stock material. A stock material much larger than the key was chosen to allow for multiple instances of the key to be machined from the same stock and so the stock could be fixtured well in the Wire EDM. The key was oriented, so it was slightly inset from the bottom left corner of the stock to allow for four separate keys to fit in the same stock and increase machinability. Figure 63 shows the locking key and which machines were used to create each feature.

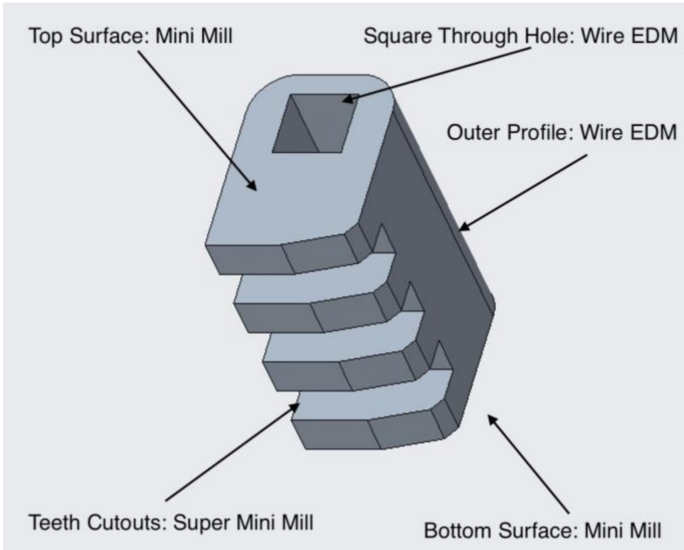


Figure 63: Tools Used to Create Each Feature of the Locking Key

The first two programs written for the locking key were performed on the Mini Mill and were used to face the stock, cut it down to the proper height, and drill pilot holes for the square through pocket. The pilot holes were drilled so the Wire EDM could be threaded through to cut the proper profile for the square through pocket. Figure 64 shows the second program for the key.

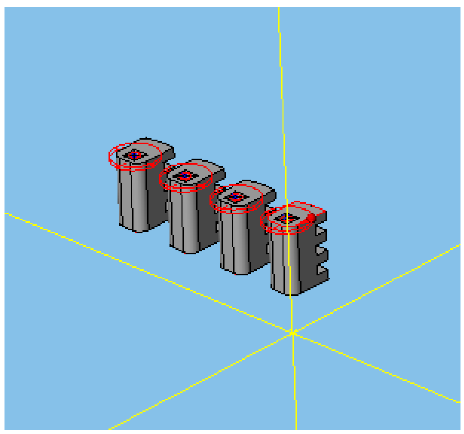
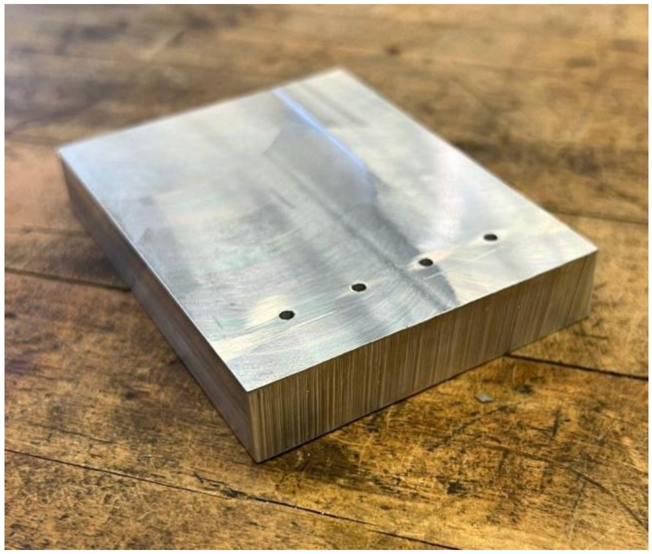


Figure 64: Screenshot of Esprit File Showing Four Separate Locking Keys and Tool Paths

The first program used the 3-inch face mill to remove a small amount of material from the bottom of the stock to give it a smooth finish. During the first operation sides three and four were held in the vice and side 2 was faced. For the second program, the stock was again held in the vice on sides three and four, but side one faced upwards so it could be machined. The face mill removed material from side one until the proper height of the key was reached. Once this operation was complete, a ⅜-inch chamfer mill was used to drill a spot hole on side one. Next, a #43 drill (which has a 0.0890 inch diameter), was used for a peck operation to drill a pilot hole on side one. The spot and peck drill operations were performed four times on side one for four separate instances of the locking key in the stock. Figure 65 shows the stock after these operations were formed.



Figures 65: Stock Material for Locking Key After First Two Programs

The stock shown above will allow the Wire EDM to cut several instances of the locking key; we chose to place four keys in the stock so if there were any issues in the manufacturing process, we could make the necessary changes and have backups.

Once the first stage of the manufacturing process was complete, the stock was fixtured in the Wire EDM for the second stage of the process; side two was placed downwards and fixtures were placed on sides three and four. Side five faced inwards towards the wire. The wire was threaded through the first pilot hole and the operation to cut the square through-all pocket was run. Once the pocket was cut, the wire was cut, repositioned, and re-threaded outside of the stock so the profile of the key could be cut. Figure 66 below shows the Wire EDM in progress.

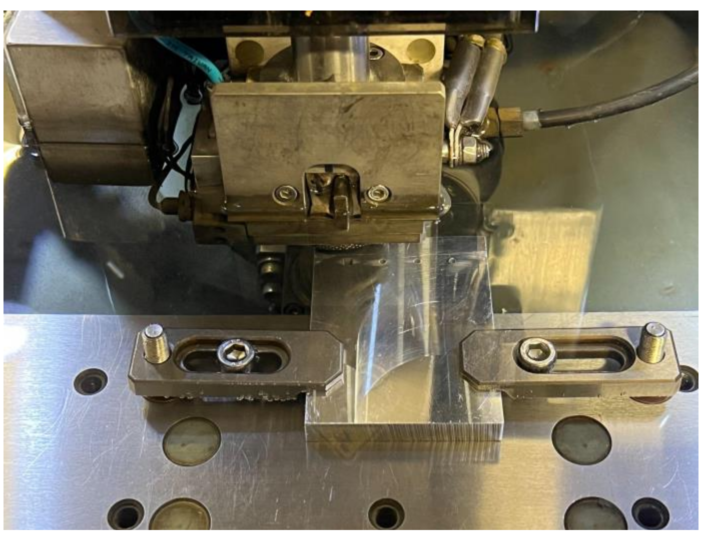


Figure 66: Wire EDM Cutting Profile of Locking Key

Upon analyzing the first locking key, it was apparent the dimensions were slightly off, and the program needed to be changed. We changed the program to account for the wire diameter and offset accordingly. Figure 67 shows how the keys were cut from the stock material using the Wire EDM.

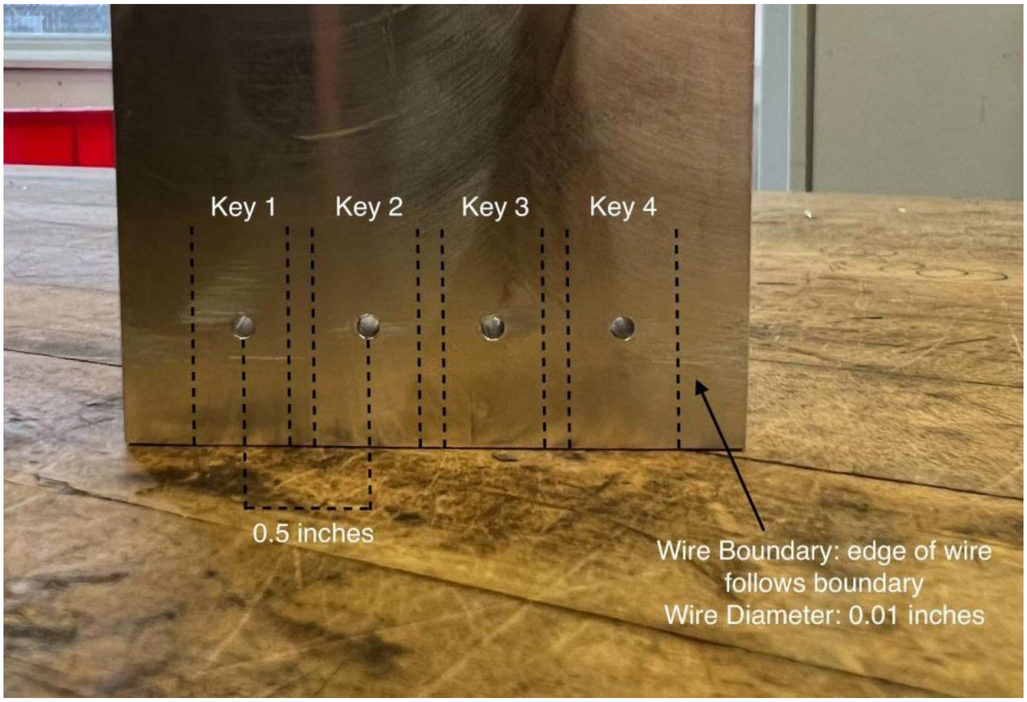


Figure 67: Wire EDM Cut Boundary for Locking Key

We ran the program again and the locking key was much more dimensionally accurate. Figure68 shows the key after cutting on the Wire EDM.


Figure 68: Two Perspectives of the Locking Key After the Wire EDM Operations

The final stage of manufacturing for the key was performed on the super Mini Mill. The super Mini Mill was used for pocketing out the teeth of the key. Since the pockets are so small a 3/64-inch end mill was used for the operation. Small tools perform better when they can be run at higher speeds and the super Mini Mill has a maximum RPM (rotations per minute) of 15,000, while the regular Mini mill only has a maximum RPM of 6,000. Sides three and four were fixtures in the vice of the Super Mini Mill with side five facing upwards so the teeth could be cut. The operation was performed successfully and figures 69 and 70 show the Super Mini Mill cutting the teeth and the final machined locking key, respectively.

Figure 69: Super Mini Mill in Progress

Figure 70: Two Perspectives of the Final Machined Locking Key

2.2.3 Key Handle

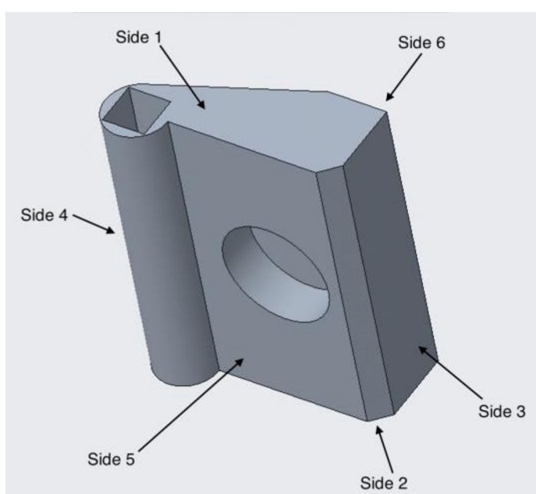


Figure 71: Isometric View of the Key Handle Designating Each Side

The key handle, shown in figure 71, was manufactured very similarly to the locking key and the same approach was taken in the early stages. Again, the first step was to modify the Creo model due to design changes. The rod extruding from the handle, initially used for the 3D printed prototype, was replaced by a square through-all pocket in the same position to allow for the key stock to be inserted. The square through pocket was dimensioned for a "loose" press-fit with the ⅛ inch key stock used for the rod. Then the model was exported as a STEP file and brought into Esprit.

The ley handle was machined using the same strategy as the locking key, using the Mini Mill for facing, pocketing, and drilling, and using the Wire EDM for through cuts and the outer profile. A piece of stock greater than the length, width, and height of the handle was chosen, and the machining stages for the handle followed the stages used to machine the locking key. The Mini Mill was used in the first stage to cut the stock down to its vertical height and drill pilot holes. The Wire EDM was then used to cut out the square through-all pocket and cut the outer profile of the handle. Lastly, the Mini Mill was used to cut the pocket on the underside of the handle where the magnet sits. Figure 72 shows the machines used to create each feature.

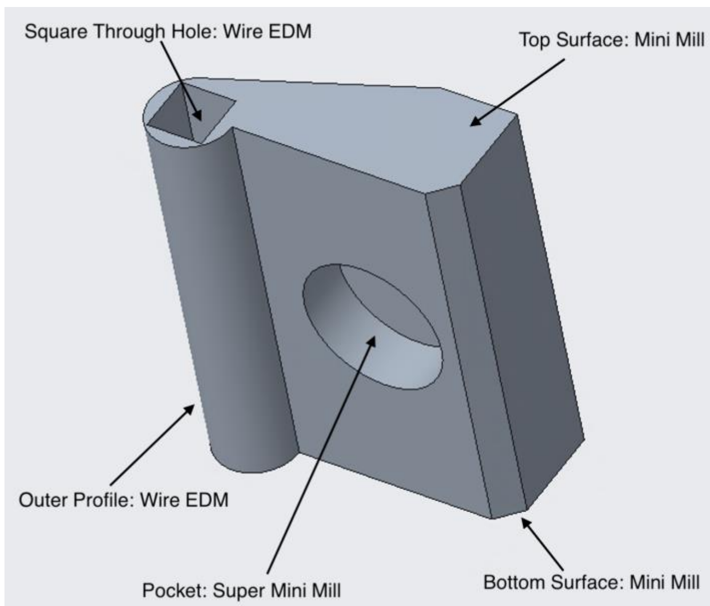


Figure 72: Tools Used to Create Each Feature of the Key Handle

A stock was chosen for the key handle, and like the locking key, a large piece of stock was selected so multiple instances of the handle could be machined from one stock and for secure fixturing in the Wire EDM. The handle was oriented in the same fashion the locking key was, but only two instances of the handle were able to fit on the stock material.

Again, the first two programs for the key handle mirrored the first two programs for the locking key, completing the same purpose and using the same tools. The first program faced one side of the stock to create a smooth and even surface; the stock was fixed in the mini vice on sides five and six, with side two facing upwards for the cutting operation. The second program used the face mill to cut the second side down to the correct height and drill pilot holes for the square through hole for the Wire EDM to be threaded through. For the second operation sides five and six were again fixtured in the vice, but side one faced upwards for the operations. The spot and peck drilling operations were performed twice to create two separate instances of the handle, shown in figure 73b.

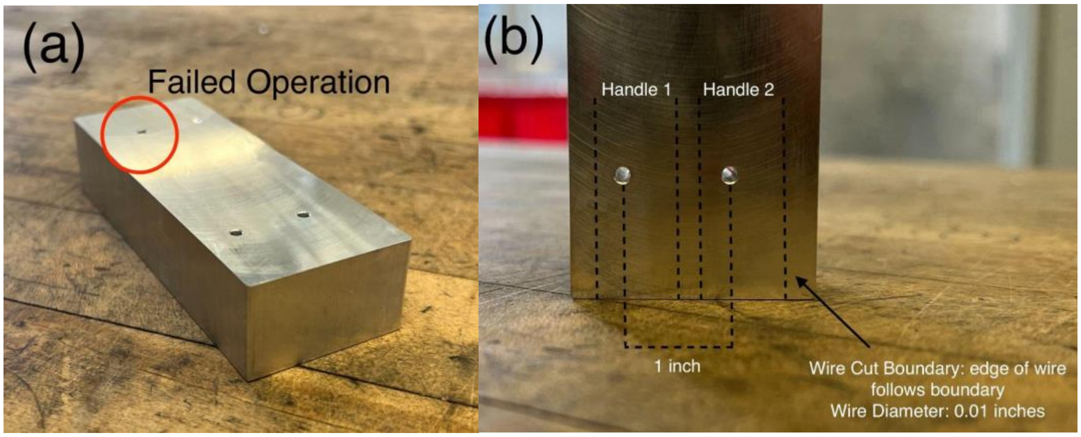


Figure 73: Stock Material for Key Handle Showing (a) Pilot Holes and (b) Instances of Key Handle

As seen in figure 73a, both sides of the stock material have holes. During the first pecking operation, the drill bit broke towards the end of the peck and became stuck in the stock material. The cause of the break is not known, but it could have been due to wear on the bit over time, poor coolant on the bit, or too large of pecking increments. The peck increments were initially set to 0.0890 inches (the diameter of the bit and standard practice) but were changed to 0.050 inches after breaking the bit. Since there was so much excess stock for the handle, the stock was simply rotated 180 degrees in the vice, so sides three and four were switched from the first attempt, and the spot and peck operations were formed on the clean side. The second run of these operations were formed successfully.

During the second stage of the manufacturing process of the Key handle, the Wire EDM was used. The stock was secured in the wire very similarly to the locking key; side two was placed downwards, fixtures were placed on sides five and six, and side three faced towards the wire. Like the locking key, the Wire EDM was threaded through the pilot hole in the handle to cut the square through-all pocket and then re-threaded to cut the outer profile. Figure 74 shows the handle after the Wire EDM performed its operations.

Figure 74: Two Perspectives of the Key Handle After the Wire EDM Operations

For the final stage of the key handle's manufacturing process, the pocket for the magnet was milled. Since the pocket for the magnet was over about 0.3 inches in diameter, the ¼-inch end mill was used for the operation. Either the regular Mini Mill or the super Mini Mill could be used for this operation, but it was performed during the final operations of the locking key, so the super Mini Mill was used. The handle was carefully fixtured in the mill since only a small portion of the handle is parallel to the surface where the magnet sits. The operation was performed successfully and figure 75 shows the final machined handle.

Figure 75: Two Perspectives of the Final Machined Key Handle

2.3 Quality of Artifact

After the manufacturing process was completed, the following final components remained: the tech toe plate, the key handle, the rod, and the locking key. Together these components form the final prototype. It is important to mention that none of the dimensions of the final product match the computer model exactly. This is due to small deflections and imperfections within the mill and mill tooling as well as the inability to perfectly fixture the workpiece in the mill's vice. Variations from the computer-based drawing were in the order of thousandths of an inch. The first component that was completed during the manufacturing process was the tech toe plate. The plate was manufactured for the most part on the Haas Mini Mill except for the slots at the edge of the rail cut-outs, which were manufactured using the AccuteX Wire EDM. The use of the Mini Mill allowed for very tight tolerances and accurate dimensions to be maintained. In addition, the Mini Mill provides a mirror-like metallic finish on the final product. Images of the finished tech toe plate can be seen below in figure 76.

Figure 76: Three Perspectives of the Final Tech Toe Plate

The images above show the various critical features of the tech toe plate. These features include the mounting holes for the tech toe mounting screws, the cut-out for the key handle and rod, the clearance pocket for the locking key, and the cut-outs for the rail. After threading the mounting holes and testing the fitment of the tech toe piece, we found that the screws sat flush with the countersinks on the toe piece, and the toe piece was securely held onto the plate. This function can be seen below in figure 77.

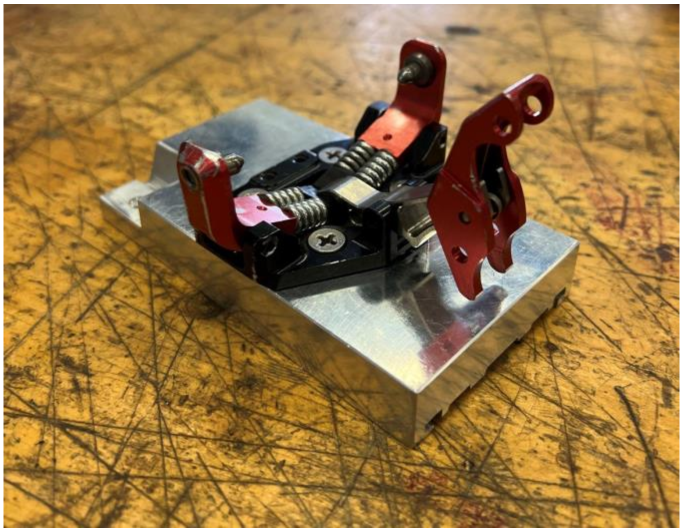


Figure 77: Tech Toe Piece Securely Bolted to Tech Toe Plate

The next critical features are the cut-out for the key handle and rod, and the pocket for the locking key. We made preliminary measurements of these two features to see if they were of a reasonable dimension, but until the key handle and locking key were machined it was not possible to perform a final check on proper dimensioning.

The last and perhaps most important feature of the tech toe plate are the cut-outs for the rail. The tolerance is crucial for this feature as the plate can either be too difficult to slide onto the rail or have too much play. Our goal in dimensioning this component and subsequently machining it was to mimic the tolerance of the alpine toe piece from Tyrolia. Their toe piece allowed for easy attachment and removal as well as a slight wiggle between the components when the locking key was not engaged. After the plate was finished, the fitment was tested directly with the mounting rail to be used in the final prototype. Figure 78 below depicts the fitment between the components.

Figure 78: Two Perspectives of the Fitment Between Tech Toe Plate and Tyrolia Rail

As can be seen above, the tech plate exhibited excellent clearance for the rail. When manipulated, the rail slid easily in and out of the cut-outs and there was slight play between the components as expected.

The next component, the key handle, was manufactured using the Haas Mini Mill, the AccuteX Wire EDM, and the Haas Super Mini Mill. Between these three machines we were able to obtain a final piece that reflected our design choices. The Wire EDM left a rough surface finish while the Mini Mill left a mirror like finish as seen on the plate. Below in figure 79, the differences in surface finish can be seen.

Figure 79: Two Perspectives of Key Handle Component Showing Different Surface Finishes

The key handle has only one critical feature, which is the square hole within the circular part of the handle as seen above in figure 79. This feature needs to be large enough to allow the ⅛ inch key stock to fit inside of it, but it also needs to be tight enough so that the key stock would press fit in place. After the square hole was finished on the EDM, we confirmed that this fitment was correct with the key stock.

The other features of the key handle: the pocket for the magnet as seen in figure 79 and the general shape to allow for free and ample movement of the handle within the cut-out on the plate came out as intended based on our design. When we compared the overall size of the handle with the cut-out on the plate, the fitment allowed for proper movement. It is important to note that due to the Wire EDM's entry and exit strategy, a small ridge was left on the top part of the handle, which can be seen in figure 79. This ridge does not affect the functionality of the part in any way, so it is not a concern, but it is important to note.

Like the key handle, the locking key was manufactured on the Haas Mini Mill, the AccuteX Wire EDM, and the Haas Super Mini Mill, so it exhibited similar surface finishes. The final locking key component can be seen below in figure 80.

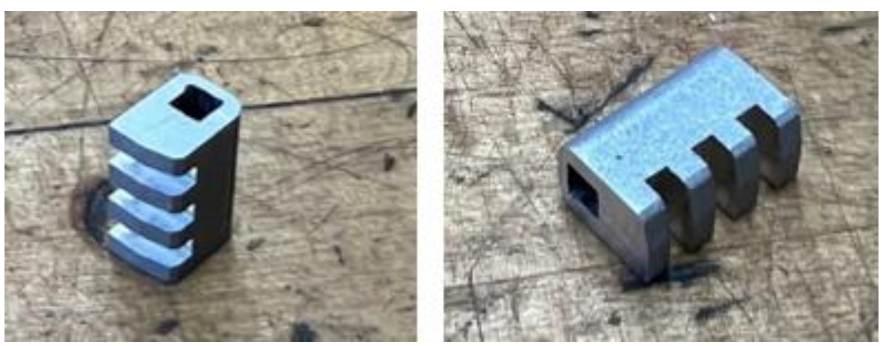


Figure 80: Two Perspectives of the Final Locking Key

The locking key has two critical features. These features are the square hole for the rod and the teeth that would mesh with the ridges on the mounting rail. After the Wire EDM was finished cutting the square hole and outer profile for the key, its fitment was tested. The key was designed, so that the rod would slide in place, but would be snugly fit inside with little play. After testing, this fitment was confirmed.

The teeth need to fit snugly on the ridges of the mounting rail, but it was also crucial that they allowed for easy movement as this piece is required to rotate into and out of these ridges after being fully assembled. After these teeth were pocketed out on the Super Mini Mill, this fitment was confirmed through testing with the locking key and the mounting rail.

2.3.1 Assembly of Final Prototype

The key handle, locking key, and rod were machined as individual pieces that were assembled with the tech toe plate once all the components were complete. While the key handle, locking key, and rod act as one subassembly of the system, if they were assembled first, they would not be able to be assembled with the plate. The loving key must be put in its place in the plate before having the rod inserted into the square hole. This is also why the locking key and rod were not machined as one piece. Initially we designed the handle and rod to be one piece, however we discovered it would be too time consuming and difficult to machine a long narrow square rod protruding from the handle. Therefore, we chose to make the rod its own component and instead of machining the rod, we chose to use steel key stock because it is much faster and cheaper.

With the completed tech toe plate, key handle, and locking key, the components can be assembled into the final prototype. The first step was to cut the rod down to the proper length. This length was based on the distance from the back of the key handle to the front of the locking key when they were properly assembled within the tech toe plate. After being cut down to length, the rod was pressed into the handle. Below in figure 81, the press fitting process can be seen.

Figure 81: Pressing the Rod into the Key Handle Using the Arbor Press (image shown for demonstration only)

This process was done using the arbor press and as anticipated, the rod slid into the key handle with relative ease. The locking key was fitted onto the rod to finish the sub-assembly seen below in figure 82. This sub-assembly depicts how the key handle and locking key will function within the plate. The hole for the rod in the locking key was made slightly larger than the rod, which means that the rod could not be pressed into the locking key. Instead, when the final assembly was taking place, a small drop of super glue was placed in the key and the rod was pushed into the hole as it would sit in the final assembly with the tech toe plate.

Figure 82: Key Handle with Rod Pressed into Place and Locking Key Attached

Before the entire assembly is put together, the magnets need to be put in the designated pockets within the key handle and the tech toe plate. These magnets will work in conjunction to hold the handle and subsequently the locking key in place when they are in the down position. The pocket in the plate was made to a diameter equal to that of the magnet. This required that the magnet be pressed into place. This was done using a similar process to what was used on the handle and rod. For the handle, the pocket was made slightly oversized with respect to the magnet diameter. This required the magnet to be glued in place. After drying, the system worked as intended. An image of the magnets when in place can be seen below in figure 83.

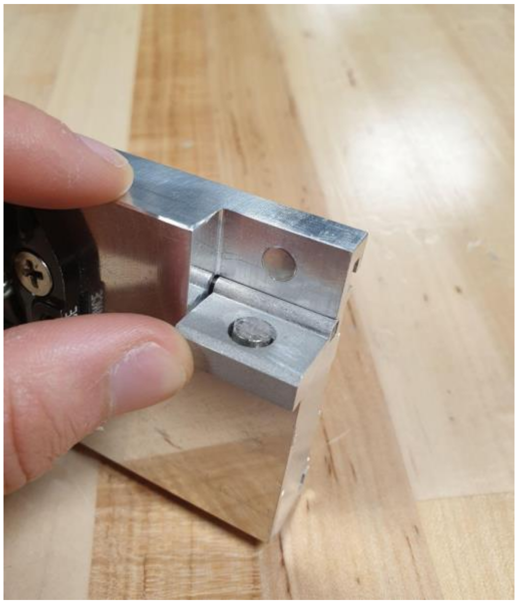


Figure 83: Magnets in place

Next, the key handle with rod attached was inserted into the tech toe plate and the locking key was attached at the opposite end in its designated clearance pocket. The ability for the locking key to properly interface with the mounting rail when toggled using the handle was tested, which confirmed the prototype's ability to function properly. As expected, the key locked and unlocked properly with the ridges on the mounting rail. This final assembly can be seen below in figure 84.

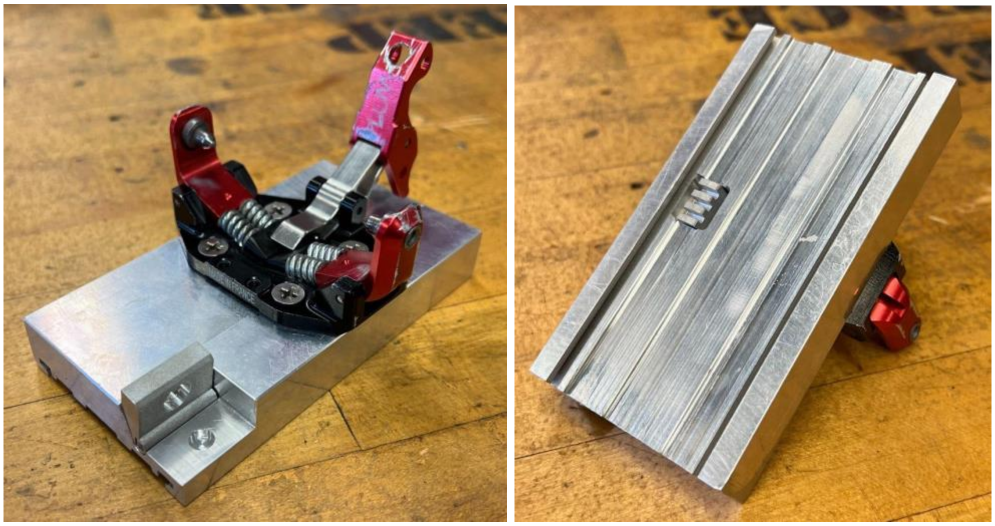


Figure 84: Top and Bottom View of the Final Prototype Assembly

3.0 Testing Report

A 3D printed prototype was fabricated to test the locking mechanism and the kinematics of the assembly. The prototype was also tested under stress to decide whether a 3D printed plastic was suitable for the final product. Next, the team sought to confirm the functionality of our binding system in both uphill and downhill scenarios. To test the uphill functionality of the system, the team brought the prototype to Wachusett Mountain Ski Resort. The downhill functionality of the system was tested at Killington Ski Resort, in which each team member took multiple runs using the system and evaluating its performance. Furthermore, durability was assessed after use.

3.1 3D Printed Prototype Strength Testing

The lab testing portion for our prototype was vital to understand how the part would break under specific forces. As a preliminary evaluation of the structural integrity of our part as it is subjected to forces during skiing, we performed hand calculations to evaluate the applied stresses on an aluminum model in various axes. Though we had previously calculated and simulated these forces for the aluminum model, we wanted to use lab testing as a means of understanding the limitations of the 3D printed model. Due to the layered effect of 3D printing, it was challenging to calculate or simulate how the forces would affect the part. The three cases we analyzed, shown in figures 85 and 85, were:

1. failure of the tech toe plate in the vertical direction,
2. failure of the tech toe plate in the lateral direction,
3. and failure of the locking key in the longitudinal direction.

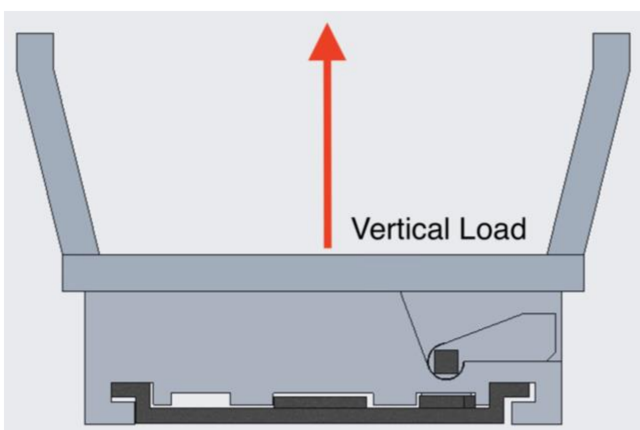


Figure 85: Schematic of Applied Vertical Force

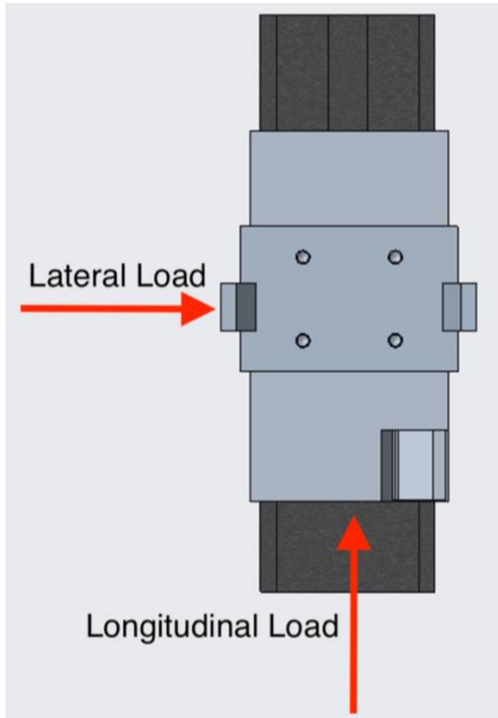


Figure 86: Schematic of Applied Lateral and Longitudinal Forces

When assessing how to test these three cases of failure in a controlled setting, our options were limited. With the testing machines available to us, we determined that we could successfully test the failure of our part in the lateral direction. To complete this test, we used the Instron tensile stress machine to pull the tech toe plate apart and determine its failure point.

To perform the test, we first needed to design and manufacture the proper fixturing components to ensure that the part would break properly under tensile stress. The image in figure 87 shows the completed components that fixture the tech toe plate to the Instron tensile stress machine. Figure 88 shows the part fixtured into the machine, ready for testing.

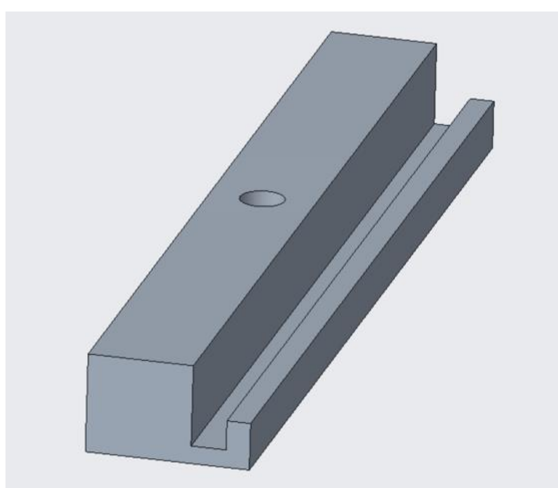


Figure 87: CAD Model of Fixturing Part for Instron Tensile Testing

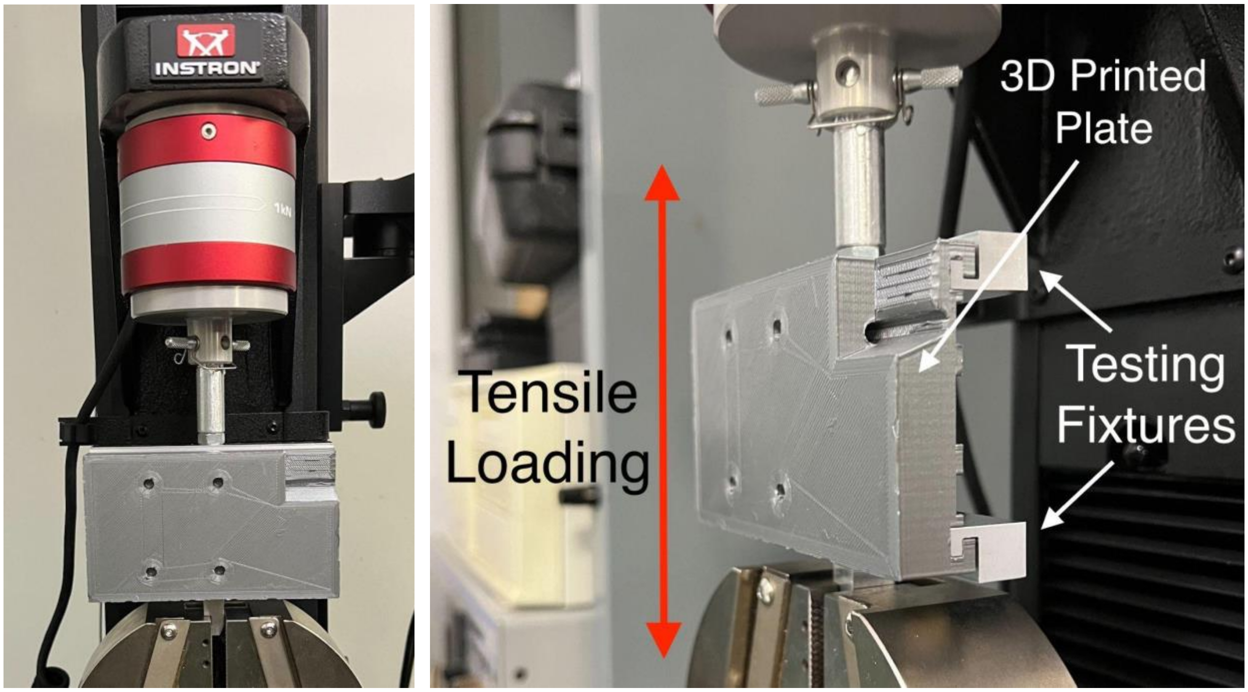


Figure 88: Two Views of the PLA Prototype Fixtured in the Instron Tensile Machine

Once the part was mounted in the testing machine using the fixturing components that we designed, a method was made to run the proper test. A tension method was created with dimensions of the part and the desired process for putting the part under tensile load. Once this tension testing method was saved to the machine, the load and displacement values were zeroed, and the test was started.

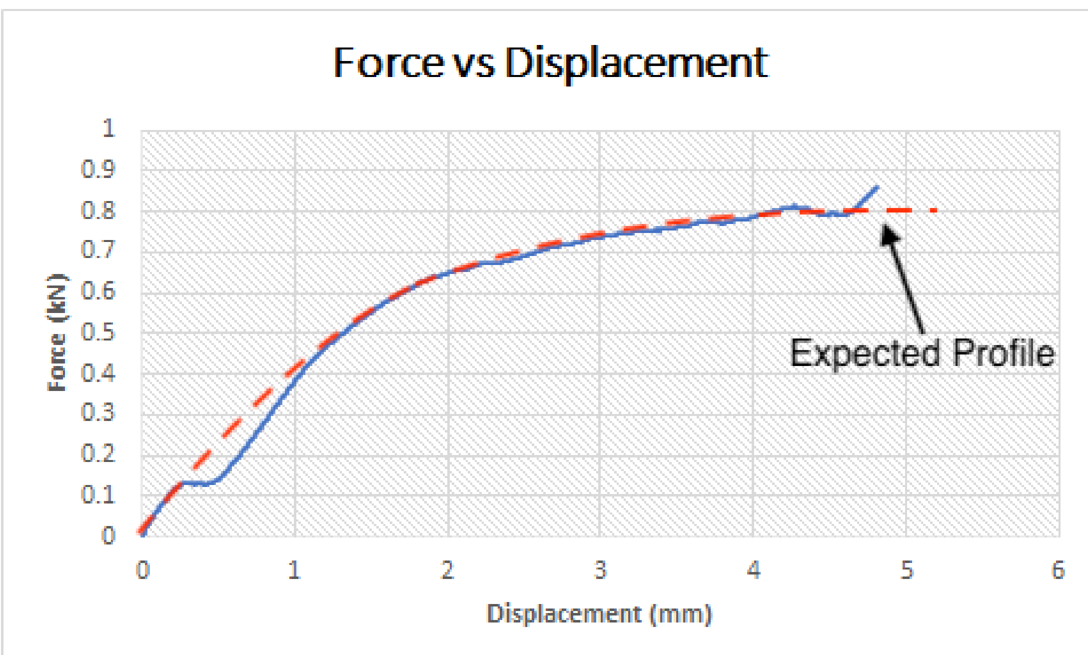


Figure 89: Force vs Displacement Results for Instron Tensile Testing

Due to the capability of the machine, we were only able to test the part up to 861 N of tensile loading. As can be seen in the graph in figure 89, this was not enough to break the part. There were minor fluctuations in the force graph. The first of these fluctuations occurs at the displacement of 0.35 mm and can be attributed to the part moving in the fixture before it is fully under tensile loading. The second flattening event in the graph at 4.4 mm of displacement because the part slipped slightly in the vice due to the extensive force applied on the system. Though the part did not break in the machine, it did deform slightly under tensile loading as can be seen in figure 90.

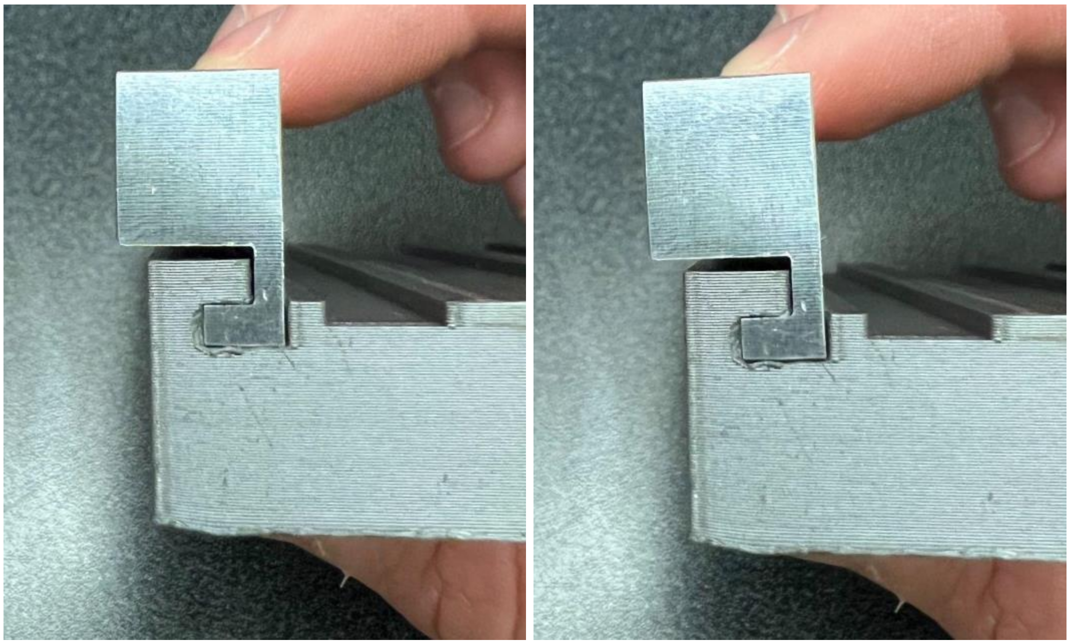


Figure 90: Deformation of PLA Tech Toe Plate from Instron Tensile Testing

The slight deformation is seen by the small gap created by tensile loading in figure 90. This deformation means that the fixtures slide more freely into the tech toe plate and the plate sits less securely on the demo rail. The play in the plate can cause movement and chatter, and other potential issues in the field while in use. This test was performed along the layers of the 3D printed PLA which shows that the material has a high resistance to tensile strength. However, we could manually break the part with minimal hand strength when loading the plate against the layers, showing that the bond between layers of PLA is very weak and much more susceptible to breaking under shear stress. Figure 91 shows the differences between tensile and shear loading in relation to the layers of the 3D printed part.

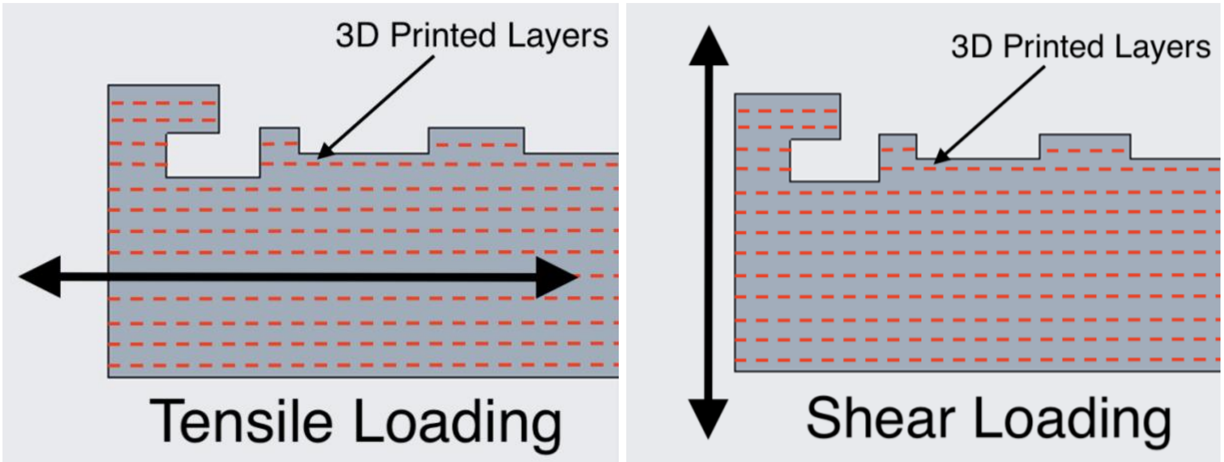


Figure 91: Tensile vs. Shear Loading of the 3D Printed Plate

For the purposes of this project, we understand that 3D printing PLA is not the right material choice for our final design. We do not have faith in 3D printed PLA for our intended use cases. Other cons of PLA are its brittleness in cold temperatures, the inaccuracies in the printing process, and the post processing time it takes to remove support material from the rail slots. However, given the results of the test and the reluctance of the PLA to break, we expect plastic materials to be an effective material with a different manufacturing process. Injection molding is a common manufacturing method used in the ski binding industry so we expect this process could be an optimal choice for our purpose, but we lacked access to this resource. For these reasons we chose to manufacture aluminum for our final product.

3.2 On Snow Testing

The on-snow phase of testing for the prototype was crucial to determine if the design would be a viable product for regular alpine and backcountry use. We expected the design to perform adequately in comparison to the industry standard and we designed our testing plan to understand if this was the case. Additionally, it was necessary to determine if the prototype would work correctly without failing in the field. Before we could test the prototype, we mounted the entire binding system to a pair of skis. The mounting rails for the Tyrolia Attack2 13 demo binding were mounted to the ski using a paper mounting template. Once the rails were mounted in place, the Voile STS risers were screwed onto the ski. With the rails in place, the Tyrolia toe and heel pieces and our designed tech toe plate could be attached to the mounting rails as desired. The final binding system is pictured below in figure 92 with one tech toe plate and one alpine toe attached.

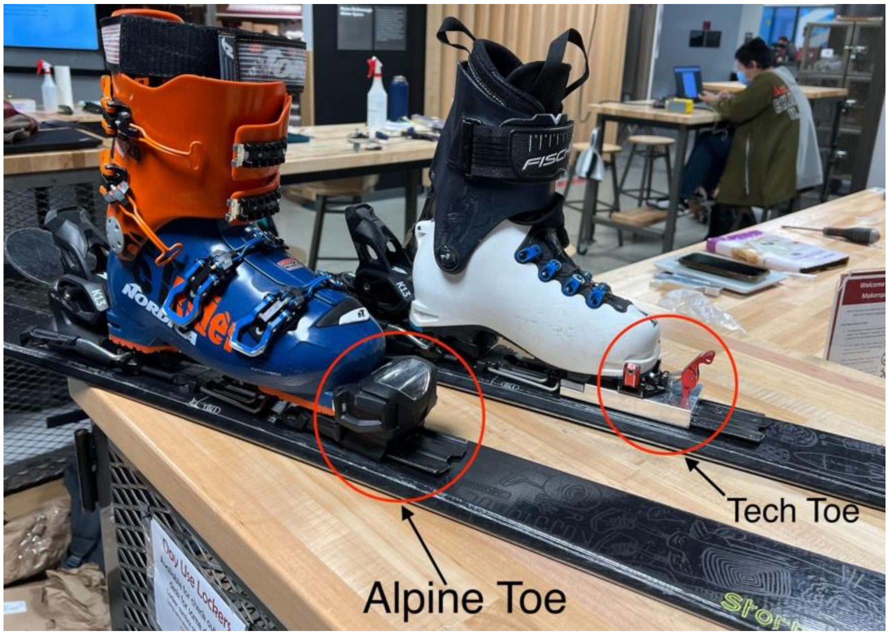


Figure 92: Binding System Mounted to Ski

With the system mounted to the skis, a testing method could be developed. Table 1 below depicts the markers of performance and functionality that were used as testing criteria. These markers of performance were tested at Wachusett Mountain Ski Resort and Killington Ski Resort. Ideally, a longer testing period that entailed use in backcountry settings would be undertaken to also evaluate durability, but due to time and snow constraints, testing was relegated to the in-bounds terrain at ski resorts. The two ski resorts offered variable terrain ranging from soft powder snow to hard freshly groomed snow to moguls, which benefited the thoroughness of our testing regimen. For our purposes, this terrain gave serviceable test results as our main concerns are the functionality of the mechanisms during use and its ability to hold up to downhill skiing, which can both be tested at a ski resort.

To get an accurate representation of the uphill performance of the system, each team member toured up Wachusett Mountain once. In addition, to assess downhill performance, each team member skied downhill twice using both tech toes. Furthermore, each team member performed a side-by-side comparison with one tech toe and one alpine toe during two downhill runs. This was done to give more perspective on the performance of the tech toe relative to the alpine toe piece. Table 1 contains brief notes on the results of our testing.

Table 1: Testing categories and results

Testing Category	Testing Sub-category	Results
Handling	Removing and attaching heel piece	Heel piece is easy to remove with gloves on
	Attaching tech toe plate	Tech toe plate is easy to attach to the mounting rail with gloves on
	Removing tech toe plate and attaching alpine toe	Tech toe plate could be removed, and the alpine toe could be easily attached with gloves on
Uphill capability	Uphill weight compared to other market leaders	The uphill weight came in lighter than all the market competition at 543 grams
	Proper function and feel of toe pivot point	The slight downward ramp present when in uphill mode is only noticeable when climbing without risers on steep slopes
	Function of risers	The positioning of the risers leads to a slightly awkward feel on the bottom of the user’s boot
Downhill Capability	Rattling and movement in tech toe plate	No rattling is discernible when using the tech toe plate
	Power transmission	The full alpine heel piece leads to very good power transfer
	Comfort during downhill skiing	The overall feel of the binding was natural and comfortable
Durability	General wear during testing	Some minor wear is noticeable on the body of the tech toe plate and the teeth on the locking key
Other	Icing/debris inhibiting handling	No icing or debris build-up affected handling

As can be seen in table 1, handling of the binding components never presented an issue even when being used in scenarios with fresh loose snow. Uphill capability was as expected for the binding system. The uphill weight met expectations as its value of 543 grams came in lower than the bindings highlighted in our state of the art discussion. Due to the height of the tech toe plate that was necessary to interface properly with the mounting rail, there was a slight upward ramp present when using the tech toe plate in uphill mode. This meant that the user's toe was slightly higher than their heel. On flat and mild slopes, this ramp was not noticeable, but when the user began to climb steep slopes without the riser in the up position, this ramp led to a slightly awkward feeling. When the risers were in the up position, this was not noticeable. This situation does not affect the functionality of the binding, only the user's comfort.

The risers were also a source of mild discomfort for the user and were a source of lacking confidence in the design. Due to the positioning in the middle of the user's boot as seen below in figure 93, the risers could be felt through the user's boot. Additionally, the risers were difficult to toggle between the up and down positions due to the tension in the system. These issues did not affect the functionality of the system, but it is an issue that should be addressed in further development of the system as it did not feel as solid as should be expected from a riser system.

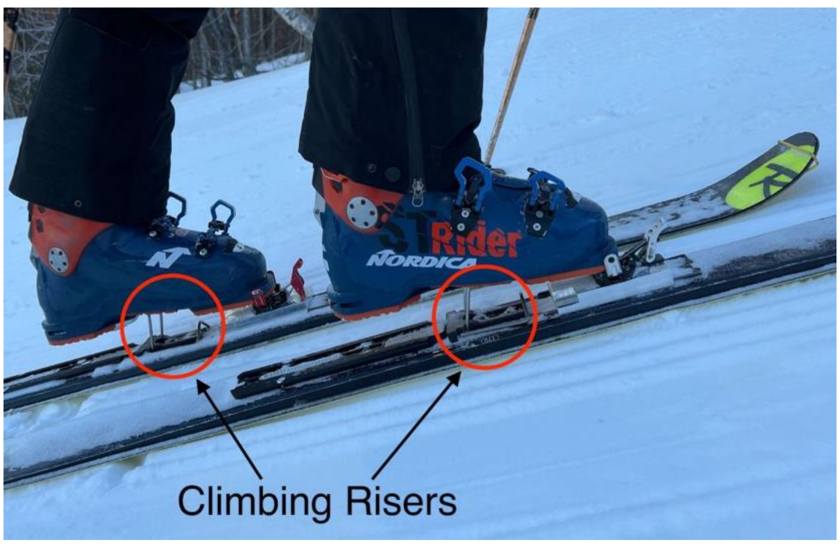


Figure 93: User's Boot Resting with Riser Located in the Middle of the Sole

The downhill capability was the most important testing category because of the significantly higher stresses and impacts imaged on the plate below in figure 94. The team's expectations were exceeded with regards to how the binding system performed with the tech toe plates attached. In addition to the absence of any rattling, the overall feel of the binding was excellent. The power transfer and performance of the system with the tech toe plate attached was on par with the alpine toe attached. Only a slight decrease in responsiveness and the ease at which a turn could be initiated was noticeable with the tech toe plate attached. This is expected as alpine toe pieces serve the sole purpose of being used for downhill skiing.

With regards to the durability of the binding system, some wear was noticed after two days of skiing. This cosmetic wear on the tech toe plate can be seen below in figure 94.

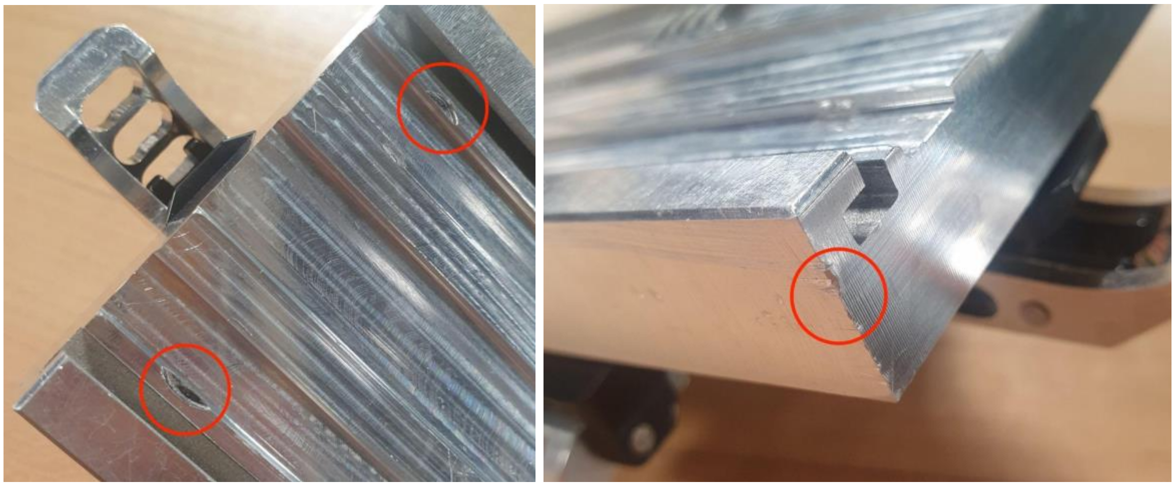


Figure 94: Two Points of Cosmetic Wear on Tech Toe Plate

This wear on the bottom of the tech toe plate likely resulted from the screws that protrude slightly from the mounting rail. During skiing, the plate likely rubbed on the mounting rail leading to this abrasion. On the corner of the plate, the wear likely resulted from the edges of the ski striking the corner of the plate. This is a normal occurrence during skiing and is of no concern. The wear seen in figure 94 is purely cosmetic and does not raise any concern over the long-term durability of the tech toe plate. Additionally, we also noticed wear on the edges of the teeth on the locking key. This wear can be seen below in figure 95.

Figure 95: Wear on Locking Key Teeth

The wear on the teeth entailed slight rounding of the teeth edges. This wear is expected as the mounting rail is made of steel while the locking key is aluminum. After two uses, this wear was not alarming, but it is worth keeping an eye on going forward given the importance of the interfacing features of the locking key and mounting rail.

Overall, the binding system performed better than expected. The uphill performance was adequate, while the downhill performance far exceeded expectations, and durability was of little to no concern.

3.3 Final Prototype Modifications

After machining the final prototype and measuring the final weight, we determined it was possible and beneficial to slim down the design and reduce weight. Weight is a huge factor when customers buy gear for backcountry skiing, and dedicated skiers are always trying to shave weight wherever possible. To make our product more attractive to users who strongly prioritize weight, we had to reduce the weight of our initial system. The tech toe plate is the only component where material removal was possible, so we focused on this component. The initial weight of the tech toe plate was 289 grams, and the weight of the whole system was 543 grams. Our goal was to reduce the weight of the plate to roughly 150 grams, therefore reducing the weight of the system to roughly 400 grams.

The initial design of the tech toe plate was very bulky and rectangular. The plate also had very high factors of safety giving us confidence that if material would be removed and the stresses increased, then the plate would still be structurally sound. Figure 96 shows the initial design of the plate with the tech toe mounted. We designed the new one based on the design of the current plate with the goal to remove as much weight as possible while staying structurally sound, rather than starting from scratch.

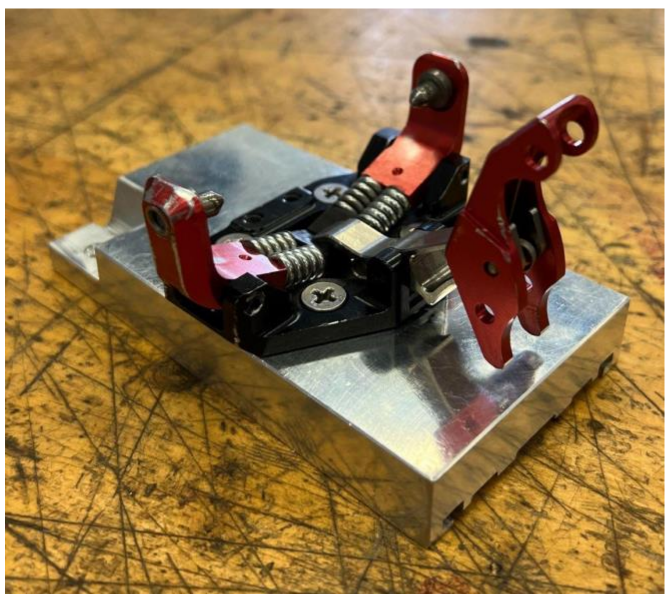


Figure 96: Original Tech Toe Plate with Tech Toe Mounted

As seen in the figure 96, the two corners above the tech toe are unused spaced and only provide for more engagement with the rail when mounted. The corner behind the tech toe across from the pocket for the key handle is also unused space since the boot does not interface with the plate in this location. Additionally, figure 97 shows the underside of the plate.

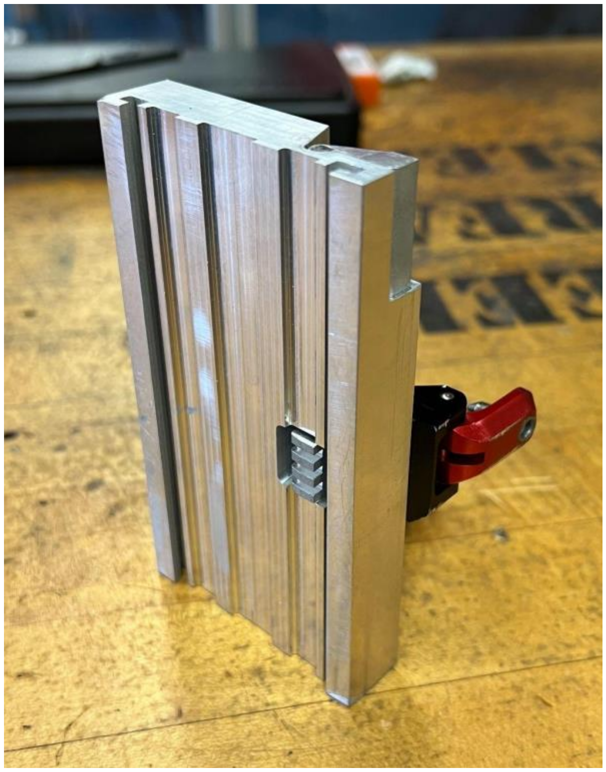


Figure 97: Underside of the Original Plate

The slot in the middle of the tech toe plate has a lot of excess material as well, so we determined this was a good location to remove weight. Rather than removing all material from the underside of the plate aside from the rail slots, we only removed material in the middle section. This left the overall profile of the plate and left all components that interact with the rail to prevent any loss in rigidness or stability.

When analyzing the initial CAD model, we also determined the overall height of the plate could be reduced. The initial height of the plate was 18 mm and we reduced it to 16.25 mm; this was the max height we could reduce it to before the holes for the mounting screws interfered with the hole for the rod. Figure 98 shows the new Creo model of the updated tech toe plate.

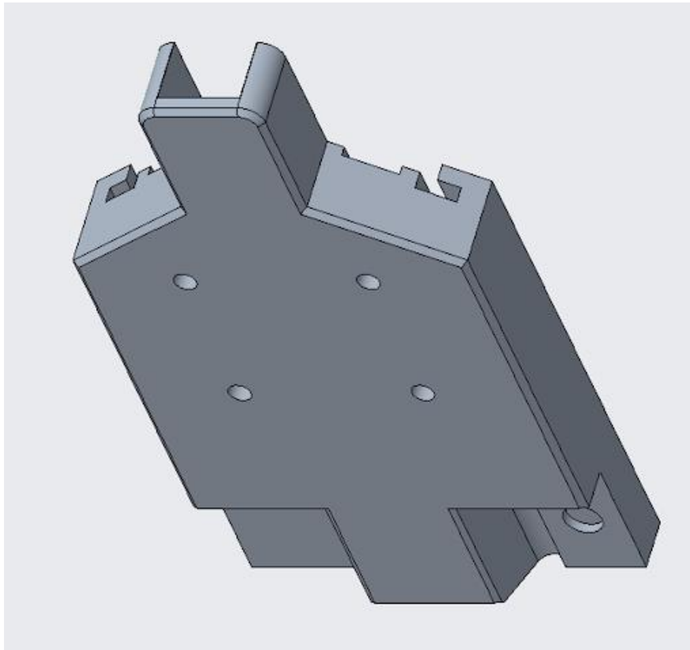


Figure 98: Isometric View of the Modified Tech Toe Plate

Before machining the new tech toe plate, we analyzed the Creo model under the same conditions to ensure it would not fail and perform to our intentions. The new plate was simulated under the lateral and vertical load cases, but not under the longitudinal case since the loving key carries the load in that case and the key was not modified.

The first case simulated was the plate under vertical load. The plate was constrained at the same points as in the initial vertical case simulation, and a 310 N distributed force was applied upwards to the top surface of the plate. Figure 99 shows the simulation results.

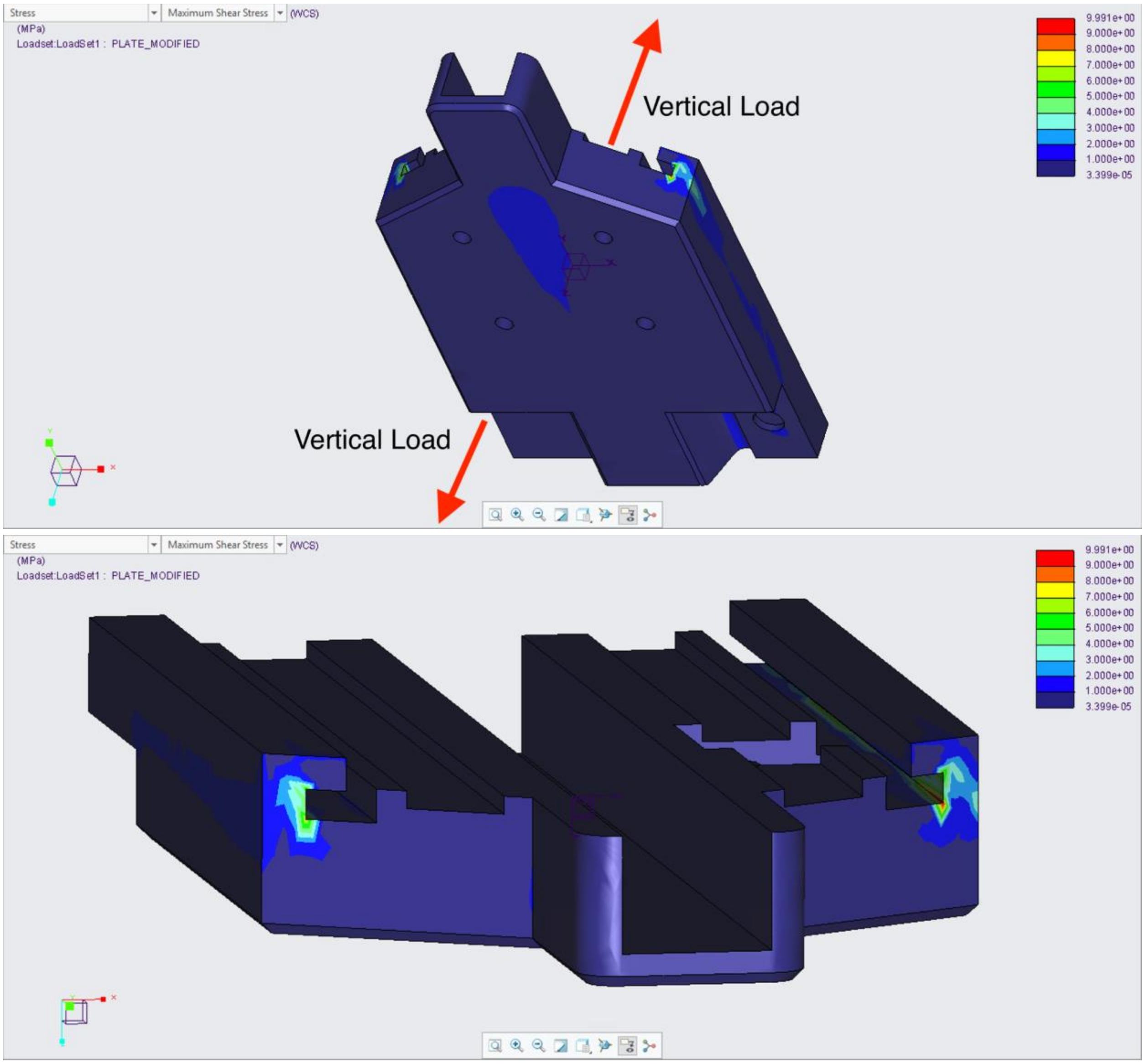


Figure 99: Maximum Shear Stress in the Modified Tech Toe Plate Under Vertical Load

These results show that the maximum shear stress increased in the updated tech toe plate design. The original design experienced a maximum shear stress of 2.935 MPa, which was increased to 9.991 MPa in the updated design. Again, the maximum shear stress occurs in the rail cutouts of the plate as expected under vertical load, but the stress is not high enough to cause concern. The new factor of safety is 27.62 which is a 70% decrease from the original, but still an extremely high factor of safety. The new stress and factor of safety cause no concern and still give high confidence that the plate will not fail under vertical loads it will experience.

The second case analyzed the tech toe plate under lateral load; again, the tech toe was added to the plate. The shaded surfaces shown in figure 100 were constrained in all directions and a 310 N load was applied laterally to the top left side of the toe piece, which is shown in figure 101.

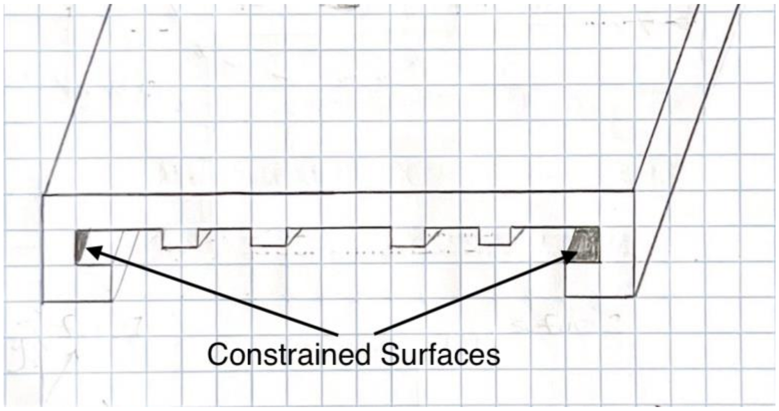


Figure 100: Constrained Surfaces of the Tech Toe Plate Under Lateral Load

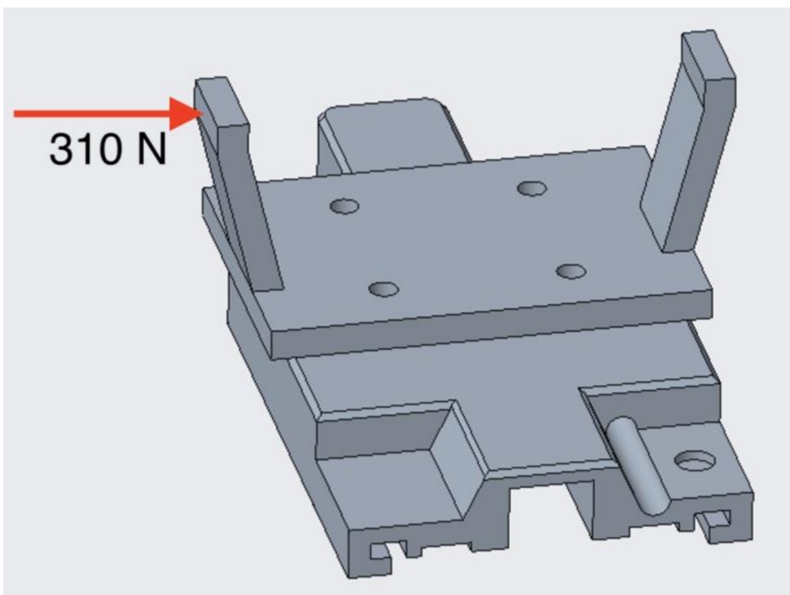


Figure 101: Lateral Force on Updated Tech Toe Plate and Tech Toe

The toe piece overlaps the new design of the tech toe plate, but since there was a rigid connection, all the load gets transmitted throughout the plate, so the results were not dependent on the shape of the toe piece. Figure 102 show the results of the simulation.

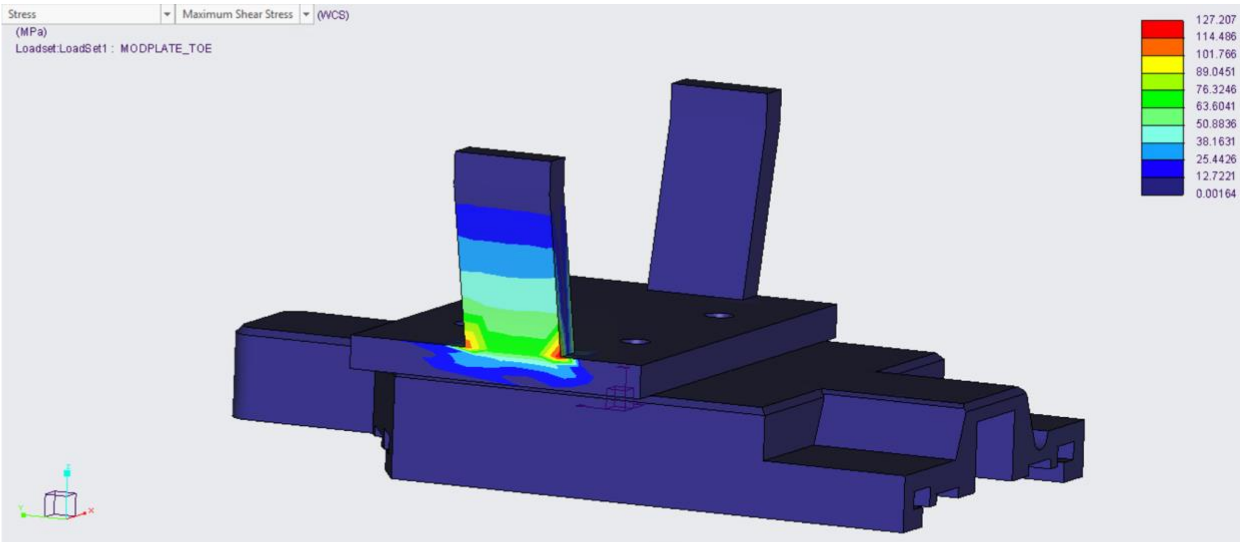


Figure 102: Simulations Results of the New Tech Toe Plate Under Lateral Load

The simulation shows that again the maximum stress occurs in the tech toe, but the maximum stress on the plate itself is roughly 65 MPa; this stress occurs directly under the tech toe and can be seen more clearly in figure 103.

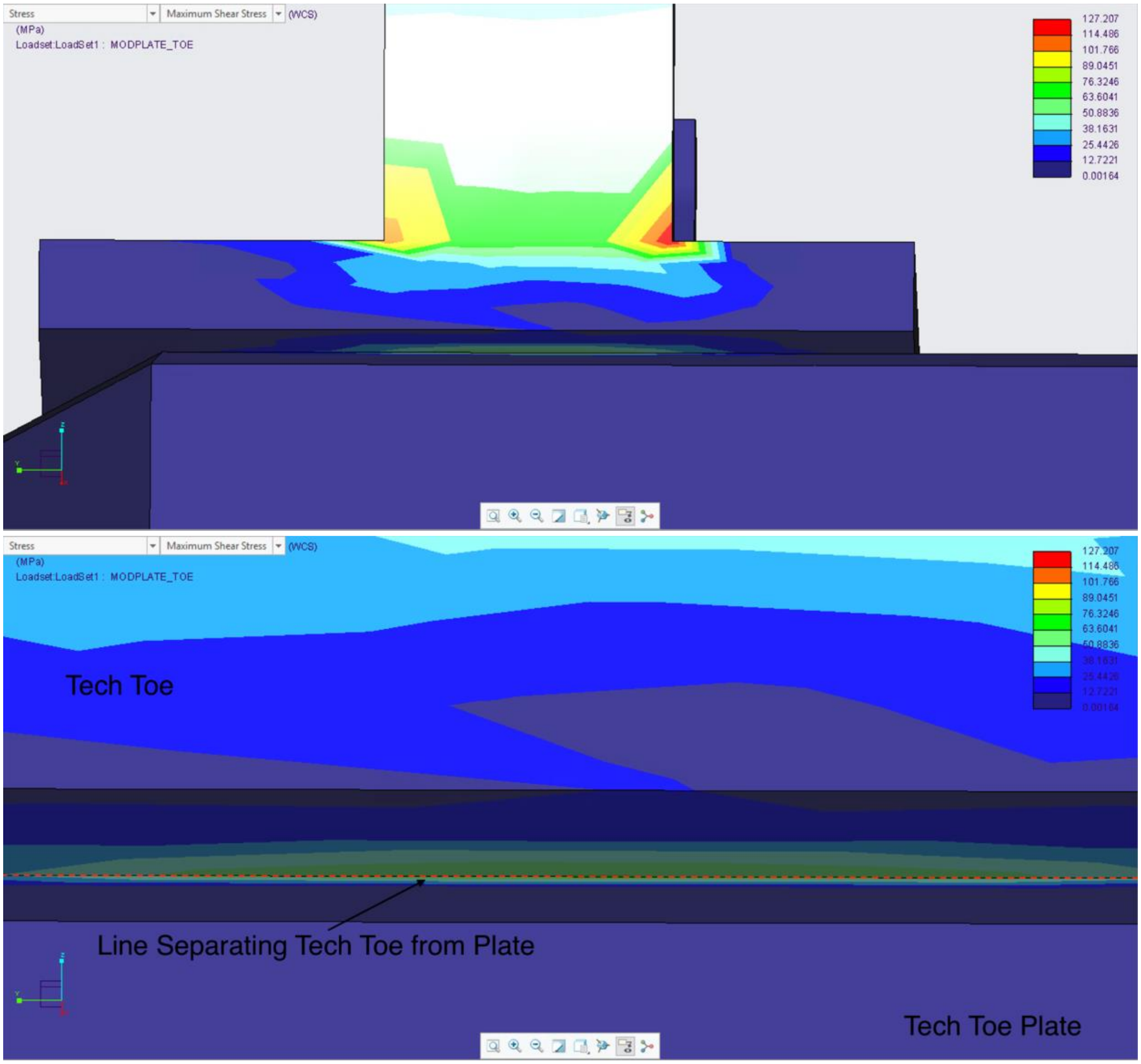


Figure 103: Stress in Tech Toe Plate Under Tech Toe

Additionally, the overall stress in the tech toe plate rarely exceeds 5 MPa as in the original design, but the maximum stress in the rail cutouts is slightly higher, reaching roughly 15 MPa shown in figure 104.

Figure 104: Maximum Shear Stress in Rail Cutout of Modified Tech Toe Plate

Overall, the new factor of safety of the modified tech toe plate is 4.24 in the lateral case, which is still a very high factor of safety and gives confidence that this plate will not fail under the expected lateral loads. Both the vertical and lateral load simulations of the modified plate show little increase in the overall stress the plate experiences and shows that the plate should not fail under proper use. These results verify the new design of the plate is structural and therefore it is safe to manufacture the modified plate.

We built the CAM for the new design by modifying existing and writing new programs, building off the design of the initial tech toe plate. We manufactured the original plate with one modification before performing the new operations. The new tech toe plate was faced down to its proper height and several pockets were milled to remove the necessary material.

The only modification made to the existing programs for the initial tech toe plate were to drill the mounting holes deeper so once the place was milled again the screws would fit properly. Once we faced it down to the correct height, we changed the fixture and milled the pocket across from the key handle. Next, we changed the fixture again and milled out the two corners at the top of the plate. Finally, we turned the plate upside down and milled out the channel on the underside of the plate. The machining process for this new plate was not the most streamlined since we used the original programs to machine the updated tech toe plate with new dimensions. The change in the height of the plate made it difficult to properly machine the final prototype with the least steps necessary. In the short term it saved time, but if we were to repeat this process in the future it would have been beneficial to completely re-write the Esprit programs. Nevertheless, we were able to machine a prototype that matched our final design and dimensions, which are shown in figure 105.

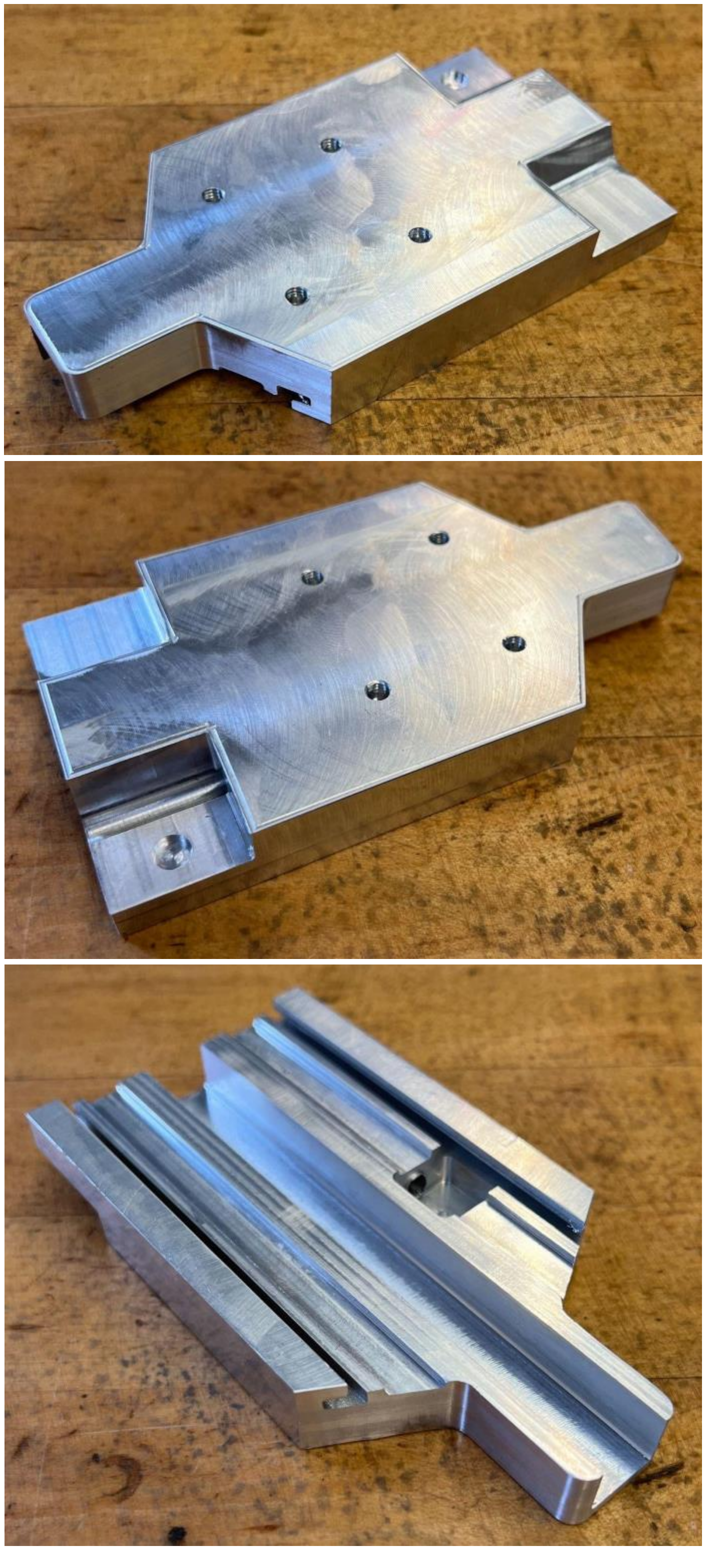


Figure 105: Three Perspectives of the Final Modified Tech Toe Plate

The new tech toe plate had a measured weight of 155 grams, giving the system an overall measured weight of 409 grams. The new weight is much more competitive with current market leaders. A Fritschi Tecton 12 has a measured weight of roughly 680 grams and the Marker Kingpin

13 has a measured weight of roughly 775 grams. These are both lighter options for hybrid bindings giving our design a clear advantage in the weight category. It is also important to note that the new plate was designed to fit the Plum tech toe we used, but the tech toe plate could be modified and manufactured to fit any tech toe on the market.

4.0 Concluding Remarks

4.1 Recommendations

Overall, our system performed extremely well in the conditions it was designed for, but as always there are improvements to make to take this product to the next level. The limiting factors we faced during this project were time, cost, and the attempt to create a system each member of the team could test and use.

We chose to use the Tyrolia Attack2 13 Demo binding as the base for our system. The decision came down to two factors: cost and versatility. The binding package we purchased was $315 for the two demo alpine bindings and the two tech toe pieces, which is relatively cheap compared to other products on the market. Additionally, the simple mechanism to adjust the binding was a strong contributing factor in selecting this binding. The binding does not require any tools to remove the heel or toe piece, so the user does not have to carry extra equipment, and the mechanism can be manipulated easily with gloves on. The binding also allowed for all members of our group to size the binding to their boot size and use the single system we produced. While the project benefited from these factors, there were also some negatives to the Tyrolia Attack2 Demo system.

The Tyrolia binding is an alpine binding, which means there are no climbing risers integrated into the heel piece. We added climbing risers to our system which had to be placed directly under the center of the boot due to the positioning of the rails for the heel and toe piece. As mentioned in the testing report, this caused some discomfort and bending in the boot, leading to overall lack of confidence in the risers. The risers were also very hard to manipulate and had to be engaged with the user's hand, rather than being able to flick them up with the user's pole, which is common in other bindings. Additionally, since the Tyrolia binding is not designed for climbing, the brakes do not lock up unless the heel is clipped in. Therefore, the heel pieces needed to be removed for uphill use. This reduced the uphill weight of the system tremendously, but the heel pieces take up a lot of room in one's pack which is not ideal.

To improve upon this system, we recommend the risers be integrated into the heel piece that can remain on the ski while in uphill mode. This would look very similar to the Marker Kingpin or Fritschi Tecton heel pieces. The heel piece would simply shift backwards and lock the brakes up in uphill mode and shift back forwards to interface with either the tech toe or alpine toe for descents. This updated design would provide a more streamlined and easier to use system and higher performing climbing risers.

Integrating the risers into the heel piece would increase the uphill weight of the system. To compensate for this increase and attempt to keep the uphill weight to a minimum, we recommend redesigning the toe piece system to reduce weight. The current toe system would work with the updated heel piece design, but improvements could be made. Simply using the modified tech toe plate would decrease weight from the original. The whole toe piece system could be modified using the same design to reduce weight and streamline components by reducing the components to fit a single user's boot, rather than having an adjustment range for multiple users. Another option would be to completely redesign the toe piece system to mimic the C.A.S.T Freetour design which would lead to the greatest weight savings, without compromising on performance or function.

Lastly, if this project were to be developed further, we recommend designing and manufacturing the whole system inhouse, rather than using existing brand's components. This would ensure the system can be designed exactly as desired without having to fit a certain mold.

We also recommend some of the components be manufactured using injection molding. Given the results of the 3D printing testing, we found that plastic, specifically PLA, is very strong under tensile load. Even though plastic is less strong under shear stress, injection molding does not have the layering issue that 3D printing presents. Removing these weak layers is a huge advantage and injection molding is an efficient manufacturing process with a great strength to weight ratio. It would reduce the weight compared to the aluminum and likely provide ample strength. Using our system, we recommend using injection molding for the tech toe plate to reduce weight, but continue to use aluminum or upgrade steel, for the key handle and locking key for the strength characteristics and to reduce wear. If the entire system were redesigned, we recommend manufacturing the housing of the heel and toe pieces using injection molding, but manufacture integral, mechanical components from aluminum or another metal.

4.2 Conclusion

During this project we were able to complete the full product development cycle. We began by identifying a gap in the market, brainstorming ideas, and designing a solution. Next, we modeled a prototype in CAD, 3D printed a model for proof of concept, and tested the model to inform our material selection process. We determined a suitable material and performed hand calculations and computer simulations to analyze the design and confirm its integrity. Next, we built machining programs and manufactured a prototype from aluminum using three different types of machines. Once we had our prototype, we tested our product on snow and confirmed its functionality. Finally, we modified our design and made recommendations for future iterations of our project.

The quality and functionality of our final prototype was excellent. Our components performed extremely well in uphill mode, with the only issue from the climbing risers which is a component we did not design. The performance while descending was very similar to dedicated alpine bindings, as well, with minimal discernable differences or limitations. The quality of the final prototype is a direct result of the steps taken during the design and model stage of the project.

This project required the use of a variety of engineering tools and served as a culmination of our education. We were able to use many different resources provided by WPI and learned a lot both on the engineering side and project management side of product development.

4.3 Broader Impacts

4.3.1 Engineering Ethics

The first canon of the Code of Ethics for Engineers as expressed by the National Society of Professional Engineers states that engineers shall hold paramount the safety, health, and welfare of the public. Throughout our project and specifically during the design segment, we kept this canon at the forefront of our thoughts. The basis for our project was to give the user a safer and higher performing option while backcountry skiing in addition to allowing the user to choose a low-tech, lightweight option. This allows the user to choose a safer option for skiing more consequential terrain when desired, and thus makes our prototype a safer option than some of the market competitors.

The second canon is to perform services only in areas of the engineer’s competence. This project was taken on knowing that our project team members belong to the market group. We believe that we understand skiing to a high enough level that we can use our engineering skills to develop a product that satisfies a large group of skier's needs. In addition to the relevance of our project towards the first two canons of engineering ethics, our team sought to take general care in conducting the project honestly and truthfully.

4.3.2 Societal and Global Impact

The product of this project has the propensity to impact individual skiers as it improves accessibility to the inherently dangerous sport of skiing. Skiing is an extreme sport and any product that is introduced to this market must be created with the understanding that the consequences of the user's participation in the sport could result in injury or death. In addition to exposing the user to skiing in general, our product also improves access to backcountry skiing, which takes the hazards of normal skiing in a resort and adds the unpredictable dangers of mountain weather and the possibility of avalanches. These hazards pose significant risk to individuals who venture into the backcountry, so it can be expected that this product could expose skiers to these risks.

In terms of positive impacts to skiers, our design allows users to experience both backcountry and alpine skiing using the same equipment, which makes the sport more accessible. The cost savings in the reduction in necessary equipment also makes the expensive sport of skiing slightly more affordable.

4.3.3 Environmental Impact

Our product has minimal negative environmental effects as it is a small product that once produced does not require any continual input of resources. The materials it is made of, plastic, aluminum, and steel are not especially sustainable, but as the product uses small amounts of these materials, and should last multiple seasons if properly used, the environmental impacts from production are negligible. On a positive hand, our product reduces the need to purchase multiple pairs of skis, therefore the effects of consumerism are reduced. This could lead to positive environmental effects because of our product being introduced to the market.

The most significant environmental impacts of the product are indirect, as they result from where the product may be used. For example, most ski areas still do not run on renewable energy, and subsequently, when the product is used at a ski area, non-renewable energy sources will be used to run the lifts and to travel to the ski area. Even when used in the backcountry where access is human-powered, the user must still travel to the trailhead, which will likely require the use of a car, train, bus, or plane; all of which will likely not be powered using renewable energy.

Lastly, it is important to consider the full life cycle of the product. Eventually, the product will either break or become obsolete, leading to its disposal. The aluminum materials within the product can be easily separated and recycled, but the plastic will likely end up in a landfill. None of the materials are particularly toxic, but the end-of-life disposal method is important to consider.

4.3.4 Codes and Standards

When being used with the alpine toe and heel pieces, our binding system adheres to ISO standard 9462:2014, which governs the testing procedure for releasability of alpine ski bindings. Our system adheres to this standard through the association with the certified Tyrolia Attack2 13 demo binding that was used as the base for our binding system. This means that the user can expect consistent releases when the binding is set to a certain DIN value as explained in section 1.2 of this report, and the alpine toe and heel pieces are used.

4.3.5 Economic Factors

Financially, our product could make backcountry skiing more accessible as the cost is significantly reduced as a skier will only need one pair of skis for both alpine and backcountry skiing. This could lead to more individuals participating in backcountry skiing. Additionally, market competitors would likely need to reassess product development if this product were introduced to the market as it offers use cases and functionality that do not currently exist. This would lead to more money being funneled into research and development for top ski companies.

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