Enhanced Digital Capability through the use of Simulation in Footwear Product Creation

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ABSTRACT

Digital simulations, such as those utilizing the Finite Element Analysis method, are a common engineering tool in product development to build confidence in product performance and robustness of design. Footwear product creation has historically been a blend of art and science, with design teams relying on 2D sketches sent to factory partners to create physical samples of shoes with the desired aesthetics. These samples were then tested mechanically and on athletes to verify the structural integrity of the design. This thesis explores how FEA simulation can be implemented into the footwear development process, especially in the environment and context of an onsite product creation center.

First, a case study on plate bending analysis to measure relative stiffness of cleated footwear design features is presented, exploring three approaches: mechanical testing, beam theory calculations using plate geometry, and FEA simulation. All three approaches will provide similar results for design teams. However, depending on the project timeline, level of complexity, and resources available, a team should evaluate the best approach.

Next, a framework for a qualitative cost-benefit analysis is developed to aid footwear business leaders to decide if investment in digital tools such as FEA are worth their expected benefits. The major costs of implementing FEA into a product creation center will be the start up time and financial cost of FEA engineers, software programs, and integration into the companies design process. However, the benefits could provide increased product quality, higher customer satisfaction with performance, and positive mindset shifts within design teams, allowing cross-functional team members to be more collaborative and efficient in their communication.

While the potential benefits could increase sales and brand loyalty in the long run, investment in a digital service like FEA may not be suited for a product creation center, whose main focus is on building low volume physical footwear prototypes. Instead, FEA simulation and other digital capabilities should be integrated directly into design teams responsible for footwear projects. The hope is that the case study and associated cost-benefit analysis developed in this thesis can be applied to the evaluation of other technologies and digital tools into the footwear industry.

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Note on Company Proprietary Information

To protect information that is proprietary to the corporate host, the data presented throughout this thesis may have been modified and may not represent actual values. Data labels may have been altered, converted, or removed to protect competitive information, while still conveying the findings of this project.

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List of Acronyms

CAD – Computer Aided Design

C-B – Cost – Benefit

DOE – Design of Experiments

FEA – Finite Element Analysis

NFL – National Football League

NPV – Net Present Value

PCC – Product Creation Center

R&D – Research & Development

ROI – Return on Investment

TPU – Thermoplastic Polyurethane

1 Introduction

1.1 Company Overview

The corporate host for this thesis (Company) is a business focused on the design, development and worldwide marketing and selling of athletic footwear, apparel, equipment, accessories and services [1]. They are the largest seller of athletic footwear and apparel in the world, led aggressively by their footwear, which accounts for 66% of their total revenue in fiscal year 2022 [1]. While Company's footwear is designed primarily for specific athletics uses, they also make a large number of products for casual or leisure wear. Almost all of their footwear products are manufactured by manufacturing partners, most of whom are outside of the United States. However, what drives Company's dominance in the footwear business is their investment in Research & Development (R&D). Teams of designers, material experts, product engineers, and project managers collaborate together to form initial product ideas and briefs, prototype and test physical samples, and ultimately freeze the product design for production and launch. This entire product development process is referred to as footwear product creation.

It is with an athlete-centered focus that Company runs its R&D, striving to innovate technologically in design in order to "produce products that help enhance athletic performance, reduce injury and maximize comfort, while decreasing our environmental impact" [1]. This investment can be seen through work done in Company's prototyping facilities such as its new innovation center, a space that also houses work done by biomechanics researchers, robotics experts, computational designers, and more [2]. While this is just one of the main centers for product development, Company has also put in a large investment to upgrade their Product Creation Center (PCC), a prototyping space with full capabilities to make athletic and casual footwear at lower volumes.

Core to Company's culture is the desire to create ground-breaking sport innovations for every athlete and to create products sustainably. One way this can be done is through the use of digital tools to limit the number of physical prototypes (referred to as samples) made and to increase confidence in product robustness prior to any physical testing. Recently, Company launched the Air Max Scorpion (see Figure 1), an example of how digital design resources came together to create a new line of sports footwear. This product was released in the holiday season of 2022, marketed to have utilized known material constraints to "optimize for performance and manufacturability without any aesthetic compromise through the use of digital tools such as Finite Element Analysis (FEA)" [3]. This is but one instance of how the footwear industry can accelerate the use of digital tools into the product creation process.

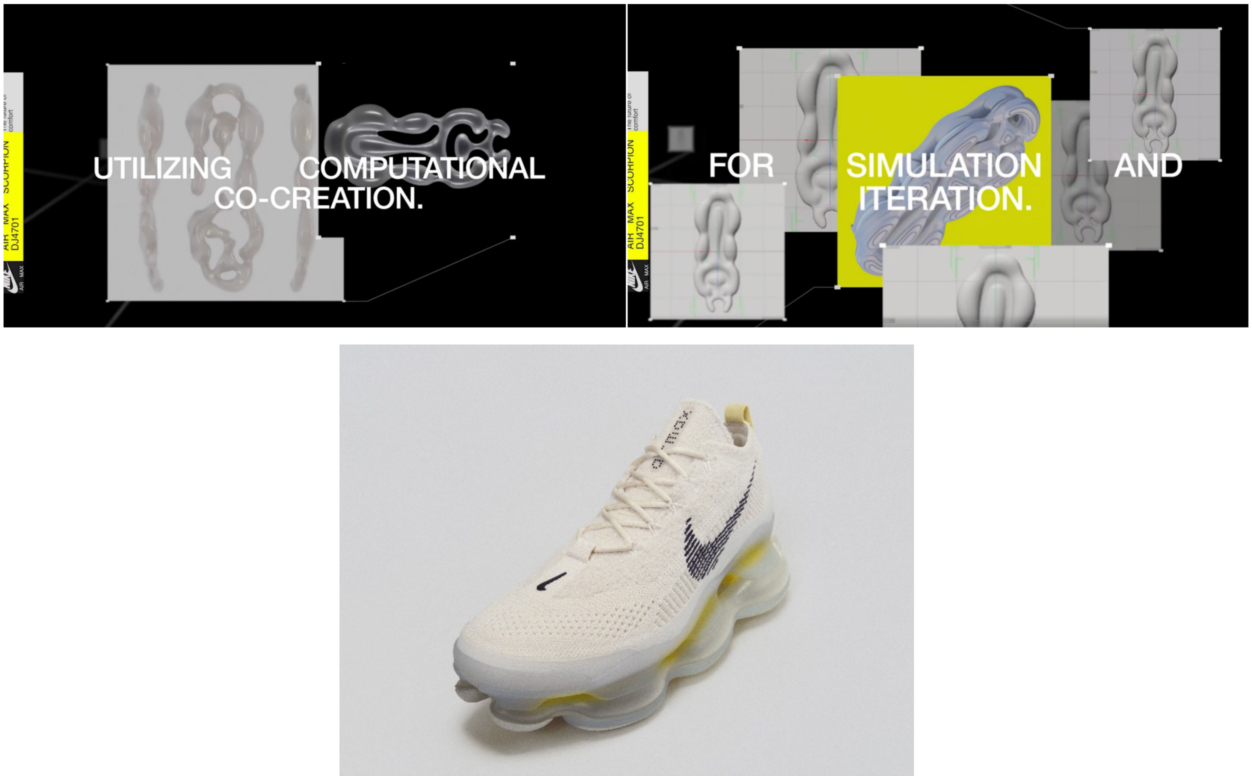


Figure 1: Screenshots from Air Max Scorpion Shoe Release Promotional Video and Image of Final Product [3]

1.2 Project Drivers and Motivation

Footwear design and development has historically been a hands-on activity. Uppers are typically stitched together by a sewing expert, and the final shoe is assembled by hand. However, as industries modernize and technologies advance there is an opportunity to incorporate more digital strategies into the earlier phases of product creation in order to speed up time to market and save on physical development costs. A footwear Product Creation Center (PCC) may be seeking to evolve their capabilities by investing in performance-focused digital tools. Specifically, one opportunity is the use of simulation programs such as Finite Element Analysis (FEA), or other design-aiding software to understand footwear performance prior to building and testing a physical sample. A PCC's main purpose is to provide prototyping services to other design teams in the company working on a variety of footwear product lines. A PCC may be consulted to help create early visual samples of footwear for design teams. Implementing simulation could be considered an additional service to offer design teams in various phases of their development process.

Footwear design often relies on two-dimensional (2D) sketches and collaboration with manufacturing partners and PCCs to develop the final three-dimensional (3D) design. This design is then manufactured into a physical sample which is tested mechanically for robustness, and to inform any further design iterations. It can be difficult for an engineer to communicate a designer's intent while also balancing the constraints of materials and manufacturing processes. There is a significant amount of time spent waiting for samples to be created and then tested in order to make any further decisions on the design. In many cases, these samples are created at overseas PCCs which then have to be shipped back to design teams for evaluation, taking up to two months of time. This process can also happen multiple times throughout the product development process as teams iterate on designs. There is hope that a digital tool like simulation can make early design communication more efficient, shorten product development timelines, as well as provide cost and material savings by eliminating rounds of physical sampling. By simulating the performance of footwear design prior to physical sampling, design teams are hypothesized to make more efficient design decisions and proceed with increased confidence in a footwear product's performance prior to any physical testing.

1.3 Problem Statement

To understand the opportunities and the required investment for implementation of digital engineering tools into the footwear design process, the author worked to understand current tools and processes being used at a modern footwear company. This was mapped out through observation and interviews with various team members at the host site to provide context and develop an appropriate scope for this project. Along with the support of literature review, the scope was narrowed down to investigate simulation of performance of footwear bottoms, a key opportunity and desired capability for footwear creation teams. In order to provide a compelling example of the technical expertise and logistics required, as well as an understanding of costs and benefits to the business, a specific footwear and simulation was selected, with the intention that learnings from this use case can later be applied to other types of footwear and digital capabilities. Specifically, FEA to simulate plate bending on cleated soccer footwear was chosen for the use case. A qualitative cost-benefit framework was also created to aid product creation leaders in visualizing the most impactful investment factors. Through presenting the technical process as well as business costs and benefits in a detailed and structured framework, this thesis provides a tool for product creation leaders to use when deciding to make investments in digital engineering tools, as well as a specific recommendation for the use of FEA in a footwear PCC.

1.4 Thesis Structure

The thesis starts by giving an overview of the footwear product development process, FEA simulation in product development, and a background on the importance of plate stiffness for cleated footwear. This is followed by a case study comparing multiple approaches to calculate stiffness for multiple design options of a sample cleated plate. A qualitative cost-benefit framework for investing in digital engineering tools will then be discussed in relationship to the case study. Finally, the thesis will conclude with a summary of the results as it relates to a footwear product creation company, as well as areas for further exploration related to the topic. The thesis will be broken down into the following chapters:

- Chapter 2 – Background will give an overview of the components of a typical athletic shoe, the footwear development process, the motivation for the cleated footwear use case, and how stiffness is calculated using three-point bend tests and beam theory.
- Chapter 3 – Literature Review will cover existing literature surrounding digital tools used in footwear and the use of FEA in product development along with the general difficulties of its implementation.
- Chapter 4 - Cleated Plate Bending Case Study – Technical Process and Results walks through a case study developed to compare different methods and results for calculating plate stiffness for several soccer cleat designs. The methods that will be explored are mechanical testing of plates, FEA simulation, and beam theory calculations. When each method should be used in product development will be discussed.
- Chapter 5 – Cost-Benefit Analysis of Implementing FEA into Footwear Product Creation develops a framework for a qualitative cost-benefit analysis when considering whether to invest in a digital tool such as FEA for footwear design. The framework is used in the context of the case study of the previous chapter, and provides a recommendation for a PCC at a footwear product creation company.
- Chapter 6 - Other Areas to Enhance Digital Capability in Footwear Product Creation discusses other digital tools that were considered during the course of the thesis work and could be appropriate for further exploration
- Chapter 7 – Conclusion summarizes the thesis work and results

2 Background

2.1 Breakdown of an Athletic Shoe

Athletic footwear is made of multiple components, sometimes up to over one hundred separate pieces, that are typically assembled by hand. A shoe is comprised of two main sections, the upper and the bottom. The upper is typically made from soft materials like leathers, various fabrics or synthetic textiles. This is the main body of the shoe that surrounds the top of the foot, and can be stitched together by hand or fused and formed together through various manufacturing methods. The upper may contain specific sections such as the toe box, tongue, heal, tip, eye stay, vamp, and collar, and is sewed to a soft piece of fabric called a Strobel, which is the surface the foot rests on and helps provide shape and support to the rest of the upper [4]. The bottom is what one would generally think of as the sole of shoe, and can be made out of one or multiple pieces. There may be a midsole, which goes immediately beneath the Strobel and above the outsole, the outsole being made from a more durable material and is the surface that will make contact with the ground when worn. Midsoles and outsoles are generally made from various foams, plastics, and rubbers. A breakdown of the different footwear components can be seen in Figure 2, Figure 3, and Figure 4.

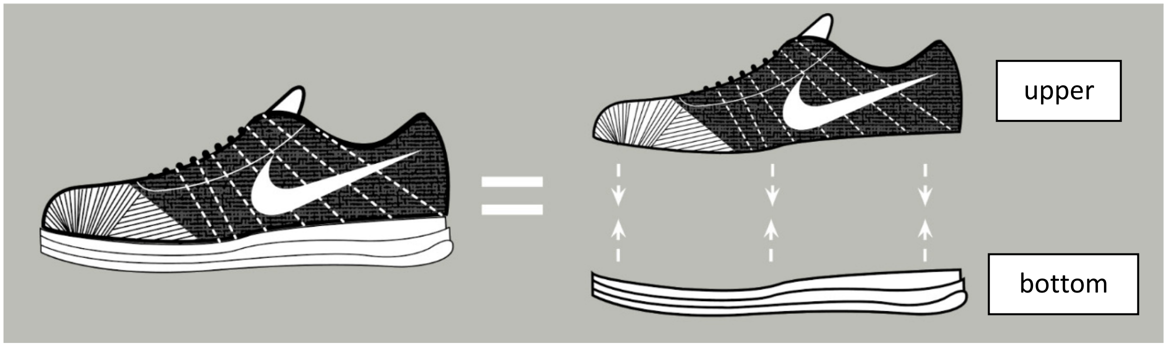


Figure 2: Basic shoe construction, upper versus bottom [5]

Figure 3: Example list of components of an athletic shoe assembly [4]

Figure 4: Breakdown of separate shoe components for an athletic shoe [4]

For the purposes of this thesis, the focus will be on the simulation of bottoms only. Upper simulation is highly complex due to the nature of soft goods and assembly. It is difficult to accurately predict the behavior of stitches and glued surfaces which are assembled manually, as opposed to a bolted connection or a weld in common structural simulations. Soft materials tend to experience high displacements under load and exhibit non-linear characteristics, making computation and setup more complex. In addition, not all soft goods have well-defined material properties, which are necessary inputs for running simulations such as FEA.

2.2 General Footwear Product Development Process

To create any great product, a company must have a sound product development process. There should be guidelines in place to take an idea and turn it into a manufacturable product at scale. The organization of the cross-functional groups that contribute to this process is also critical to help everything come together efficiently. Team members from marketing, design, and manufacturing are almost always central to the design process [6]. This is true in terms of footwear, where teams from sports research, sports marketing, engineering, and technical development may also contribute. The product development process has a series of stages, and each one may have a key timeframe, milestone, or deadline associated with it. In general product development, the overarching phases are concept generation (ideation of product concepts and identification of the target market), system-level design (definition of the product architecture, decomposition of product into components, and preliminary design of these components), detail design (specification of product requirements in terms of geometry, materials, and tolerances, as well as a process plan for production), testing and refinement (evaluation of product through the creation of prototypes against the product intent), and production ramp-up (final refinement and preparation to move to full scale production) [6].

The footwear design process follows a similar flow. Projects will begin with concept generation through the creation by marketing of the product brief, a document listing desired features, overall shoe function, and a description of the wearer or athlete [7]. Designers will create sketches, and work alongside materials engineers, product engineers, and technical and general product managers to come up with a visual concept for the final product that matches the brief. System-level design is defined at this point through the components needed for the shoe and how they will interact together functionally and aesthetically. Detail design will be done through the refinement of 2D drawings of various orientations of the shoe, defining thicknesses and size of components as well as how they should be assembled (for example, is the upper entirely hand stitched, or is there a different forming process needed for a desired effect?). At this point the creation of prototypes will typically be the responsibility of overseas manufacturing partners who have PCCs will full production capabilities. In some cases, early prototypes could be made at an onsite PCC within a company. However, overseas partners are typically used by most footwear design teams due to their quick turnaround times, expertise and full-scale manufacturing capabilities. These partners will be responsible for turning the 2D drawings into 3D models that are used to generate tooling and patterns for manufacturing. Once the 3D model is verified by the onsite design team, the manufacturing partner will create footwear prototypes, referred to as samples. Once samples are completed and initially tested for quality at the partner site, they are shipped back to the design team for onsite testing and validation.

Testing and validation of footwear can take many forms. It could be mechanical life testing in a lab with specialized equipment, or it could be wear-testing with athletes. Validation is also required for ensuring the aesthetics of the sample meet the design intent. After a team learns from testing and validation, they may iterate and make design changes as needed, possibly requesting further rounds of sampling. The key milestone after iteration will be the design review, in which the team gives approval of their confidence in the product and requests production level tooling and samples to be made. The production level samples will be tested and validated one last time before the product is approved for full production. This is the official conclusion of the product development process, and from there on it is the responsibility of the manufacturing partners as well as the sales and marketing teams to handle production and product launch to the customer.

For footwear, this entire process is typically completed in one to two years depending on the product (based on interviews at the host company for this thesis). Initial ideation and creation of the product brief could start years prior to that as future looking teams brainstorm new innovative looks or footwear technologies. These ideas could come from improvements on previous generations of footwear, collaborations with special designers, or even from data resulting in sports research. However, the biggest challenge to this process is the ever-evolving opinions and attitudes of the consumer. For a large footwear company serving youth and many young adults, marketing teams have to be aware of shifting fashion trends or athletic needs. Having a two-year development timeline becomes risky since the product brief based off of the attitudes of one consumer archetype could shift or change completely by the time the product is on store shelves. It is therefore critical to find inventive ways to shorten the product development process or increase the confidence in the robustness of the product.

2.3 Sports Footwear – Cleated Plates for Soccer and Football

The case study in this thesis will focus on a specific type of athletic footwear: cleats used in sports such as soccer (may also be referred to as global football), and American football. The construction of cleated footwear follows a similar shoe construction to that described previously in Section 2.1, however, there may be fewer upper components, and the bottom outsole is typically a harder plastic plate with studs added for traction on different grass and turf playing surfaces. The uppers are commonly made from leather, synthetic leather, or flexible woven plastic fibers adhered to the Strobel, glued to a midsole or thin cushioning material that is then bonded to the plate. The plate is typically injection molded with a tough but flexible material such as a thermoplastic polyurethane (TPU). These injection molded parts can be single or multiple shot (see Figure 6) depending on the design and desired behavior or playing surface. For example, a turf stud may be a softer material and less pronounced than a harder stud for grass and other surfaces, as shown in Figure 5. The case study presented later in this thesis will be for a generalized, single-shot, firm ground cleat.

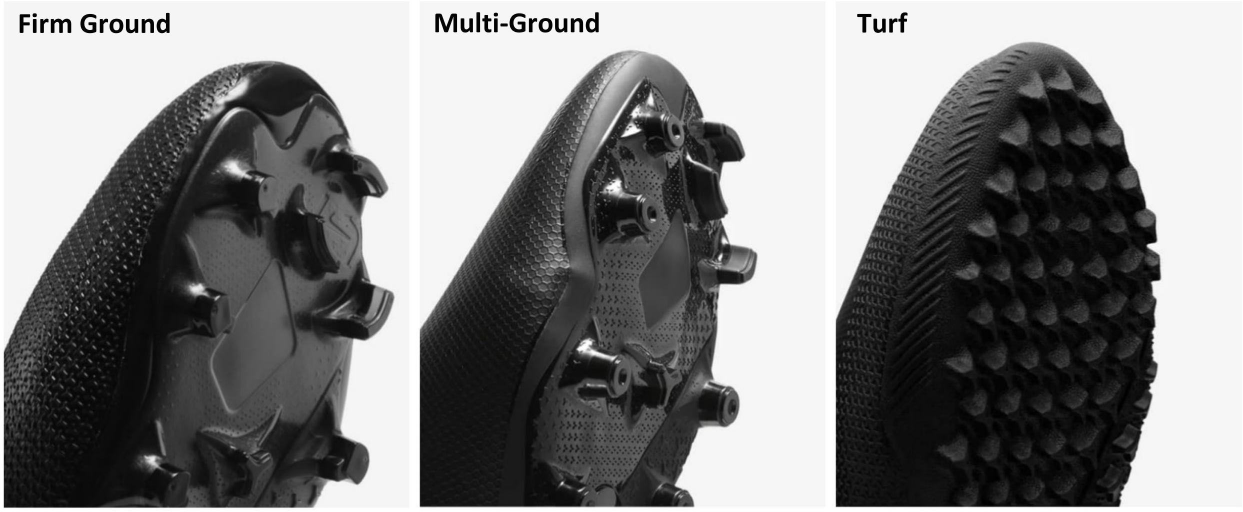


Figure 5: Examples of stud patterns for soccer cleats depending on intended playing surface. Firm ground is a traditional grass field for professional levels of play, with short grass and limited mud. Multi-ground is designed for multiple purposes. Turf is intended for short traditional artificial fields [8]

Figure 6: Nike Zoom Mercurial Vapor 15 Elite FG Model Soccer Cleat [9]

Design teams for cleated products rely heavily on physical testing in lab and field settings. Soccer athletes tend to be very particular about the feel of their cleats, as it is the main piece of equipment players personally purchase and utilize in a game. A survey of the most desirable features soccer players expect from their footwear found that the most important factors were comfort, traction, and shoe stability [10]. All of these factors cannot be empirically measured in a lab, and instead design teams rely on user perception data gathered from field tests with athletes. In this case, soccer cleat design (and other types of athletic footwear design for this matter) relies on a comparison to past designs. New footwear designs may start with a previous model of a cleat that was successful and aim to improve a few factors, such as weight or perceived stability.

The typical cleat design process can take anywhere from one to two years from ideation to production depending on the product needs. For example, an upgrade to a shoe upper, either by changing material or aesthetic, could use the same plate as a previous model and may only take a year to develop and test. A new plate design, however, can take much longer. This is due to the manufacturing costs and timelines for injection molded plate samples. Injection-molded plates require hard tooling, usually a metal mold machined by manufacturing partners overseas. The creation of a physical sample for one size and gender can take up to two months from when a design team approves a 3D model with the manufacturing partner and when they receive the finished sample. While new technologies such as additive manufacturing have helped onsite design teams print and visualize a cleat prototype, they still heavily rely on injection molded samples for validation. Samples provide realistic performance for testing, as injection molded materials will behave differently than a 3D-printed prototype.

On top of the lead time for acquiring samples, there is also a high cost associated with cleated plate tooling. Depending on the number of shots and complexity of a plate design, the cost of tooling for one sample round could be shy of $100,000. Iteration is encouraged and crucial to a successful product development process, so design teams may go through at least two to three separate rounds of tooling for a new plate design. Assuming that at least one month of physical testing on samples is conducted each iteration as well as a couple of weeks needed for teams to update the design, the sample iteration process to get a final plate design can take up to a year of time. In a fast-moving consumer market for sports footwear, a company has to risk trying to understand the user need at least one to two years in advance of a product release, at which point user trends and attitudes could have changed. It is critical to save time on product development and shorten this gap to reduce any product risk in the market. Because of this core need and the long timelines required for sampling, cleated plates were chosen for the case study in this thesis as a candidate to implement simulation into the design process. The hypothesis is that simulated testing as opposed to physical testing can eliminate sampling rounds, save cost, and most importantly, reduce development time. One example of an important test that is done on cleated plates is a bending test. Bending tests are used to calculate stiffness, which correlates to user comfort and perceived shoe stability by influencing pressures on the foot [10]. In addition, stiffness is a crucial property for cleated products when it comes to athlete safety.

2.3.1 Significance of Cleated Plate Stiffness on Athlete Safety

While footwear may seem to be just a part of an athlete's uniform, cleats in soccer and American football can also be considered pieces of safety equipment [11]. Cleats help protect an athlete's lower body by providing traction and support as they move aggressively on the playing field. In the National Football League (NFL), 60% of injuries are from lower limb trauma, such as torn ACLs, fractures of bones in the foot, or ankle sprains [12]. One common foot injury in football is a sprain of the first metatarsophalangeal (1 MTP) joint, colloquially known as 'turf-toe'. This happens when the MTP joint, or the joint of the big toe, becomes hyperextended, known specifically as hyper-dorsiflexion (see Figure 7).

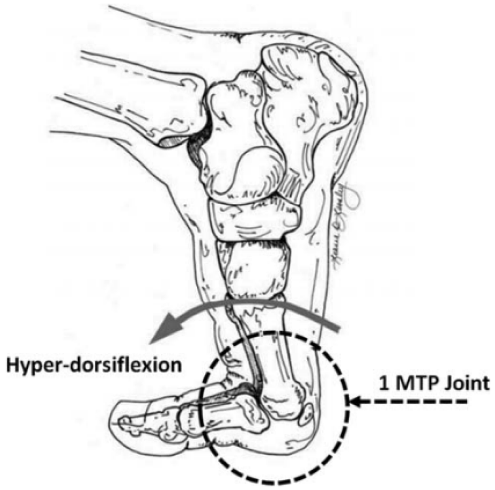


Figure 7: Hyper-dorsiflexion of the MTP joint, a common injury in sports like American football [13]

Recently, researchers have been investigating how footwear design, and specifically the stiffness of cleated footwear, can impact this type of injury. It is now well known that increased bending stiffness of footwear can reduce foot joint extension, which not only can lower injury risk but also serve as a treatment for current injuries by offloading pressures in the foot [14]. One study quantified bending stiffness of American football cleats at the location of the MTP joint and suggests that footwear design could balance athletic performance while also lowering MTP joint risk by purposefully designing to certain levels of stiffness [13]. However, this study also points out that while footwear stiffness does impact safety and performance, there are not agreed upon standards or desired stiffness values. Nor is there consensus on the proper way to measure it.

Despite a lack of consensus on stiffness measurement, soccer and football leagues are taking steps to address the importance of stiffness for player safety by conducting their own tests and providing cleat suggestions to their athletes. An example of this is cleat testing conducted by the NFL. The NFL tests popular models across brands and reports out their results to all players. They provide internally created scores for both traction and flexion, and claim higher scores correspond with higher laboratory performance [15]. The NFL partnered with the University of Virginia on the development of what they call "The Beast", a footwear testing machine to simulate the forces and movements experienced by football cleats on synthetic turf [16]. To inform players about the tests, the NFL will publish posters with cleat rankings based on their scores [17], as well as more detailed documents breaking down how each cleat scored in various tests [15]. It is critical for design teams at major footwear companies to be aware of this test, and many will create internal test procedures to mimic the tests done on "The Beast" to ensure that their cleat design will be recommended for players to buy.

While the NFL has tried to score stiffness, there is still no standard for an exact range for cleated footwear to fall into. Soccer leagues do not perform a test like this, but teams and their doctors understand the importance of stiffness for protection, and players will often take a new pair of cleats out of the box and immediately start bending it by hand to judge if it will have the correct feel. Without a standard and only data on user perception, it makes it difficult for design teams to know if their exact design will be accepted by players. Therefore, when creating new plate designs, teams test samples for stiffness against past models with known stiffness values and a certain player perception. In general, product engineers and designers tend to rely on intuition to update plates to achieve a certain stiffness. For example, if they know a past model was considered unstable by a player and lacked stiffness at a certain location along the arch, they can design in features to increase stiffness for the new design, possibly by increasing thickness or adding rib structures. Because of the reliance on intuition going into designs, there is no guarantee that the stiffness will be correct on the first physical sample. Teams may risk development time and cost in a first round physical plate sample only to receive it, test it, and realize quickly that stiffness may be insufficient. Calculation of stiffness using FEA simulation prior to first round samples could help eliminate this risk, and ensure that teams design robust products that provide the best performance and safety to athletes.

2.4 Stiffness Analysis Methods – Three-Point Beam Bending

In this thesis, a three-point bend test will be used to calculate the stiffness of a cleated plate for soccer. The following is a summary on beam bending and the equations used.

Beam bending theory is a common concept taught in mechanics and is required knowledge for most mechanical engineers. A beam is considered to be a slender member (much longer in one dimension than the others) undergoing a transverse load [18]. Most simply supported beams are assumed to be rectangular, and follow two key kinematic assumptions: perpendicular planes remain perpendicular after bending and the center plane does not stretch. These assumptions as well as a basic understanding of physics allows one to draw free body diagrams and calculate forces, moments, strains, and stresses felt along a basic beam. In this thesis, there will be a focus on a three point-bend, which assumes a uniform beam of length L is simply supported on either end and experiences a downward force at the center of the beam. A diagram of a three-point bend set up is shown in Figure 8.

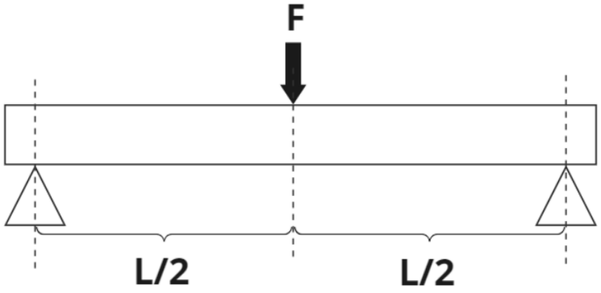


Figure 8: Free body diagram of a simply supported beam undergoing a three-point bend

In the case study for the cleated plate, the desired mechanical property to understand is stiffness. For beams, this could also be referred to as flexural stiffness, k. Stiffness is defined as the force, F, required to deflect the beam a given distance, δ. In this case, force is in newtons (N) and distance is in millimeters (mm). The value obtained for stiffness of the plate will then be the required force in Newtons to deflect the plate by one millimeter. Another calculation of stiffness, as used in the study on forefoot bending stiffness by J. Crandall et al. (2015), is to measure change in torque, τ, and deformation angle, θ, as a plate is bent, which similarly gives stiffness as torque input required to bend a plate by one degree [13]. Given beam theory mechanics, stiffness can also be expressed in terms of the beam's material and shape. In this case, one needs to know the Young's Modulus, E, in MPa or N/mm^2, the cross-sectional moment of inertia, I, in mm^4, and the length of the beam, L, in mm. Depending on the type of bending (i.e., three-point bend versus cantilevered bend), there is also a multiplier coefficient which can be found in common beam bending tables (for example, see Table 8.1 in Crandall et al. [18]). For three-point bending, the coefficient is 48. A summary of all equations for stiffness can be referred to in eq. 1.

$$stiffness, k = \frac{F}{\delta} = \frac{\Delta\tau}{\Delta\theta} = \frac{48EI}{L^3} \tag{1}$$

To measure stiffness of a physical sample, a universal testing machine, such as an Instron, is used. The test sample will be simply supported by two supports, with force applied from above by an indenter at the center of the two supports. The machine can output force versus displacement data which can then be used to calculate stiffness. Examples of three-point bend test set-ups can be seen in Figure 9. In research and industry, a standard procedure for the three-point bend test of plastic materials is outlined in ASTM D790 [19]. It is normal that theoretical calculations and tested values may differ slightly, as beam theory assumes the perfect environment, whereas physical testing is subjected to many external factors that could affect a measurement.

Figure 9: Example of a three-point bend test set-up on a universal testing machine [20]

3 Literature Review

This chapter is intended to give the reader a background on several topics in this thesis based on existing literature. The current state of digital tools in footwear design, a background on FEA simulation use in industry and the difficulties of its implementation, as well as how R&D project decisions need to consider qualitative factors will be covered.

3.1 Current Digital Capabilities in Footwear

Footwear design teams have historically relied on manufacturing partner's expertise to create 3D computer aided design (CAD) models of their footwear designs and translate that into patterns for uppers and tooling for bottoms. It is up to designers to creatively sketch footwear concepts and on product engineering and manufacturing partners to turn that sketch into realistic CAD models. Product engineers may act as the liaison between the two, helping designers understand the manufacturing limitations of their design. In this case engineering analysis and the use of digital design tools has not been heavily relied upon, and a product creation footwear company may be slow to implement new capabilities due to fast moving development timelines. However, as computer and simulation technologies have advanced along with better research on how to simulate various materials, new digital tools for footwear design have evolved and are being introduced into industry.

Digital design tools for footwear development typically are focused on bottoms, and the design of materials like foams, plastics, and rubbers. Due to the nature of upper materials and manual assembly methods (usually stitching or adhesive), there is variability across footwear assembly that makes it difficult to simulate an entire shoe design [21]. Instead, digital design aids focus on singular components or sub-assemblies, such as a bottom separate from the upper. Uppers are complex and difficult to simulate digitally. Several studies from the Higher Technical School of Industrial Engineering at the Polytechnic University of Valencia have investigated the simulation of uppers and soft materials such as leather. Rupérez et al. (2012) tested the deformation of physical samples of calfskin and compared results to that of an FEA simulation. While the team was able to simulate the behavior of the samples, they outlined some key difficulties for simulating leather in footwear design, and these difficulties translate to other textiles as well. One difficulty is the lack of standardized methods for measuring material properties such as Poisson's ratios and shear moduli, as these can vary for the same material that comes from different sources or batches, or may demonstrate nonhomogeneous properties if it is a biological material like leather [22]. In addition, textiles experience large displacements under load and deformation, making numerical analysis much more complex due to the nonlinearity of material behavior [22]. In addition, the loads and pressures exhibited on an upper assembly varies widely depending on the foot of the wearer, as well as their gait and movement patterns. Models have been developed to visually simulate possible pressure on an upper from a foot, such as a Simucal simulator created by Rupérez et al. (2010) [23]. However, the accuracy and consistency of these models needs to be researched further in order to be used reliably in footwear design.

Due to the challenges of simulating uppers, the footwear industry has focused more on the simulation of bottom assemblies and components. While it is obvious that an upper attached to a bottom will have an effect on overall structure and behavior, the behavior of the bottom provides a large impact to the performance of the entire shoe assembly. In a bending stiffness study on polyurethane foam midsoles in running shoes, Park et al. (2007) has shown that the bending stiffness of the entire shoe assembly will be greater than a midsole alone, however, the midsole stiffness can inform behavior of the entire shoe and is still worth understanding [24]. Going back to the design of soccer cleats, this implies that it is still of benefit to a design team to calculate and simulate the stiffness of plates alone if they already have an understanding of the influence of the assembled upper from previous designs.

As for as the digital design of bottoms, FEA simulation has been developed in multiple studies, and research is being conducted to find related methods to characterize bottom materials like foams and rubbers, such as a meshless model developed by Penta et al. (2018) [25]. The latest research on digital footwear tools involves the customization of bottoms for the individual user as well as implementing computational tools to develop bottom designs. The NFL has partnered with HP to scan players feet to understand their unique shape and pressures experience, and use this to design custom cleat bottoms that can be 3D printed [26]. Additive manufacturing is currently making a big impact in the footwear industry as companies such as New Balance and Adidas have partnered with companies such as Formlabs and Carbon respectively to develop 3D printed bottoms (see Figure 10). The advantage of these bottoms is a computationally informed lattice design intended to distribute footwear loads efficiently. Through a partnership between MIT and Adidas, Fay (2021) has explored how additive manufacturing and rapid design evaluation through digital tools like FEA can aid design teams and increase running performance [27]. While this area of research is still primarily in an academic setting and not fully integrated into companies outside of the few models mentioned, it has shown that there is a great opportunity for the footwear industry to use computational design and digital design tools to help create designs early in the development process.

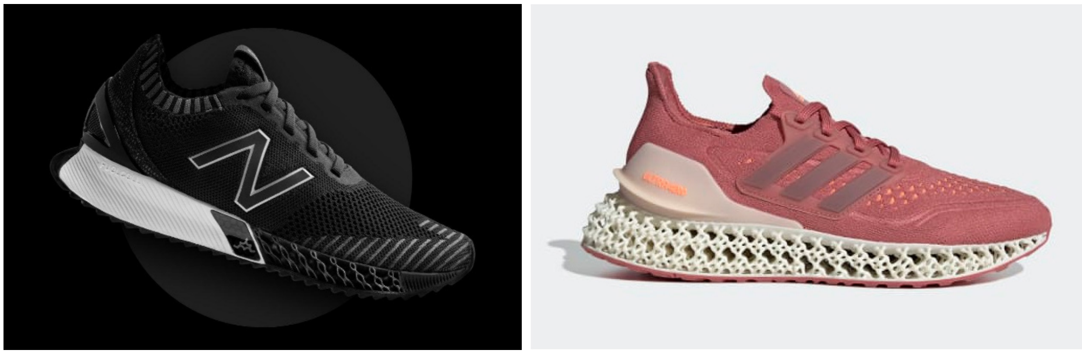


Figure 10: New Balance FuelCell Echo Triple shoe (left) [28], and Adidas Ultra 4DFWD running shoe (right) [29], both utilize 3D printed bottom components

However, similar to uppers, a difficulty with simulation of footwear bottoms is the material characterization. In the footwear industry, this can be especially tedious as companies tend to have their own teams of material scientists and chemical engineers that innovate propriety materials for shoe bottoms. This means there is no public database or research backed material properties to reference, and it is up to the company to test and calculate these values themselves if they wish to perform any sort of digital simulation.

3.2 Uses of FEA in Product Development

The finite element method (FEM) is a numerical method to solve differential equations, and is utilized to solve a variety of engineering problems. FEM was originally developed for structural mechanics applications, but has since evolved to cover other problems including thermodynamics and heat transfer, fluid dynamics, and electromagnetism [30]. As computers have advanced, so too has the ability to solve problems using FEM, making it a popular engineering tool across industries. The actual analysis is referred to as FEA. When performing FEA, there is a typical flow of processes an engineer follows. Shih et al. (1998) outlines five operational steps: information gathering, pre-processing, analysis, post-processing, and making conclusions [31]. An outline of these steps can be seen in Table 1.

Table 1: Typical FEA process steps, adapted from Shih et al. (1998) [31]

FEA Process Steps	**Description**
Information gathering	- Define analysis goals - Develop action plan - Collect background information
Pre-Processing	- Geometry cleanup of CAD model - Model meshing - Define material properties, loading, and boundary conditions
Analysis	- Run analysis on computer (time varies based on computer resources, complexity, and experience of analyst)
Post-Processing	- Evaluate results (could involve stress and deformation plots or animations)
Making Conclusions	- Decide whether design is sound based on relative comparison of stress and deformation of similar designs, yield failure, or durability requirements

According to Kim et al. (2018), there are two main types of design that FEA can help with: creative design and adaptive design. Creative design focuses on completely new structures and concepts, whereas adaptive design is about enhancing or modifying previous designs [30]. While footwear companies are constantly innovating new shoe concepts, the basic shape and behavior is similar allowing for a blend of creative and adaptive design. FEA is especially powerful when there are existing standards or past design data [31]. While many industries have strict mechanical, structural or safety standards to adhere to, such as the IEC 60601 standard for the medical device industry followed by the Food and Drug Administration, there are no required standards for the footwear industry. However, there exists years of historical perception data by users on design. The perception of feel of past designs can be linked to design properties such as stiffness, and give design teams a range of stiffness values to aim for. FEA can be implemented at almost any stage in the product development process, such as concept, prototype, pre-production, or product re-design, however given that it is time and resource consuming it is up to the company to decide at what stage it is most valuable [31]. In the case presented in this thesis, FEA has the highest value in the early concept and prototype phase prior to the first physical sampling round. This will give design teams the best chance to ‘do it right the first time’ and minimize additional costly sample rounds.

3.2.1 Difficulties of FEA Implementation into Industry Practice

While FEA can be a very powerful tool and has been used and studied extensively in academia, it is not always straightforward for a company to choose to implement it as a digital capability. One challenge highlighted by Nerenst et al. (2021), is that FEA in industry is typically reserved for nominal or comparative designs in late development phases, as a company may test a mostly developed product for standards and a high safety factor, which could potentially lead to overdesigned products [32]. Comparative FEA is able to refer to previously run simulations, saving time on pre-processing, analysis, and post-processing. Companies that focus on newly innovative products cannot benefit from the reuse and legacy knowledge of comparative FEA [32]. These companies will also encounter the challenges of immature CAD geometry (the key input to FEA), lack of a defined best practice when performing a design of experiments (DOE), access to DOE and FEA expertise, and the tedious manual setup that discourages the automatic execution of multiple simulations [32]. In modern times FEA software has become more user friendly, opening up the tool to general design engineers whereas previously it was required for the analyst to be a trained FEA expert. This is great for very common and well-defined engineering problems. However, FEA still requires an intuition and understanding behind the theory, as well as constant practice to keep up the skills to run an effective simulation. Fast-moving design companies do not always have time or resources for their engineers to practice and become adequate, and the time-consuming nature may also make the process longer for a general engineer to perform, especially on non-common engineering problems. This is especially difficult in the footwear industry where very few members of design teams have the adequate engineering backgrounds. The non-linear nature of footwear materials also increases the complexity of an FEA analysis, requiring an expert or customized FEA software to guide the engineer. As Shih et al. (1998) points out, specifically customized FEA procedures for specific products would greatly simplify the process, but often these tools are not available off the shelf and would require investment for the company to develop internally [31].

FEA is not only difficult to implement due to the complex technical nature of the capability, but also due to poor business strategy. In fact, Shih et al. (1998) lays out how many common problems with having an FEA capability in industry can be tied either to policy, planning, or execution (see Table 2) [31]. FEA is not only a big investment with obvious costs like software licensing, computer resources, expertise, and training, but it will be an investment in the overall strategy and operations of a design company. To run a successful digital capability, there must be a structural, political, and cultural prioritization within the organization. Time will need to be invested to create a robust FEA pipeline as well as internal guidelines and tools. There are technological, business, and human factors involved. This sentiment was validated onsite during interviews conducted by the author with the footwear company hosting this thesis.

Table 2: Sources of the causes of system problems in FEA, adapted from Shih et al. (1998) [31]

Problem Sources	**Policy**	**Planning**	**Execution**
Software Incompatibility		▨	
Hardware Inadequacy		▨	
Computer Down		▨	▨
CAD Incompetence	▨	▨	▨
FEA incompetence	▨	▨	▨
Miscommunication			▨
Lack of Communication			▨
Lack of Data		▨	
Database support	▨	▨	▨
Lack of FEA Guideline	▨		▨
Lack of Technical Support			▨
Lack of Management Support	▨		▨

3.3 Decision-Making Analyses in Product Development or R&D

Many companies will turn to quantitative analyses when evaluating new projects or long-term investments. These could include Net Present Value (NPV), Return on Investment (ROI), Cost-Benefit (C-B), and Pay-Back Period (PBP) [33]. Each analysis has its own time and place and should be considered only a tool to aid leaders in making an investment decision, and should not be taken as the end-all solution. For R&D projects in creative environments, a single quantitative analysis likely will not be very informative as many factors that affect an investment decision can be qualitative or abstract. They could involve the perception of product quality or even a cultural mindset shift for design teams to adopt. For these reasons, a qualitative cost-benefit analysis was identified as the most informative tool for footwear leaders.

C-B analysis has been a historical tool dating back to its first formal use in the 1930s by the U.S. Federal Government [34]. In fact, in modern times some publicly funded projects are required by state law to perform a C-B analysis [34]. Many private sector companies have also recognized its usefulness as a decision-making tool and implement it into their project proposals. Some C-B analyses will output a ratio to understand which side may outweigh the other. Due to the nature of the analysis relying on opinions among leaders on what may be considered a cost or a benefit and how big of an impact it has, the C-B analysis is inherently subjective [34]. Given the subjective nature, it is best used as an aid to lay out the pros and cons on both sides and be one piece of information to guide an investment decision. As the analyst lays out the costs and benefits, they may also be influenced by their own opinion. In this sense, Thamhain (2014) argues that such an analysis tool must be supplemented by managerial judgement and the collective experience of stakeholders based on past strategies and performance [33]. In short, it is the qualitative 'people side' that is often a missing link in quantitative analysis and should not be ignored.

For most R&D projects, it is difficult to define specific success metrics since there are not only complex technical measures to consider, but also financial, marketing, social, legal, and ethical factors involved [33]. Thamhain (2014) outlines four key dimensions that must be evaluated for R&D project decisions, summarized in Table 3. These dimensions highlight that while there are quantifiable costs and benefits that can be measured (such as personnel and facilities cost, or added value), there are a lot of costs and benefits that cannot be directly measured, and are based on political and cultural impacts to an organization.

Table 3: Four dimensions of an R&D project analysis, adapted from Thamhain (2014) [33]

4 Key Dimensions to Evaluate in a Cost-Benefit Analysis	
1	Added value of the new project, consistent with organizational objectives
2	Resource requests, such as cost, personnel, and facilities needed to complete the new project
3	Readiness and ability of the enterprise to execute the project
4	Managerial belief and desire

While there is not a standard practice for creating a qualitative C-B analysis, one general technique is to categorize the different types of costs and benefits. Conn et al. (2004) performed a qualitative ROI on the implementation of an updated software tool (called Blackboard) for instructors in an educational environment, and they were able to sort all identifiable costs and benefits into one of three categories: cost, time, and quality [35]. While this analysis was for a public educational application, a similar approach can be applied for R&D projects. Conn et al. (2004) also suggested that for each cost a possible solution be brainstormed [35]. This strategy could prove useful in R&D focused companies, especially those more technically and logically guided. It may be hard to quantify the increased perceived product quality or more efficient communication between teams, but if it can be addressed as a solution or worthwhile effect of a given cost or effort, it may help convince leaders.

3.3.1 Considering the Technology S-Curve

A final consideration for decision makers in product creation is the technology S-curve. Technologies typically fall onto an S-curve of time or effort versus either performance, profit, or level of invention [36]. The argument is that technology tends to advance in a series of S-curves (see Figure 11). For example, a new technologies initial performance and profit may be low while time and effort is high. It will eventually hit a point where the performance and profit will steeply increase, with little time and effort required. Finally, it will plateau at a certain level of performance with sustained time and effort. When that plateau is close to being reached, a new S-curve is just beginning. For companies to benefit from future technologies, they have to make the decision to jump away from a current technology and into a new one, despite knowing that there will be a slow ramp up.

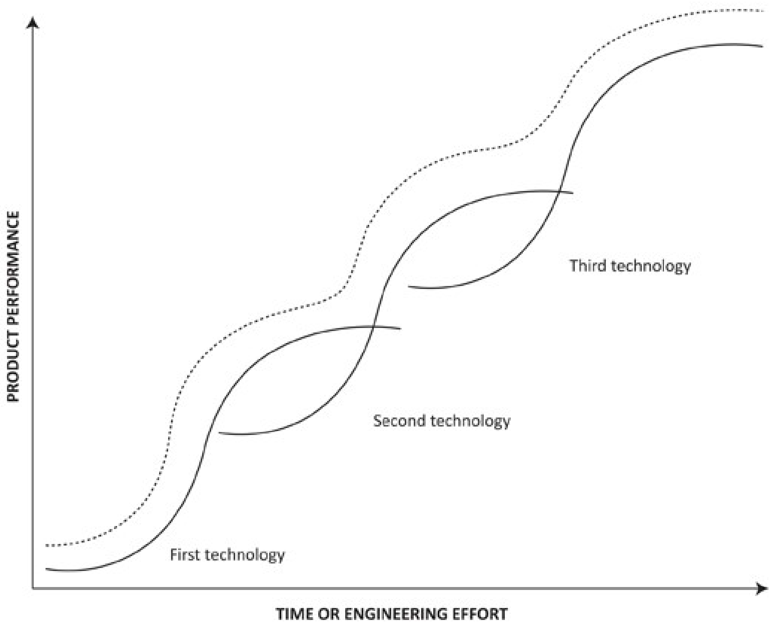


Figure 11: Technology S-curve [36]

The reason this idea of S-curves is being addressed is because it could be an important strategic factor when considering to implement new technical capabilities in an R&D environment. Given a list of costs and benefits, it will be important for decision makers to understand where on the curve they may be, and where they hope to get with the investment in a new capability. For instance, in a footwear company a certain level of product performance may have been reached with current design processes and capabilities. If a company wants to sustain that, they can choose to do so, but will have to dedicate continued time and effort while profits and performances may not increase. To move up to the next S-curve by innovating a whole new design, it may require investment in new technologies, which will require a longer period of time and effort up front without any perceived increases in performance. This could be a tough sell for a fast-moving footwear company with strict development timelines. But if a team is willing to add time to their process to build up a new capability, they could see long-term innovative benefits.

4 Cleated Plate Bending Case Study – Technical Process and Results

This chapter will walk through a technical case study on cleated plate bending. Three main approaches will be used to calculate the stiffness of different plate design options: mechanical testing, FEA simulation, and a moment of inertia calculation using beam bending theory. The goal of this chapter is to provide a comparison on the requirements and resources needed for each approach and the varying levels of detail and design confidence they can provide.

4.1 Overview of Plate Bending Analysis

4.1.1 Why Plate Bending

As mentioned in Section 2.3, cleat stiffness is essential for player safety and informs perceived comfort on the field. It is very hard to predict exactly how a cleat will feel to an athlete in the early design phases, but perception data from past models can help guide a design team to create the best features for a desired feel. Stiffness is a well-known characteristic by design teams and players alike, and one of the first things they will check for by hand when a physical sample is made. Without performing any engineering calculations on stiffness for a 3D design, teams may take on risk by relying on intuition and waiting until first samples are received to understand the feel of the cleat. While teams have been able to use additive manufacturing for quick prototyping and to get a gut feel for the stiffness of their design, it is still a trial-and-error method. A three-point bend test is performed on the plates of all new design samples, and there is a general understanding of what stiffness means for different areas of the plate. Given the opportunity to increase design confidence and robustness prior to any sampling rounds and that design teams already have an understanding on what stiffness means to an athlete, this case study was chosen as a great example to implement FEA and engineering calculations into the footwear creation process.

4.1.2 Case Study Set-Up

For the purposes of this analysis, a CAD model of a simple plate for a soccer cleat was created. This plate is for the right foot of a men's size 9 cleat, as this is a typical size for initial shoe designs which is able to be scaled up or down to accommodate the size range requested in the product brief. The material for the plate will be Nylon 11, which was chosen due to the similarity in performance to other TPUs that are typically injection molded for cleated products, as well as the availability of Nylon 11 as a rapid prototyping material used often by footwear design teams. The simple plate has basic contours for the general shape of a cleated product as well as simple studs for a firm ground playing surface. From this plate two more design options were created. For each option a different type of rib feature was added to the arch area of the foot. For one, a thick single ribbed feature was added, and for the second a more streamlined double rib feature was added. Both provide examples of different aesthetic looks a design team may desire while also providing different levels of stiffness. General mechanics knowledge will tell an engineer that any addition of thickness will increase stiffness, so it is expected that the two rib designs will give much higher stiffness values than the original plate. From this point onward, the base plate will be referred to as Option 1, the single rib design as Option 2, and the double rib design as Option 3. Images of the designs and their cross sections can be seen in Figure 12.

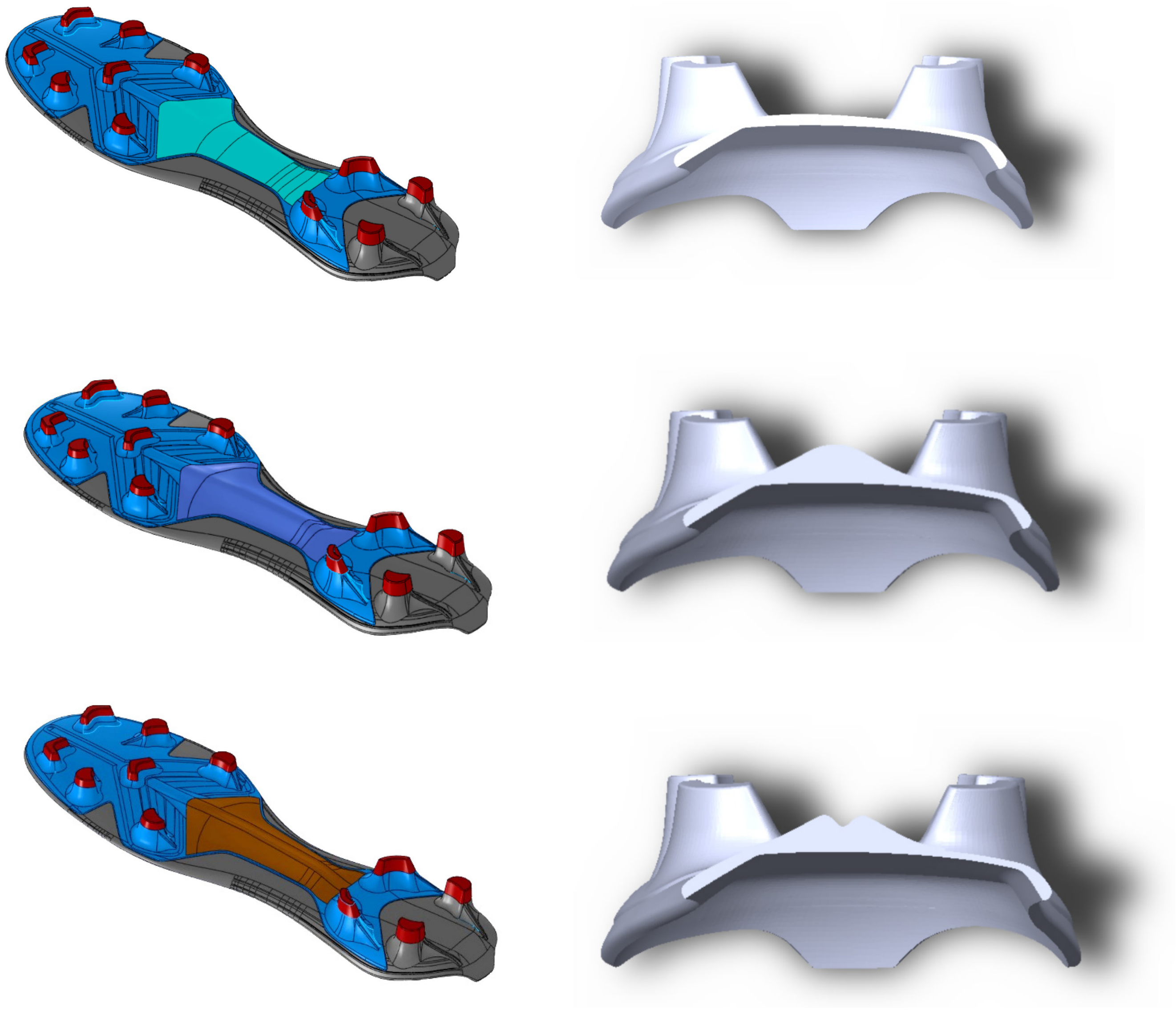


Figure 12: CAD models of plate design Options 1, 2 and 3 (left) and their respective cross-sections at the arch (right)

The arch area was chosen as it is a standard location to measure stiffness for all physical samples. A stiff and supportive arch area is preferred by athletes, giving them stability while the forefoot is able to flex. This area was also chosen because it has the least amount of interference with studs during testing. If other areas of the foot were to be analyzed, the plate would have to be modified to allow the plate to rest freely on the supports for a three-point bend test, and this would add a level of variability that design teams would need to consider. The exact location of the bend will be the same across all approaches. A template was created to mark this location for all CAD and physical models (see Figure 13). The size of the hole in the template represents the approximate size of the indenter used in both the mechanical and FEA test.

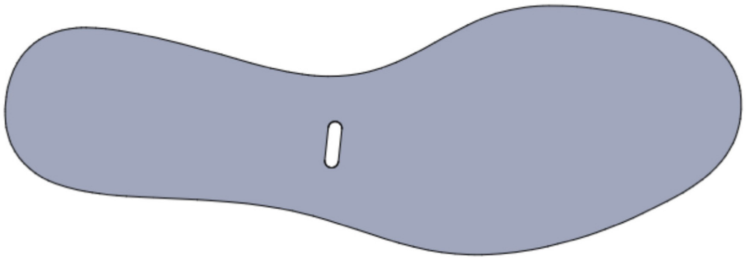


Figure 13: Bending location template for plate bending case study

In this use case, the main comparison will be between the two ribbed models, although the base model will be tested as well. This will represent a design team adding new features and wanting to calculate a relative stiffness comparison between the two.

4.1.3 Interpreting Results and Desired Outcomes

In the world of footwear design, all comparisons are relative to past models and legacy knowledge. There are no standards or guidelines for values of stiffness to be achieved. It is especially important to note that in the case of plates, any stiffness value for the plate alone will not be the same as the final assembly of the shoe with the upper. However, understanding the relative impact of different design features on stiffness and feel is very valuable to design teams, especially when they already know the design of the upper and the only variable is the bottom plate. A footwear designer may not have an engineering background, and their main goal is to generate appealing aesthetics for the customer. This makes the engineer’s main goal to translate material, manufacturing, or performance constraints such that they can be easily understood and accepted by designers. In the case of performance, engineers want to convey specific design feature behavior to the designer in a way that is not technically complex. In this case, a designer would like to understand if one of their design features is stiffer than another, and whether it is by a small or large margin, without necessarily needing to know the actual values of stiffness. The goal is to present a percentage difference in stiffness between the two ribbed design features. It will be useful for the design team to know if Option 2 or Option 3 is stiffer, and if it is only on the order of 10%, or more than 50%. The analysis is not intended to give teams the best or correct option, but to add more detail and context to better inform their final designs.

The goal of doing all three approaches is to demonstrate varying levels of effort a design team can give for understanding stiffness. The three approaches that will be evaluated in this chapter are:

- Mechanical Testing of Physical Samples
- FEA Simulation
- Beam Theory – Moment of Inertia Calculation

Each method will take a different amount of time, require a different level of expertise and resources, and provide different levels of accuracy and information. The prediction prior to performing the case study was that all approaches will give similar relative results. Given similar results, senior leaders could choose which methods they would want to invest in for their teams based on what level of effort they are willing to put in. This investment decision will be discussed in more detail in Chapter 5.

4.2 Current Approach – Mechanical Testing of Physical Samples

The following approach for stiffness measurement is a standard test used by footwear design teams on all cleated products. Teams will send physical samples of their cleats to a mechanical testing lab, typically an internal lab onsite at the company for quick turnaround and familiarity with the procedure. The procedure is for a basic three-point bend test on a universal testing machine.

4.2.1 Sample Creation and Testing Process

In most cases, physical samples of cleats arrive from overseas manufacturing partners fully assembled to the upper. Test engineers must then deconstruct the sample to get only the cleated plate. For the purposes of this case study, an unassembled plate was tested. This will provide the best comparison to the FEA and bending calculation methods that use only a CAD model of the plate without any other components. The test samples of all plate options were 3D-printed out of Nylon 11 on an industrial scale multi-jet fusion printer with a standard XY print resolution of 1200 dpi and layer thickness of 0.08mm. Images of the printed samples for each plate option can be seen in Figure 14.

Figure 14: 3D-printed samples of plate Options 1, 2 and 3. The samples were printed on a multi-jet fusion printer out of Nylon 11.

The ability to create complex geometries and provide similar behavior to injected molded TPU makes this is a common material and printer used in footwear design. In fact, design teams may print out these samples solely to be bent by hand and provide the team intuition on feel. For example, after the samples were printed, it was quickly discovered that Option 1 is flimsier and more bendable compared to Options 2 and 3 (see Figure 15).

Figure 15: Demonstration of how 3D printed plate samples can be bent by hand to give design teams an intuition of the stiffness of their designs prior to testing

The template from Figure 13 was printed to scale on paper and used to mark the bending location for each sample (see Figure 16). This mark was used to visually align the sample to the indenter on the universal testing machine while the sample rests on the two lower supports (see Figure 17). The samples were bent such that the bottom surface with studs was resting on the supports while the indenter pushed downward on the top surface of the plate.

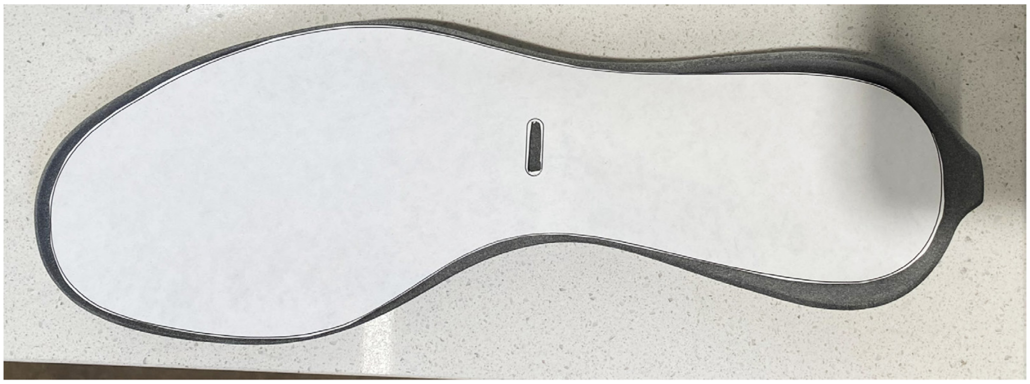


Figure 16: Paper template used to mark bending location on test samples

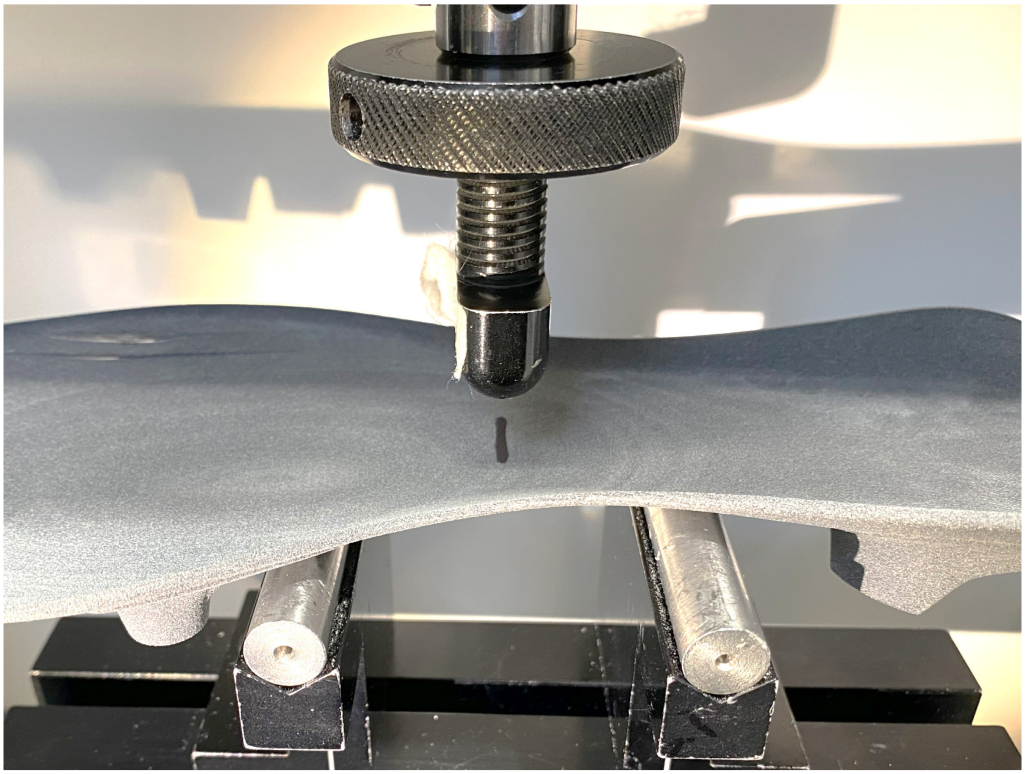


Figure 17: Alignment of sample on three-point bend testing set-up

For each sample, the machine cycled through multiple displacements of 5mm, with the 0mm displacement set by lowering the indenter until it makes first contact with the top of the plate. See Figure

18 for images of each plate option at a 5mm displacement. Several runs were made for each option, however, only the results from the first run were considered for final calculations. This is due to the fact that the plastic sample will ‘break in’ and become fatigued, showing slightly lower stiffness values over time.

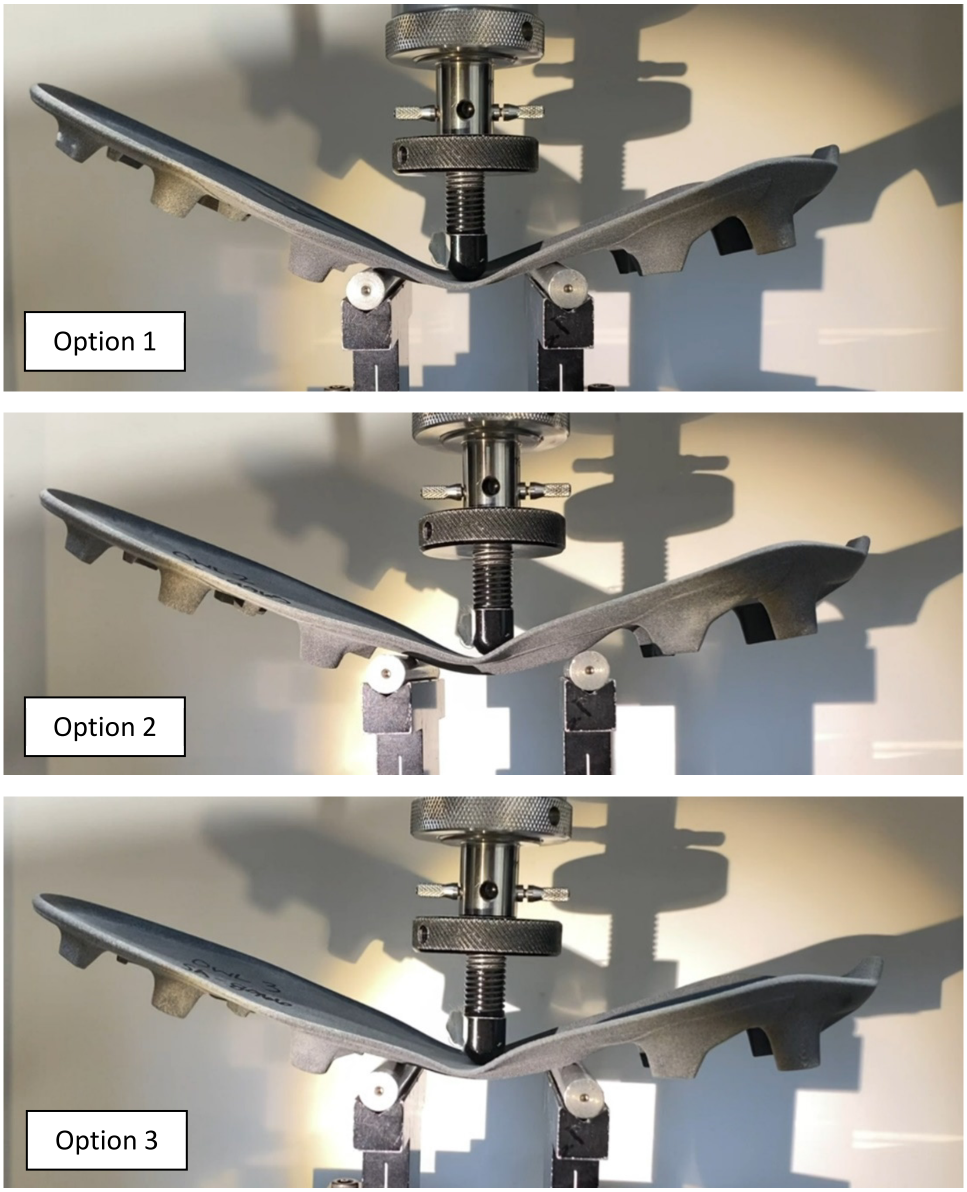


Figure 18: Three-point bend test on samples of plate Options 1, 2, and 3 shown at 5mm displacement

Once a complete CAD model was available, it only took one day for the three samples to be 3D-printed. In the testing lab, it took less than one hour to complete several bending runs on all samples. This process could easily be completed within a few working days if a design team wanted to use this approach to measure stiffness differences in their plate designs. Even if a fully-assembled physical sample was tested as opposed to a 3D-printed prototype, it would only add a few extra hours of work at most to deconstruct the samples for testing. This is an efficient way to quickly test early designs when using 3D-printed samples. However, if a team wants to use fully assembled samples, they will have to wait longer lead times to receive their first designs from overseas manufacturing partners. This approach is easily accessible to design teams, especially when the footwear company has dedicated test engineers in a mechanical testing facility onsite. Even if a product engineer were to run this test as opposed to a dedicated test engineer, it would require very little training. In the case of this thesis work, it took the author less than 10 minutes to receive an overview of the machine and setup by the onsite test engineer.

4.2.2 Mechanical Test Results and Process Discussion

The output from the universal testing machine gave both displacement and load data for all plate options. This data is plotted in Figure 19 below.

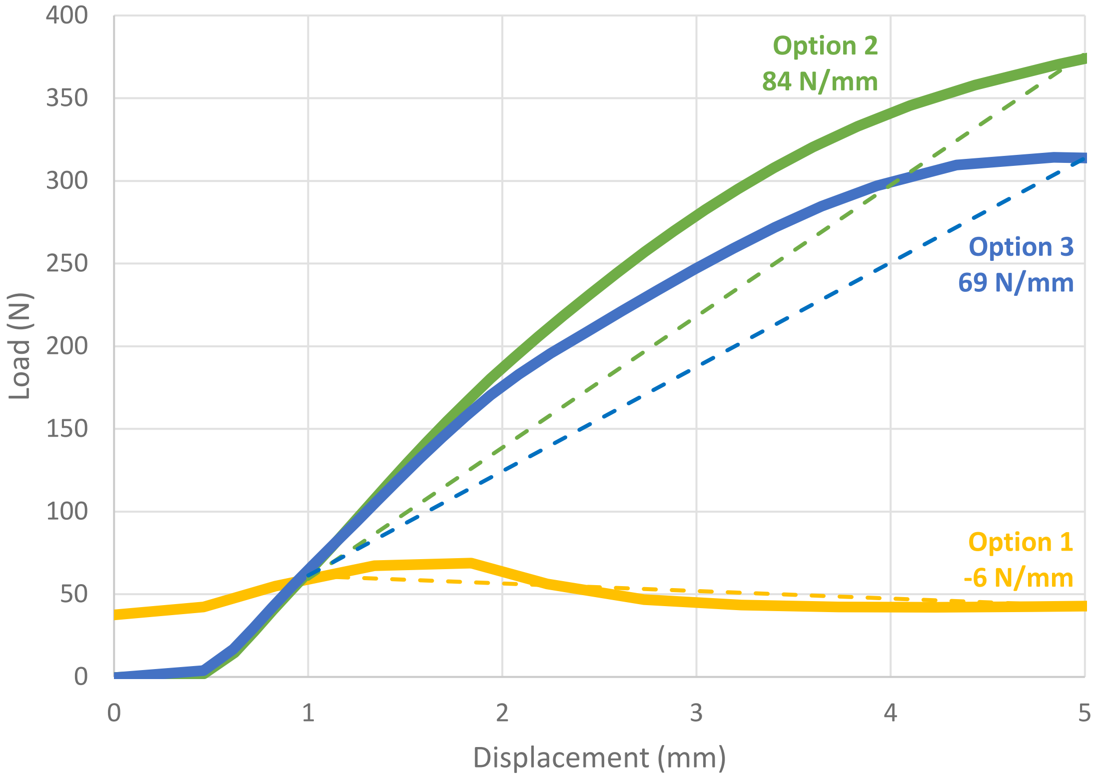


Figure 19: Load (N) versus displacement (mm) of all plate options from mechanical three-point bend test with computed slope values from 1-5mm

It is normal to see a rise in the load versus displacement curve, slowly leveling off but never decreasing. With this in mind, Option 1 produced abnormal results, and will not give an accurate calculation for stiffness. This was likely due to Option 1 being much less stiff than the other options, and the sample is thought to have experienced slippage on the universal testing machine due to the uncharacteristic dip after about 1.5 mm of deflection. The final stress calculations will still be completed for Option 1, but they will not be used for comparison of the other methods shown in sub-sections 4.3 and 4.4.

As defined in eq. 1, stiffness is force over displacement. In the case of the data presented in Figure 19, stiffness is the slope of the curve. The slope is calculated between 1mm and 5mm of displacement (the initial ramp-up data from 0-1 mm of displacement is discarded). The final results from this test for all plate options are shown in Table 4.

Table 4: Mechanical three-point bend test stiffness results

	Option 1	**Option 2**	**Option 3**
Stiffness (N/mm)	-6	84	69

Due to the previously described issues with Option 1, a negative stiffness is generated, which is unfit for comparison. However, Options 2 and 3 provided usable results. In this case, a relative comparison of stiffness would tell design teams that Option 3 is 82% the stiffness of Option 2, or 18% less stiff.

4.3 FEA Simulation Approach

For the second approach, an FEA simulation was run to mimic the same set-up as the mechanical test. The material properties for a Nylon 11 plastic were used, and the same size and positioning of the indenters and supports for the three-point bend setup were modeled. This sub-section will walk through the process to set up and run the simulation and discuss the results.

4.3.1 Simulation Process

While many FEA software programs have become more user-friendly, it is critical to have experience with FEA software and an understanding of the FEM calculations that will be done by the computer. This is especially true in the case of footwear models, since softer materials undergo large deformations and require non-linear mechanics equations as described in the background chapter. The results an engineer receives from a simulation are only as good as the inputs they provide, so proper training, expertise, and experience will produce the best simulations. The following process was completed alongside an experienced FEA engineer that has worked on footwear simulations in the past. The analysis was done on a robust FEA software program that is able to handle large displacements and non-linear behaviors. An entry level FEA program, for example the simulation package add-in for SOLIDWORKS, will not be sufficient to accurately capture the behavior of footwear. Due to confidentiality, the exact program, detailed settings and reasoning behind the setting choices are omitted from this discussion. However, this section hopes to provide the reader with an awareness of the tediousness and expertise needed to set up a simulation for footwear design.

The most tedious part of an FEA simulation is the setup, which primarily involves geometry clean-up of the CAD model as well as meshing. First, the CAD model must be imported into the FEA software. Some FEA software programs do have some capability for CAD model creation, but other CAD tools are much more efficient for model design, especially in footwear. When importing geometry, it is common that not all surfaces and edge lines import correctly. In order to run an effective simulation, the model must be watertight, meaning all edges and boundaries are closed to form a solid object. During import, some surfaces may be duplicated or some edges may not be connected. To make a watertight model, the FEA engineer must go in and manually fix all surfaces and edges that are not watertight. FEA software can aid in highlighting problem areas to address. For example, Figure 20 shows a close-up of a single stud on the imported plate geometry. There is a yellow-red line, signifying that there may be multiple unstitched surfaces. This is verified by looking at the cross section. The FEA engineer will then go in and manually delete the extra surfaces and stitch the edges together. Figure 21 shows the finalized geometry of Option 1 after it was cleaned up. In this view, some edges are also highlighted blue, signifying that the FEA engineer chose that as an edge to be used while generating the 2D mesh. To simplify meshing, it is common for an engineer to tell the software to ignore certain edges.

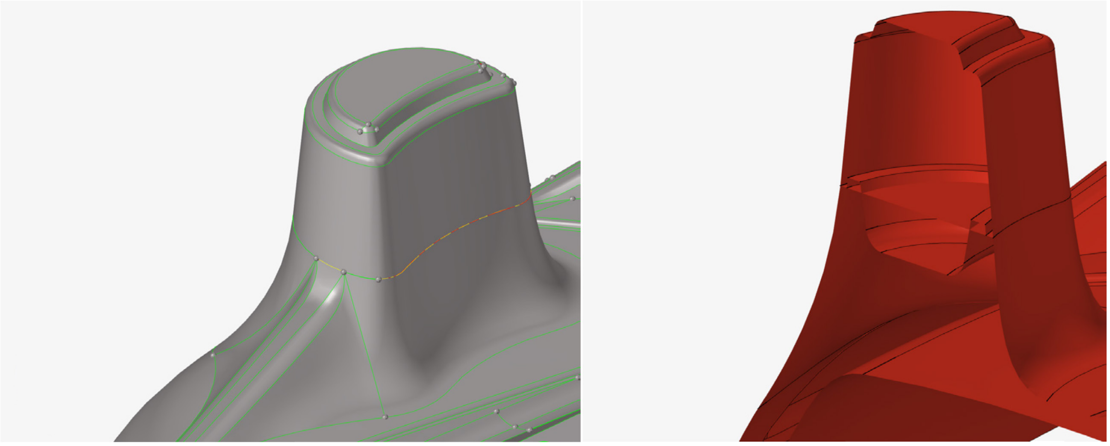


Figure 20: Close-up of imported geometry of a cleat stud into the FEA software. The yellow-red edge in the left-hand image alerts the engineer to multiple surfaces in the model, which can be verified in the cross-section (shown right)

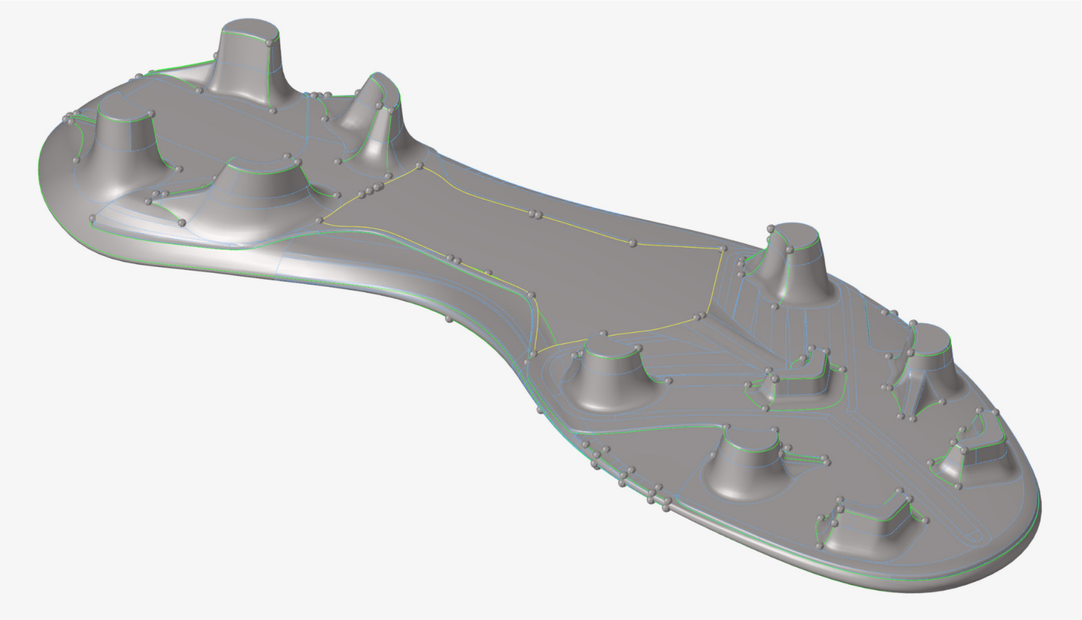


Figure 21: Plate Option 1 after geometry clean-up. Green and blue edges signify edges that will be used to generate the mesh.

Once the geometry is watertight and the appropriate edges are defined, the next step is meshing. Meshing first involves generating a 2D mesh of the outer surface. Using engineer defined settings (such as element size or shape), the software will divide the surface into a series of finite elements, in this case triangular elements. These elements contain nodes and sides that the computer will use to define the differential equations in the simulation. It is the engineer's responsibility to check over the mesh generated by the software and ensure all areas meshed correctly, as the automatic meshing features in some programs may not always give the best results. They may also manually change element sizing in areas of interest, making them smaller to improve accuracy (although this is at the cost of increased run time). In this use case, the same mesh was reused for Options 1, 2 and 3, and only the area of interest around the arch on the bottom side was re-meshed. This helped simplify and speed up the meshing process for comparison. Figure 22 shows the final 3D mesh for each plate option. For a better view, a close-up of the 2D mesh for the heal area of Option 1 can be seen in Figure 23.

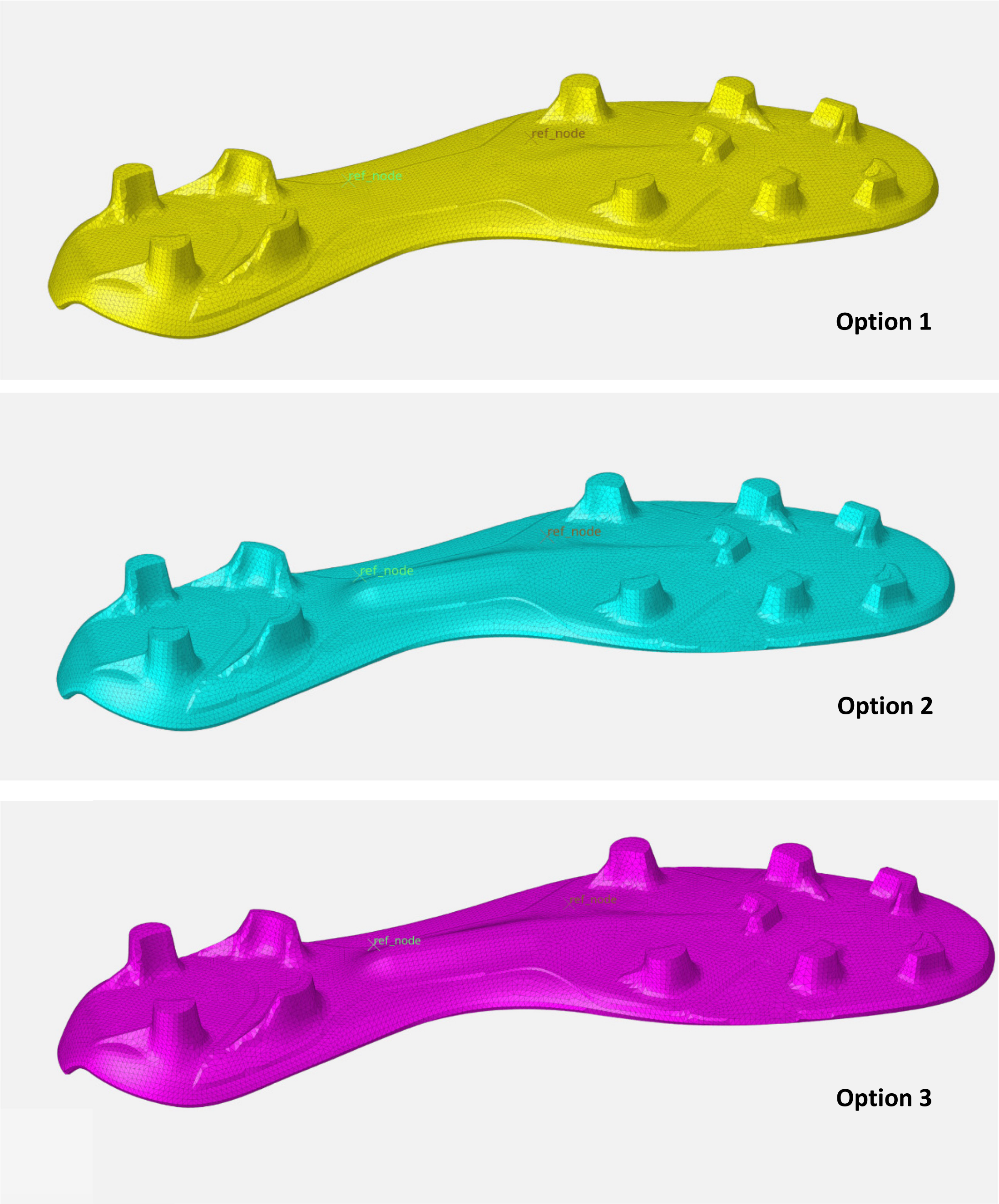


Figure 22: Final 2D mesh for plate Options 1, 2, and 3.

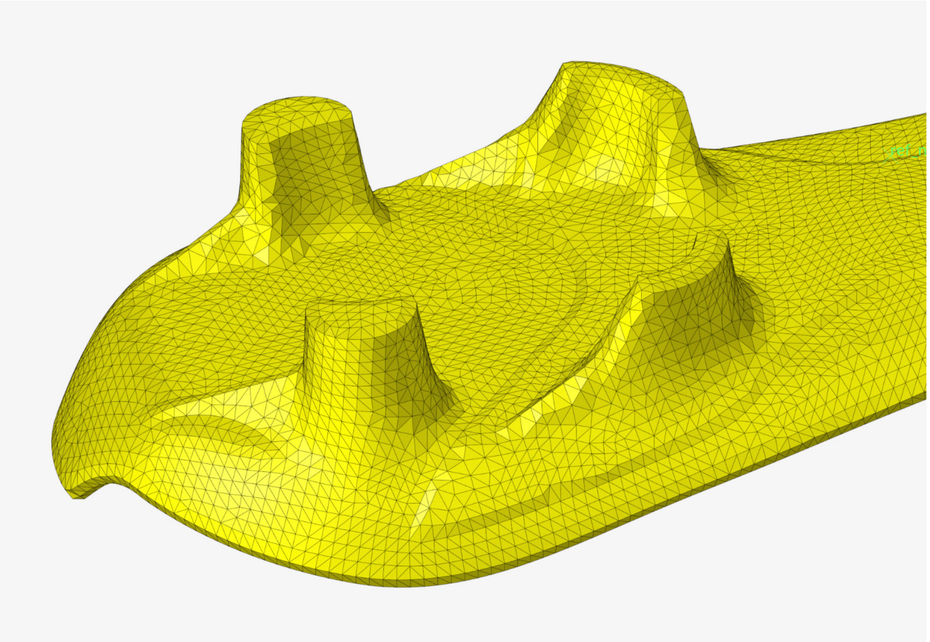


Figure 23: Close-up view of 2D mesh on the heel area of plate Option 1

Once an engineer is content with the 2D mesh, a 3D mesh needs to be generated. The software will use the existing 2D mesh to generate 3D finite elements throughout the solid plate. Instead of triangular elements with three nodes, the software will now generate pyramid shaped elements of 4 nodes connected by 6 lines. A cross-sectional view of the 3D mesh for Option 1 can be seen in Figure 24. The 3D mesh is what will be used by the computer solver for the simulation. The 2D mesh was generated only for the purposes of aiding in the creation of the 3D mesh.

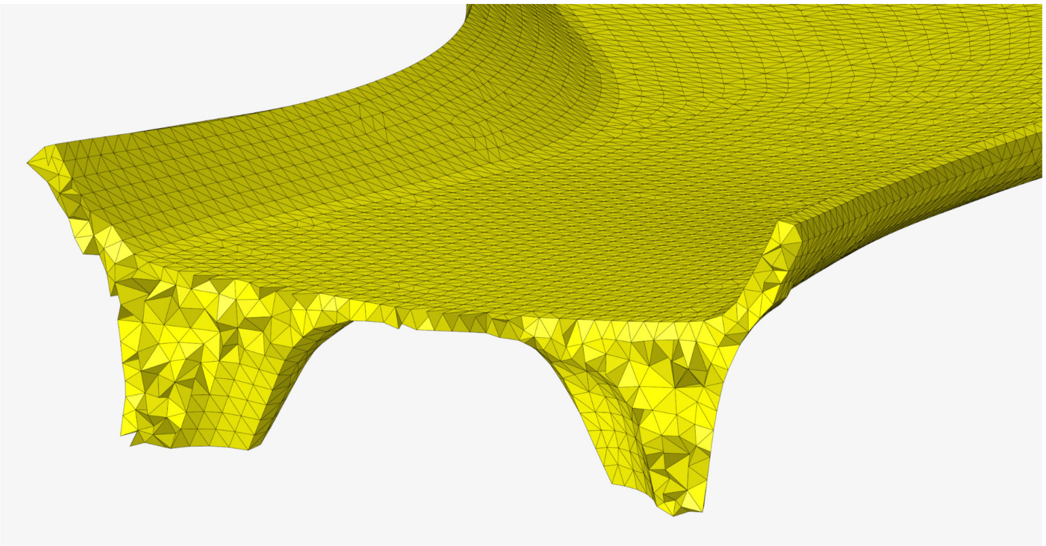


Figure 24: Cross-sectional view of 3D mesh generated for plate Option 1

The next stage of the process is to import the geometry of the indenter and supports for the three-point bend test. In this case, these models already had a mesh associated with them from previous footwear simulations and could be used as-is. In other situations, the imported geometry of test equipment will also have to go through the meshing process. The engineer will first import the bend location template and align that with the plate model (see Figure 25). From there, the plate can be aligned with the indenter with the aid of the template (see Figure 26). The indenter and supports are placed at the proper distances to mimic the physical test set up.

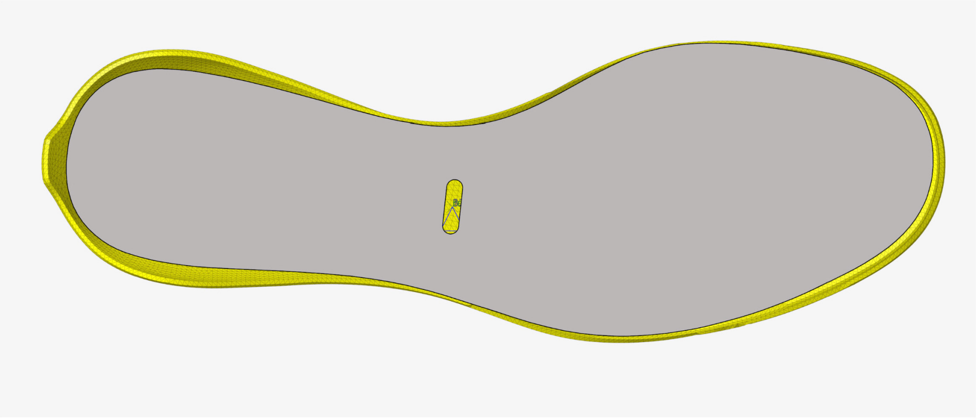


Figure 25: The bend template is imported into the software and aligned with the meshed plate model

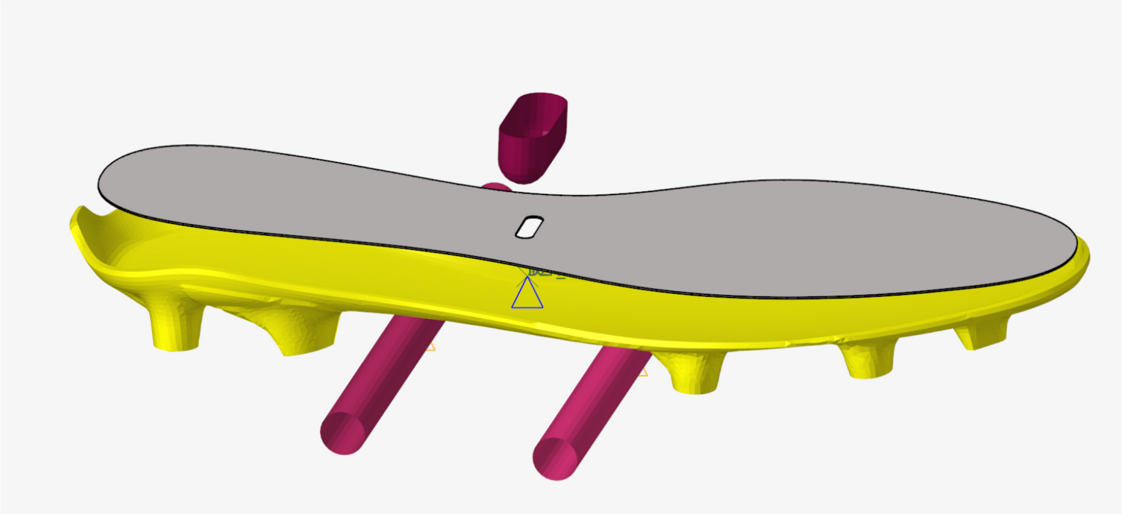


Figure 26: Pre-meshed models of the indenter and supports are imported into the simulation and aligned using the bend location template

At this point, the template can be removed, and the plate is adjusted to make contact with the supports and indenter to define the starting position (see Figure 27 and Figure 28).

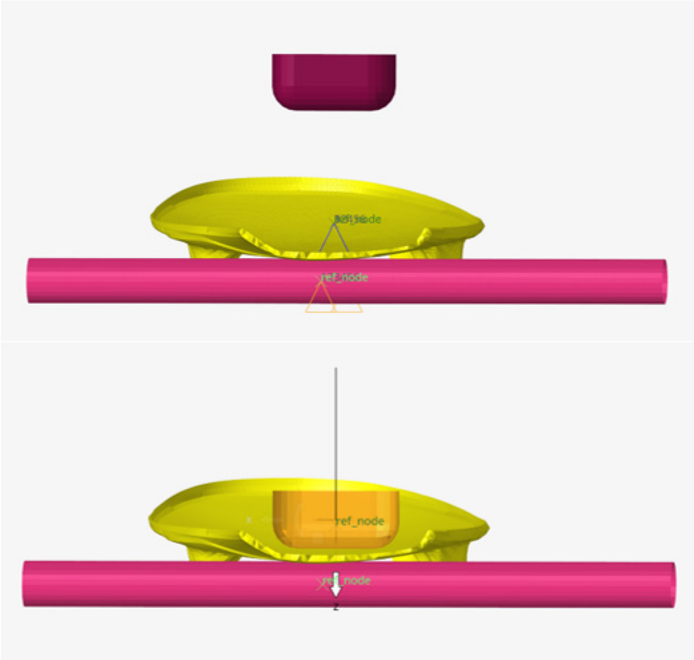


Figure 27: The plate is moved to rest on the supports, and the indenter is manually moved downward to make first contact with the plate model

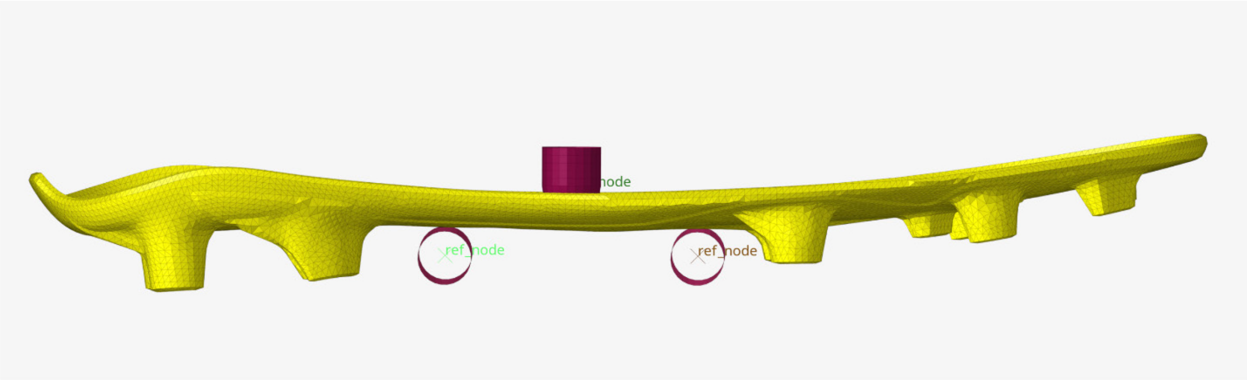


Figure 28: Final alignment of the plate model, indenter, and supports based on physical setup

It is common practice to mesh the entire plate (as was done above) if there is chance other simulations are to be run on the same model (this helps eliminate the need to re-mesh). However, in the case of the three-point bend simulation, it is unnecessary to simulate the entire plate, and instead the only area of interest is the arch area in close proximity to the indenter and supports. To decrease computational time and resources required, the toe and heal ends are removed (see Figure 29). At this point meshing and alignment are complete, and the next step is to define the simulation parameters.

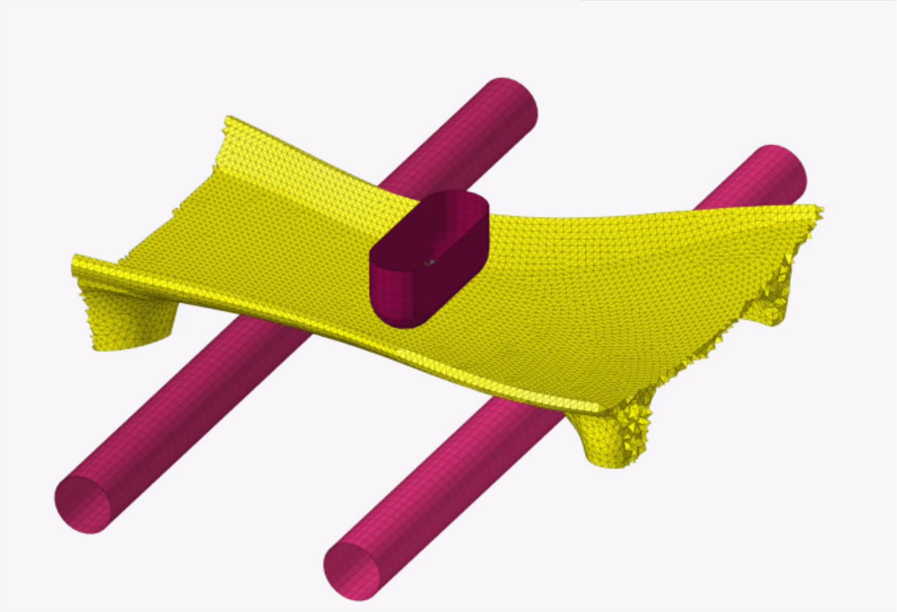


Figure 29: The toe and heal ends of the plate model are removed to reduce computational time.

Defining simulation parameters before running is another time-consuming part of the process, and will go quicker for more practiced FEA engineers. The naming of parameters can vary program to program, but the inputs for this specific bending simulation are defined in Table 5. This list of inputs is not exhaustive, but highlights key parameters for the three-point bend simulation.

Table 5: Description of selected simulation parameters

Parameter Category	**Description**
Components	Defines the geometry or elements to be exported to the simulation solver (in this case, only elements from the 3D mesh are exported)
Curves	Defines set curves for simulation to follow, such as stress-strain curves, or amplitude curves for how elements should move (this is where the speed and distance of the indenter movement is defined)
Elements	Defines the types of elements. In this case, elements are changed to second order for more accuracy. This changes the first order finite elements with 4 nodes and 6 sides to second order with 10 nodes and 6 sides).
Groups	Defines how different components interact with each other. In this case, general contact between the plate and the supports and indenter are defined by adding a standard coefficient of friction.
Loads and Load Collectors	Here degrees of freedom and the movement of the indenter is defined in different load step folders. The supports are given no degrees of freedom, and the plate is unrestricted and has complete freedom for movement.
Materials	Here the material properties of components are defined. In this case, the properties for Nylon 11 are applied to the plate. No material properties are assigned to the supports and indenter as they will be defined as rigid bodies.
Nodes	Here the moving nodes are defined, in this case a single node at the center of the indenter. The support nodes are also defined in space. Here is where it is requested that reaction force at the indenter node be measured.
Output Blocks	Here the engineer defines desired outputs. In this case, nodal displacement, stresses, strains, and history data.
Rigid Bodies	Supports and indenter are defined as rigid bodies since the focus is on deflection of the plate only.

At this point, all meshes, positioning, and parameters can be saved and exported. This is created in what is called an input deck, or file that defines all the work done above in a way the FEA solver can understand. After the FEA engineer checks all inputs are written correctly for the solver, the file can be sent as a job to be run on the computer server. Depending on the company, engineers may have access to different solvers and have reserved server space for simulations. The simulation can now run and the engineer waits for results. Run time varies significantly depending on simulation complexity, from hours to days of time. In this case, the simulation was simple as the plate geometry was less complex compared to other footwear designs, and the total run time for all plate options took about an hour (roughly 20 minutes per option).

The final step is post-processing, or retrieving and evaluating the output data from the simulation. Most FEA software programs have built in graphing and animation features to present the data. The desired data must be imported into the software from the solver's output deck. In this case, reaction force (N), displacement (mm), stresses (MPa) and strains of the plate options were exported. This data can be used to generate graphs and tables, as well as contour plots and animations to help a design team visualize what is happening in the material as it undergoes deformation. For example, in this case, it might be beneficial for a design team to see where the highest strains are in the material at maximum displacement for the different design options (see Figure 30). This can highlight potential weaknesses or failure modes in the design. Video animations of the change in contour plots over time can also be helpful for design teams to visualize the footwear component as it moves. However, in this case study, the only data required is the reaction force and displacement data to calculate plate stiffness.

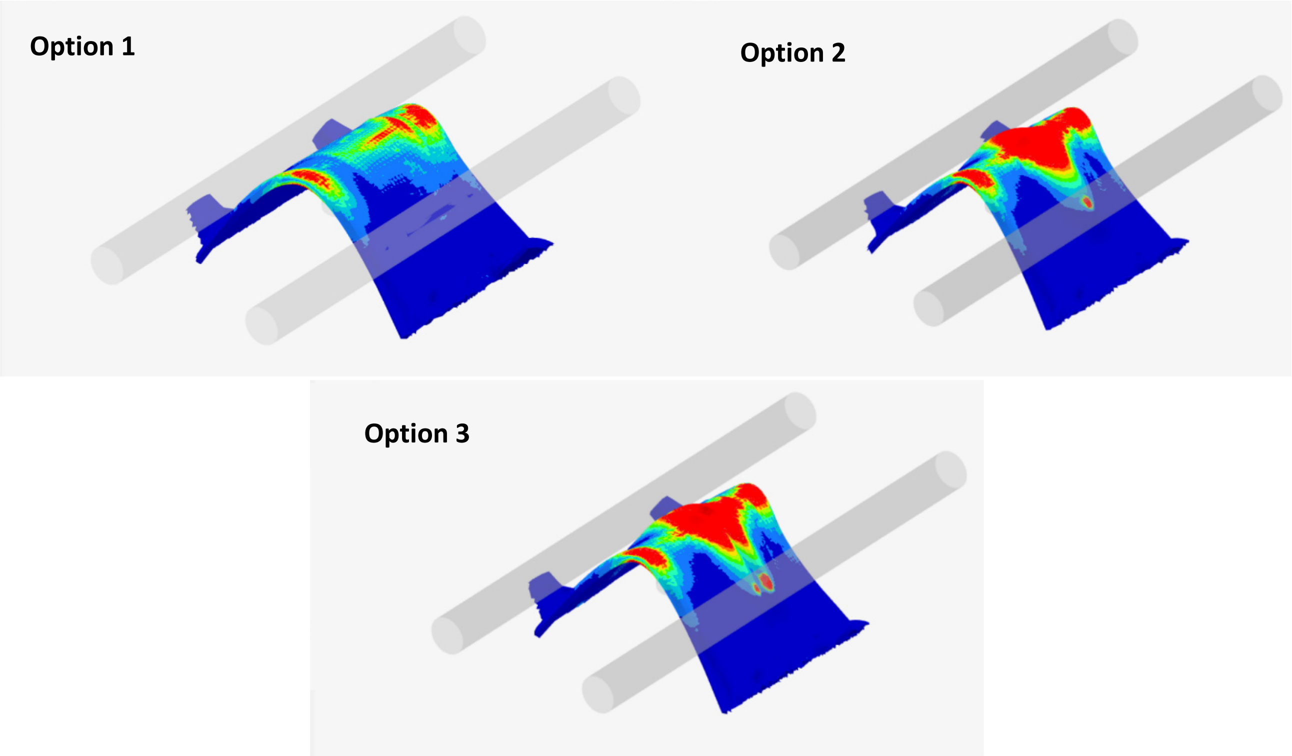


Figure 30: Bottom view of strain contour plots at maximum simulation deflection for plate Options 1, 2 and 3

4.3.2 FEA Simulation Results and Process Discussion

Similar to the output graph generated from the mechanical test, the output data from the simulation can be exported to generate a force versus displacement curve (see Figure 31).

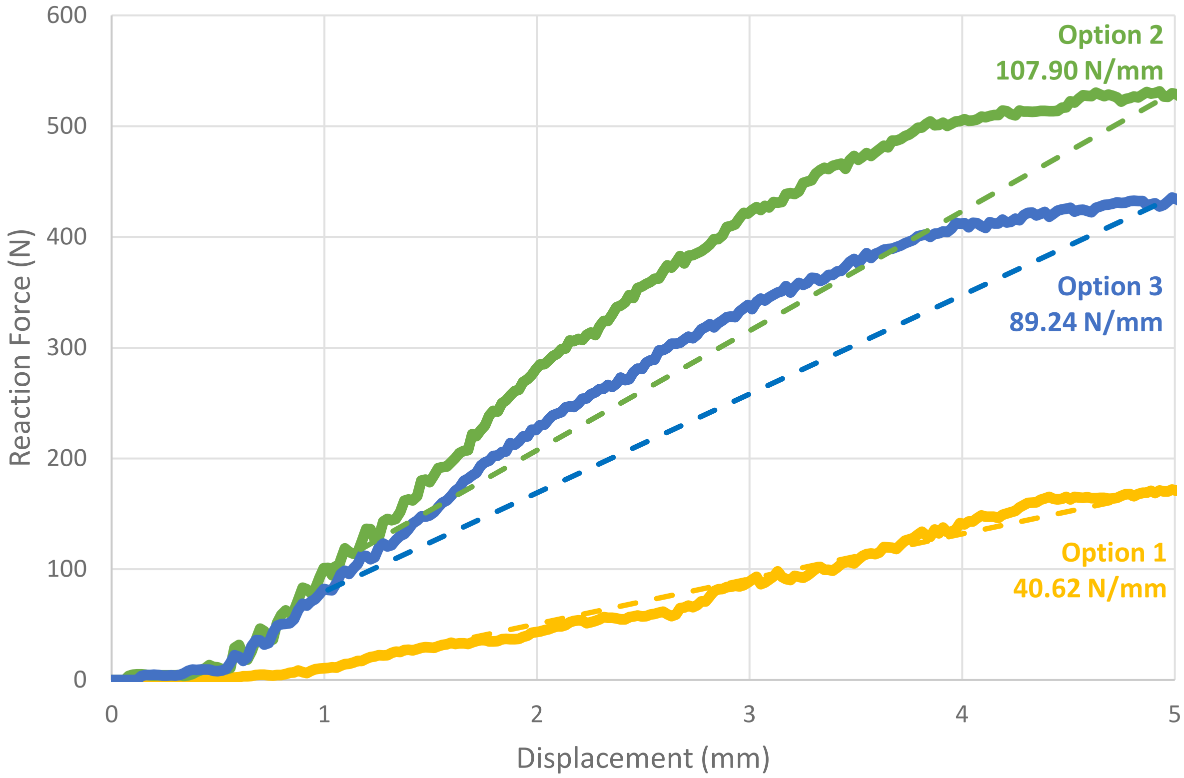


Figure 31: Reaction force (N) versus displacement (mm) of all plate options from FEA simulation with computed slope values from 1-5mm

From first glance, the results are similar to the mechanical test, with Option 2 having the steepest slope. In this case, Option 1 was able to be simulated fully, giving a more accurate curve than the failed mechanical test. Option 1 is much less stiff than the other plates, which was expected after bending physical samples by hand.

To calculate stiffness, the slope will again be calculated between 1mm and 5mm of displacement. The FEA stiffness results are shown in Table 6.

Table 6: FEA simulation stiffness results

	Option 1	**Option 2**	**Option 3**
Stiffness (N/mm)	41	108	89

These stiffness values are higher than those in the mechanical test. This could be for a variety of reasons, mainly being the fact that the mechanical test used a 3D printed Nylon 11, whereas the material properties defined in the simulation were for an ideal injection-molded Nylon 11. It is common for 3D printed samples of plastics to differ in behavior from their injection-molded counterparts. For example, even though tensile strength may be similar between 3D printed and injection-molded parts, the 3D printed parts tend to fracture at lower strains [37]. Regardless of the actual stiffness values, a ratio of the difference between options can still be calculated and presented to design teams. Here the stiffness of Option 3 divided by Option two is 83%, meaning Option 3 is 17% less stiff than Option 2. This is similar to the 18% difference in the mechanical test.

The main difference between this FEA approach and the mechanical test is the time and level of expertise required. The timing for the overall FEA process is shown in Table 7. A total of 11 hours of focused work time was needed for the simulation of plate Options 1, 2, and 3. This timing was with an experienced footwear FEA engineer, and total timing could be double or triple this time for a new engineer with basic FEA training. While most engineers or design team members could perform the mechanical test, only trained engineers with a background in mechanics and FEA can successfully set up and run the simulation.

Table 7: Timing for FEA simulation process steps (times are assumed to be lower bounds, as the process was completed by an expert FEA engineer)

FEA Process Step	**Time (hours)**
Geometry Clean-up & Meshing (2D & 3D)	3
Simulation Set-Up	4
Run Simulation	1
Post-processing (review results, generate graphs and animations)	3
TOTAL	11

4.4 Alternate Engineering Approach – Beam Theory

The final approach used in this case study uses beam bending theory to estimate stiffness of the plates based on geometry and material properties. This approach is a middle-ground between the physical testing and FEA simulation. Since this method is for estimating stiffness based on geometry, it can be used immediately once a CAD model is available and before any physical samples are made. However, it will not be as accurate or give additional details like the FEA approach.

4.4.1 *Moment of Inertia Calculation Using Plate Cross-Sections*

For this approach, a finalized CAD model is needed as well as a CAD program that has the ability to take cross-sections and provide geometric properties like moment of inertia. SOLIDWORKS was used for this specific use case.

Similar to the FEA approach, one of the first steps is to define the bending location by utilizing the template from Figure 13. Using the template, a reference plane can be inserted that is parallel with the bending location and normal to the base of the plate. See Figure 32 for an example of a reference plane created using the template. From there, a cross-section can be created using the reference plane (see Figure 33).

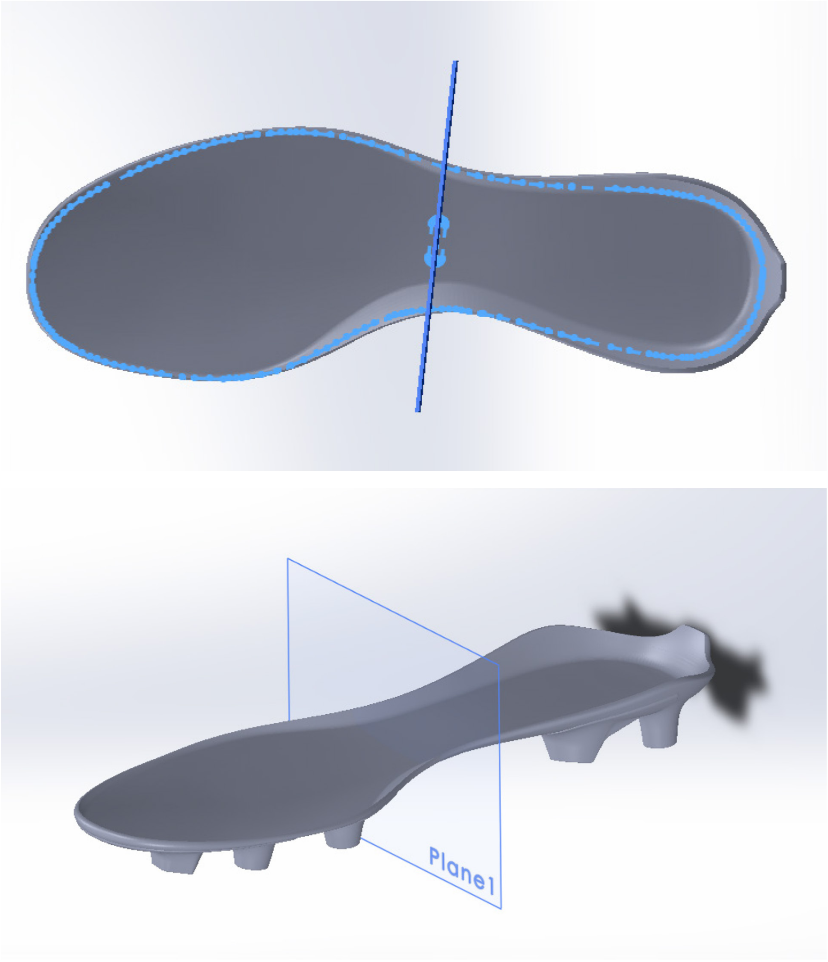


Figure 32: Creation of reference bending plane for plate Option 1 using bend location template

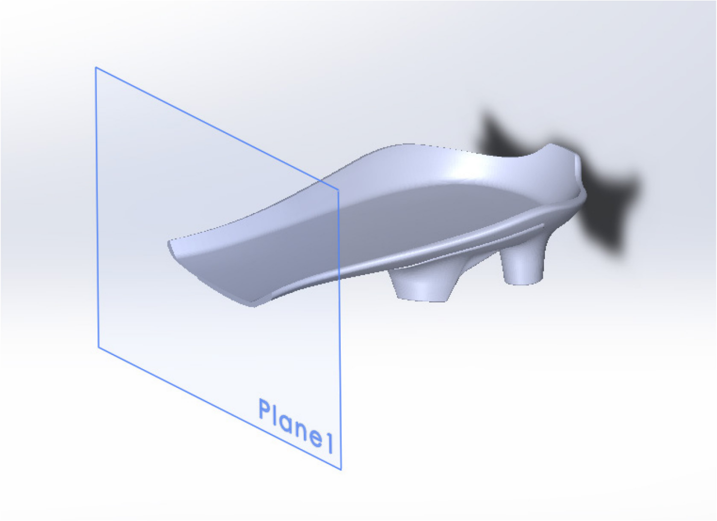


Figure 33: Cross-section taken using reference plane on plate Option 1

Next, in order to calculate the moment of inertia along the bending axis, a reference coordinate system is added. The coordinate system is aligned such that it makes contact with the top of the plate (similar to how the indenter first makes contact), and has an axis (in this case, the x-axis) in line with the cross-sectional plane and parallel to the top surface of the plate. The coordinate system for plate Option 1 is shown in Figure 34. At this point the model is set-up to calculate the moment of inertia about the bending axis.

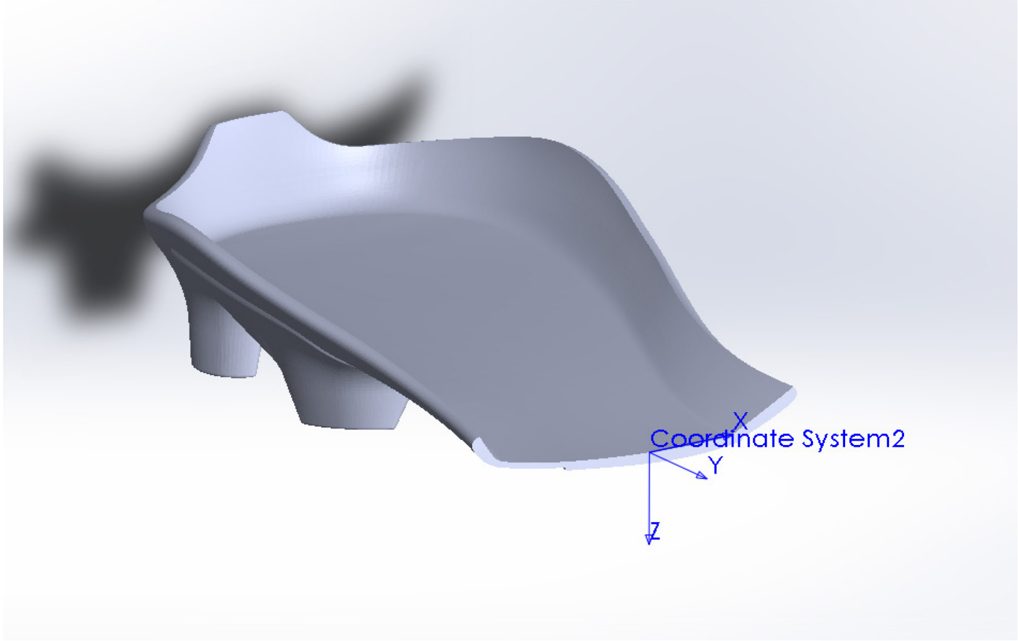
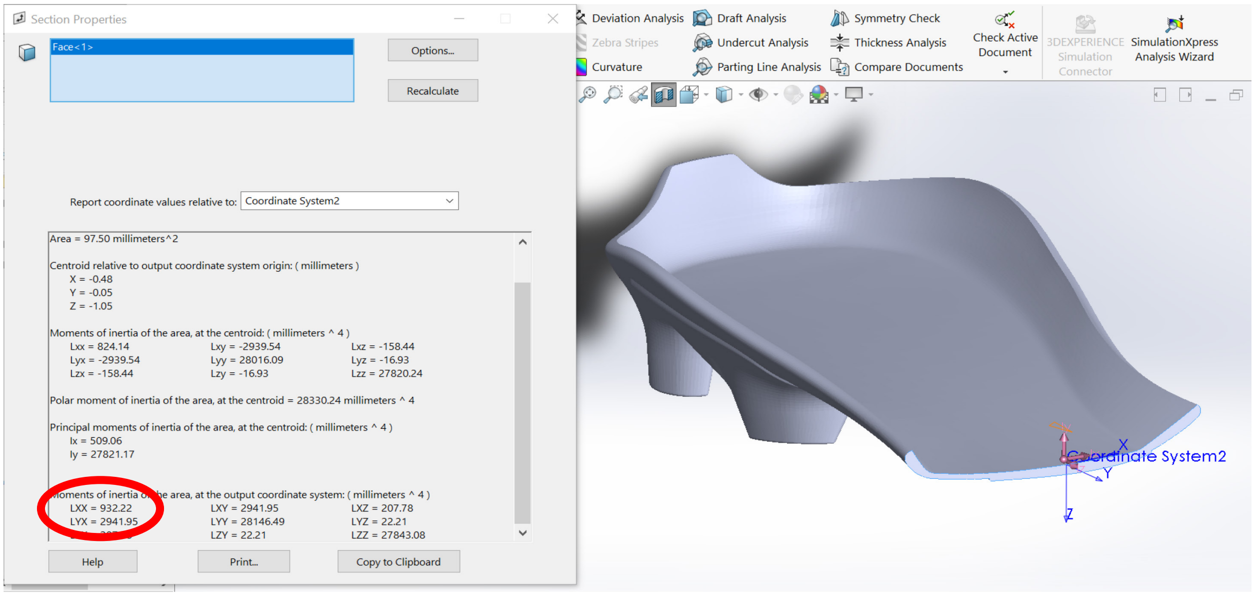


Figure 34: Reference coordinate system for moment of inertia calculation on plate Option 1 cross-section

In SOLIDWORKS, the moment of inertia can be calculated by selecting the cross-sectional area and opening “Section Properties”. The program is asked to report coordinate values relative to the reference coordinate system previously defined above, and will display a list of all section properties. The value of interest in this use case is I_{xx} (shown as LXX in SOLIDWORKS), which is the moment of inertia about the bending axis defined as the x-axis. For Option 1, this value was shown to be 932.22 mm^4 (see Figure 35). A summary of the I_{xx} value for all plate options is shown in Table 8.



Report coordinate values relative to: Coordinate System2

```
Area = 97.50 millimeters^2

Centroid relative to output coordinate system origin: ( millimeters )
     X = -0.48
     Y = -0.05
     Z = -1.05

Moments of inertia of the area, at the centroid: ( millimeters ^ 4 )
     Lxx = 824.14                Lxy = -2939.54              Lxz = -158.44
     Lyx = -2939.54              Lyy = 28016.09              Lyz = -16.93
     Lzx = -158.44               Lzy = -16.93                Lzz = 27820.24

Polar moment of inertia of the area, at the centroid = 28330.24 millimeters ^ 4

Principal moments of inertia of the area, at the centroid: ( millimeters ^ 4 )
     Ix = 509.06
     Iy = 27821.17


Moments of inertia of the area, at the output coordinate system: ( millimeters ^ 4 )
     LXX = 932.22                LXY = 2941.95               LXZ = 207.78
     LYX = 2941.95               LYY = 28146.49              LYZ = 22.21
     [illegible]                 LZY = 22.21                 LZZ = 27843.08
```

Figure 35: Cross-sectional moment of inertia calculation using "Section Properties" in SOLIDWORKS with respect to reference coordinate system. LXX is the desired value for the flexural stiffness calculation

Table 8: Summary of cross-sectional moment of inertia for all plate design options

	Option 1	**Option 2**	**Option 3**
I_{xx} (mm^4)	932.22	1723.21	1505.72

4.4.2 Moment of Inertia Calculation Results and Process Discussion

After I_{xx} is found for each plate option, the flexural stiffness can be calculated. Flexural stiffness is defined as $E*I_{xx}$, or the Young’s Modulus times the cross-sectional moment of inertia. For Nylon 11, the Young’s Modulus is 1562.9 MPa. The final results for flexural stiffness are reported in Table 9.

Table 9: Flexural stiffness results from moment of inertia calculation for all plate design options

	Option 1	**Option 2**	**Option 3**
Flexural Stiffness (N^*mm^2)	324	598	523

In this case, flexural stiffness N^*mm^2 is used instead of stiffness in N/mm as was used for the other approaches. The stiffness can be calculated using eq. 1, however, the coefficient for this case would require extra work. Readily available coefficients for different beam bending scenarios assume the use of a uniform rectangular beam, so standard tables cannot be used for the plate CAD model. Coefficients are dependent on material geometry, and require experiments and calculations beyond the scope of this thesis. However, since only a relative comparison between Options 2 and 3 is needed, both flexural stiffness (Nmm^2) and stiffness (N/mm) will give the same ratio and can be used interchangeably. For this approach, Option 3 divided by Option 2 is 87%, meaning Option 3 is 13% less stiff than Option 1.

Timing and expertise required for this approach is similar to the mechanical test in that it takes about an hour of time to setup and calculate the stiffness. This calculation also requires much less time and effort than the FEA approach. For expertise, an engineer with a basic mechanics background and competency with CAD programs will be sufficient. This provides another option for design teams to estimate on the stiffness difference of their designs. Since this only takes into account geometry of a single cross-section, the entire 3D geometry of the plate is not considered, and will not provide details on potential failure modes that could be seen in physical testing or simulated through FEA.

4.5 Comparison of Approaches

4.5.1 Comparison of Results

A summary of the stiffness ratios of plate Option 3 to Option 2 are shown in Table 10. All values are within 5% of each other, giving confidence that any of the above approaches could be utilized by footwear design teams.

Table 10: Stiffness ratio of Option 3 to Option 2 plate designs for all three approaches

	Option 3 / Option 2 Stiffness Ratio
Mechanical Test	0.82
FEA Simulation	0.83
Beam Bending Calculation	0.87

This comparison of only three samples is considered a pilot test to obtain initial estimates on similarity. Due the small sample size, testing for statistical significance may give wrong results and is inappropriate for this case. However, the similarity of the ratios will be enough to help teams make relative design option decisions. There is likely variance among the results due to the difference in accuracy of each approach, and that no approaches perfectly represent the ideal case of an injection molded plate.

4.5.2 Comparison of Labor, Resources, and Time Requirements

Since all approaches could provide similar information to a design team, it comes down to the difference in labor and expertise required, available resources, and time. A comparative summary of these factors is found in Table 11. In this comparison, it is assumed that a CAD model is readily available and the proper capabilities are already established within the footwear company.

Table 11: Comparison of time and resources required for each approach

	Mechanical Test	**Beam Bending Calc**	**FEA Simulation**
Total Work Time	Low	Low	High
Who	Design Team Member, Lab Test Engineer	Engineer	Experienced FEA Engineer
Software Required	Provided by lab with universal testing machine	CAD Program with internal calculators (i.e., SOLIDWORKS)	FEA Software and Solver License, computational server space
Special Expertise Required	Training on testing equipment	Engineering degree or understanding of beam theory and mechanics	Engineering degree and full FEA training, understanding of non-linear mechanics
When to Use	- Physical samples are already available - Lack of available engineering resources	- Early design phases - Limited time, but want more design confidence	- Longer project timelines - Desire to understand more than just stiffness (i.e., stresses, strains, potential failure modes)

In general, the quickest approaches give the least amount of detail and accuracy. As more time is put into an approach, more accurate details are available to design teams, but it is at the cost of an increase in required expertise and resources. Which approach is chosen should vary project to project, and the decision will be based on the level of design fidelity, the phase of product development (early concept versus later iteration phases), and the resources at the disposal of the design team.

4.6 Approach Selection Given Project Scenarios

Due to the variety of cleated products and the development phase they are in, design teams may rely on different levels of engineering approaches to gain confidence in their design. There are several scenarios a project could be in, and each would have a best suited approach given specific circumstances. The first scenario considers a new cleat model that is only updating aesthetics of the upper and reusing a past plate. The second explores a new generation of a cleat model that requires a new plate design, but has requirements to be met in comparison to the previous model in the family. Lastly, there is the scenario that a completely new cleat model with no prior reference is being designed. While there may be other types of footwear projects, these three scenarios were found to be the most common. For different footwear types there may be other scenarios that require evaluation when selecting an appropriate analysis method.

The first scenario assumes a new model is being created that plans to utilize an existing plate design while only updating the upper and overall aesthetics of the cleat. In this case, no engineering analysis is needed since the team decided that the previous plate behavior is adequate based on user perception data. Designers may make slight adjustments to the look or how it bonds with the upper, but having no significant changes in plate design will not require a team to perform calculations for a property like stiffness. A significant portion of all cleat projects can be assumed to fall under this scenario.

The next scenario is that a new generation cleat model is to be created with a new plate design. Since there is a prior model to refer to, the development timeline is on the shorter and standard side. The past model received good feedback from athletes, but they wished that the cleat could have been more stable. In this case, a design team knows that stiffness needs to increase in certain areas. Assuming stiffness changes only need to be minor, the moment of inertia approach would work well in early design phases to gain confidence prior to the first physical sampling round. This could be supplemented by physical testing of 3D printed models; however, the prior generation model would also need to be 3D printed for a direct comparison. Doing FEA may be excessive, and will likely lead to added time on the project. If the first-round samples happen to come back and not behave as expected, then it may be worth utilizing FEA to ensure the second (and sometime final) round of sampling is near production ready. It can be assumed this scenario makes up about one quarter of total cleated projects.

Finally, the last scenario is that the company wants to design a brand-new cleat model with innovative characteristics. These projects typically are given longer development timelines to ideate and test different designs until a final prototype is approved to go through the standard development process. In this case, given access to more time and likely more resources, FEA simulation would be a great option. The animations of stress and strain can help teams visualize how a plate may behave beyond knowing just an estimated stiffness value. Past cleat models with certain performance characteristics may also under go FEA simulation if they had not been already in order to add a basis of comparison. In this case, it is likely that FEA will be done both before and after physical sampling, since completely new designs have little to reference in terms of player perception data.

Of course, there will be edge cases and one-off scenarios that will require teams to think critically about what level of information they need for their project. In this case, the team should take into account expected market value of the product. Lower volume or more accessibly priced cleats may only require simple calculations in the design process. High volume, or high-priced elite products that provide more value to the company in the long run may incentive teams to utilize all resources and information at their disposal, and would likely perform FEA simulations.

Whether or not a footwear company should invest in FEA will depend on the team and product lines it will be used for. The next chapter will walk through an example qualitative cost-benefit analysis framework for the investment of FEA into an onsite PCC. While the final recommendation will only be for a PCC, the steps and development of this analysis could be reused for other digital tools a footwear company may wish to implement.

5 Business Case Analysis of FEA

This chapter will walk through the creation of a qualitative cost-benefit (C-B) framework to aid in making digital capability investment decisions. The specific case that will be analyzed is the investment of FEA simulation into the design process for a footwear PCC, drawing off of the learnings from the plate bending use case. A simplified business case will also be presented as an example for design teams outside of a PCC to evaluate FEA implementation.

5.1 Development of Qualitative Cost-Benefit Framework

Implementing a digital capability such as FEA into a creative design environment will come with a host of costs and benefits, many of which may not be quantitative or directly measurable. It is common for leaders to request an ROI when evaluating a new project or capability, however a strict ROI analysis focused only on financial returns will often miss abstract effects of the capability. An example of an abstract benefit in footwear creation is positive influence on user perception of quality. Increased user satisfaction could lead to future purchases, brand loyalty, and long-term sales growth, but this is difficult to predict and quantify. Similarly, a substantial abstract cost could be effort required to make fundamental changes in design team culture and communication. This factor does not necessarily have a dollar value to analyze. For footwear creation a standard ROI may not be sufficient and a qualitative approach of costs and benefits is warranted. The qualitative C-B framework developed for this thesis is meant to be used as a tool to help leaders answer the question, “For this known range of foreseeable benefits, is it worth undertaking these required costs or efforts?”. It will serve as a visual tool by laying out the impact of all expected costs and benefits to the PCC, whether in time, monetary value, or product quality and team workstyle. For the case of FEA simulation, this tool is also useful for educating footwear creation leaders in the technical complexities of FEA and the associated benefits.

The first step in the proposed framework developed for this thesis is to brainstorm an exhaustive list of all potential costs, efforts, benefits, or opportunities of implementing FEA into the footwear development process. At this initial stage, any idea is useful, even if it may seem abstract or not directly measurable. All ideas brainstormed in the list will be referred to as line items. Once a list is complete, each line item should be thoughtfully evaluated and given a metric and value if one exists. Any relevant notes that may influence the investment decision or provide more detail to the line item should also be written.

Next, each line item will be categorized. In this framework, there are four categories: financial, time, product quality, and mindset. These four categories were inspired by the process outlined by Conn etal., in which all inputs to their qualitative ROI analysis are categorized by time, cost, or quality[35]. Traditional ROIs and C-B analyses will focus mainly on cost and time, which here are categorized as either financial or time driven. For this analysis, a line item that falls into the financial category will have a dollar amount associated with it. For the cost list, this will be a real dollar investment the company will have to make to successfully implement FEA capabilities (such as licensing cost for a software program). For the benefits list, this could be any dollar value added, such as any known future sales. The time category will highlight line items that reflect time required for the setup and implementation of FEA, or time saved in the product development process. This will have a direct time metric associated with it, such as work hours or product development weeks. To best address the qualitative nature of footwear design costs and benefits, the additional categories of product quality and mindset are included. Line items that get sorted into the product quality category will directly or indirectly impact the robustness and perceived quality of the final product. This line item may not have any measurable metric and value associated with it like time or cost. Finally, the mindset category is a catch-all for remaining line items that may be more abstract or cultural in nature. Mindset can be seen either as an effort required (like a mental cost to teams), or an internal business benefit that allows teams to operate more efficiently. One example of this is more productive communication between cross-functional design team members.

Once each line item is assigned a category they are then evaluated for relative impact. For this framework, impact can be either high, medium, or low. These designations are purposefully qualitative, as it gives any specific team the judgement to decide what factors matter most to them and their company. Medium impact should be the default for all items at the start. To be considered high impact, a line item must be more impactful relative to other line items in the same category. For example, a financial line item will be considered ‘high’ impact if it is generally more expensive than other financial items. In the product quality or mindset categories, level of impact will be based upon leader opinions or company strategy. Low impact line items follow the reverse line of reasoning. Compared to other line items in the same category, low is generally less impactful than similar line items. For example, a benefit that could save one day of time is low impact compared to another benefit that saves weeks of time. Once every line item is assigned an impact value, it may be helpful to visually highlight or bold the line items defined as high, as these could factor most into a leader’s decision.

Once both the cost list and benefit list are complete and all items are categorized and assigned an impact value, the list is now ready for evaluation. One method to interpret the results is to observe which categories are most dominant on both the costs and benefits side, and which of those are the highest impact. A summary can be generated and presented to a decision-maker at a footwear creation company along with the detailed list to guide the final investment decision. The following sections will walk through this framework for the case of implementing FEA into a PCC environment.

5.2 FEA Implementation Costs

The analysis begins by defining all possible costs. A cost may or may not have a dollar value associated with it and may instead be any sort of effort required for the implementation of FEA into a PCC. It is best to brainstorm all possible costs and efforts without yet thinking of sorting into categories. However, for the purpose of clarity in this discussion, all line items will be discussed in terms of their category. The fully detailed list that was originally created for this analysis can be reviewed in Appendix A: Detailed List of Costs and Efforts for C-B Analysis.

There will be substantial financial cost line items for implementing FEA into a PCC that does not currently have the capability. First, to run a successful FEA simulation a dedicated and experienced FEA engineer is required. Design teams may already have engineers with adequate backgrounds on the team, but likely headcount and salary will need to be generated for an FEA engineer position. Starting FEA engineer salaries range from $80,000 to $130,000 a year or higher depending on the U.S. state [38]. On top of that, there will be a cost of training required. Both general design engineers and experienced FEA engineers will need to go through some level of training on the chosen FEA software, especially as it relates to footwear. An engineer should be trained on specific settings or software tools that are footwear specific and nonlinear mechanics theory associated with soft materials and complex geometries. Training could be done in house or with an external consultant from an FEA software company. The cost of a consultant could run on the order of $100 per hour or more for training. The next financial costs to consider are for running the FEA software itself. Single licenses for basic FEA packages are a minimum of $40,000 to $60,000 per year, and this price increases with more accurate and robust programs. In addition, server space and data file management systems will need to be put in place and paid for. This will be a substantial financial cost. However, if a footwear company already has server systems set up, they may be able to modify or upgrade to accommodate FEA simulations.

In terms of time, most anticipated cost line items are related to the ramp up time of implementing an FEA process into the company and its product development timeline. There will be a time cost associated with hiring FEA engineers and training them, which can take anywhere from four to twelve months or more depending on the skill level of the engineer and available time they have dedicated to training from their manager. Similarly, there will be a set up time associated with implementing a new software, licensing, and data management system. There may also be strategic development time needed for a company to decide when and how this new capability will be utilized in the footwear creation process. When thinking about the actual FEA simulation, as discussed in Section 4.3, set up and running of simulations can take a minimum of 11 hours of work, which could be at least a week or two of an engineer's time assuming they are balancing multiple projects. FEA also requires that a CAD model is already created, which could add time to projects that typically rely on overseas manufacturing partners to generate CAD models based off of 2D design drawings.

In terms of the product quality category, the only potential cost is that certain behaviors cannot be simulated and still require the testing of physical samples on athletes. FEA simulation is great for direct comparison to existing designs, but a new simulation can only provide certain footwear behavior data, and nothing about how the product actually feels to an athlete. In a sense, FEA still has some level of risk since it cannot predict athlete perception.

Finally, there will be some effort required by design teams in terms of mindset. Training, set up, and time spent building up the FEA capability will require dedication by leaders and managers. It will be up to managers to budget adequate time for their teams and engineers to learn the system, which could mean taking work time away from other projects. This is an extra effort for leaders and managers to budget the appropriate time and learning space for their teams. The adoption of FEA into the product development process will also require a mindset shift in how design teams operate. Highly successful footwear companies have been creating athletic footwear in a similar fashion for decades, and the process of shoe design may feel set in stone to many teams. This is especially true for the designers, who may be used to relying on their 2D sketches and receiving a physical sample without much discussion about the 3D model. Designers may need to be more open to communicating with engineers as they take time to analyze their designs. It may also be a shift for designers to receive more technical feedback and constructively use that to improve their designs.

The highest impact items discussed above are FEA training time and cost, as well as the cost for logistical set up of an FEA system in the product development process. The potential costs associated with added time to run the actual simulation within the existing design process and product quality risk factors are relatively low.

5.3 FEA Implementation Benefits

Next, all potential benefits are generated into a separate list. In this scenario, many benefits from having an FEA capability may not be directly measurable, and more line items in the analysis are qualitative. All benefits will again be discussed in terms of assigned category, although when first brainstorming the list category was not yet assigned. The fully detailed list for all benefits can be reviewed in Appendix B: Detailed List of Benefits for C-B Analysis.

In terms of financial benefits, the largest savings could come from the elimination of sampling and tooling rounds. In the case of cleated products, tooling for the plates themselves could cost on the order of $100,000 per sampling round. If FEA simulation is able to provide more confidence in the first sample design, it is possible additional sampling tooling will not need to be made. Similarly, this will be a large savings to design teams in terms of time. A design team could wait significantly longer to receive a physical sample from an overseas manufacturing partner after finalizing their first pass on a cleated plate design. In a fast-moving design environment, the time saved could be substantial. It is worth noting that this is specific to cleated plate design, and sampling cost and timing may vary for other footwear products (cleated plates are considered one of the most expensive and time-consuming components for sampling). Regardless, eliminating a sampling round could free up time for design and engineering resources to be dedicated to other projects, add more time for validation of testing with athletes, or potentially even speed up the entire product development timeline. Additionally, as FEA is routinely practiced and the integration process becomes streamlined, teams could utilize learnings from past simulations and speed up the next simulation process by reusing setups or successful design features. Learnings do not have to be from a single performance characteristic like stiffness, but also knowing how certain aesthetics features may impact stresses and strains in the material. Creating well-informed designs on the first pass has the potential to shorten the early concept phase.

Other expected benefits of FEA will be in regard to product quality. Increased confidence in design performance from FEA simulations will likely result in a more robust product, especially in early design phases. While final quality checks will still require sampling and physical testing, teams are able to test more design iterations early in the design process using FEA, resulting in higher confidence for the first round of sampling. While this cannot be measured, more robust first samples could lead to higher performance in the final product than through physical sampling alone. Better performance may translate to a better perception of feel by athletes, increasing buyer satisfaction. Increased satisfaction could lead to more purchases and a loyal customer base (although the exact financial value of this is hard to predict and the scope of this thesis did not allow for a true comparison of market performance of products using FEA versus those that do not). Another benefit for the final product is being able to iterate through more design options in the early product development phases. When testing only physical samples, design teams are more likely to go with one or two design options due to the timing and cost associated with receiving samples. With simulation, it is more efficient to test multiple variations on a design. In the cleated plate stiffness use case, this was made evident by being able to reuse the same mesh and simulation setup for all three options in order to do a comparative analysis. By simulating more design options than would be done for only physical sampling, a better product quality can be expected in the first round of sampling.

Finally, many potential benefits are positive mindset shifts within the design team and business as a whole. By running simulations on more design options, design teams will be able to develop sets of best practices in terms of design feature performance. If FEA simulations for projects are well-documented, this can become a valuable resource to design teams on future projects as they create initial concepts. Having physical models and animations created through simulation will also help design teams communicate more efficiently. Traditionally it may have been hard for engineers to discuss manufacturing or behavior constraints to a designer only with a 2D drawing. If a designer can visibly see deformation and failure modes of their designs, it will be easier for an engineer to communicate appropriate recommendations for improvement. For a footwear company that relies traditionally on designers and skilled cobblers, implementing FEA has the potential to build up the engineering community within a retail-focused company. An internal engineering community allows for better communication, passing on learnings and failures from various projects, and makes the company a more desirable workplace for those in engineering or technical fields. Success in the implementation of one digital capability can open the doors for future digital investments across the footwear development cycle. Finally, one large benefit, especially in today's global climate, is more a sustainable design practice. Physical sampling requires energy through machining and assembling samples, uses up material that cannot be sold to a consumer and ultimately needs to be destroyed, and may rely on transportation back and forth between a footwear company's prototyping site and their overseas manufacturing partners. For companies that have dedicated environmental sustainability goals, a digital tool such as FEA can be championed to push forward and demonstrate the strategy of making and using fewer physical materials.

Of all the anticipated benefits listed above, the highest impacts will be time saved from eliminating physical sample rounds and better communication among designers and engineers. When fighting against changing market trends, additional time in the product process is invaluable. For a large footwear company that receives high revenues year over year, this time saving matters more than any financial cost saved by eliminating sample tooling. In addition, footwear companies can become large machines, with each cross-functional team member feeling culturally siloed. If an engineer can visually express feedback to designers with the aid of simulation, then some of those cultural walls can begin to breakdown, creating a better environment for collaboration and future innovations in the industry.

5.4 Recommendation and Takeaways from Framework Results

Now that all the expected costs and benefits lists have been detailed, the next step is to evaluate any trends or key takeaways that may aid a leader in their investment decision. One method is to first look solely at all the categories, and see how many line items fall on either side. Looking at all financial line items, there was a vast majority that were costs, and only one financial benefit. Time is similar, where there are more time cost line items that benefit line items, however both of those time benefits were high impact. In terms of product quality, there is little to be considered on the cost side, but there are many product quality benefits. Finally, the mindset category is similar to product quality in that many are benefits with few cost-related line items.

Considering the distribution of line items into categories, it should be noted that costs for the implementation of FEA into a PCC environment will generally be financial and time driven. Benefits, on the other hand, may not have a direct financial gain, but will positively affect time saved, product quality, and company mindset. Many items on the costs list may be directly measurable in terms of dollars or time, but many of the benefits are less directly measurable. For example, many benefits are product quality related, implying that an investment in FEA can give design teams higher confidence during early stages of product design, especially ideation stages that precede the first round of sampling. While product samples will still be required for final quality checks, increased confidence in early design samples grants teams more time to test their designs and create a more robust product than what they might get out of the traditional process that relies on sampling and physical testing alone. Though it is difficult to accurately predict and quantify, a more robust product gives the company an opportunity to create future financial value (through increased sales) from an increase in athlete satisfaction and loyalty. Aside from the product quality benefits, the most impactful benefit is measurable, that being the time gained through the elimination of sampling rounds. While costs could be saved through the elimination of tooling and materials required, a company wanting a quick speed to market may be much more interested in time savings. In a company that wishes to speed up development timelines, any time saved is very valuable, as it represents an ability to get product to the consumer more quickly, or conversely, more time to validate the product through testing with users. This time saved can have a substantial impact on product development. However, to achieve the potential time savings and product quality benefits, the largest cost driver will be start up time and dollars required to invest in engineers, FEA software, data management, and implementation into the product development process.

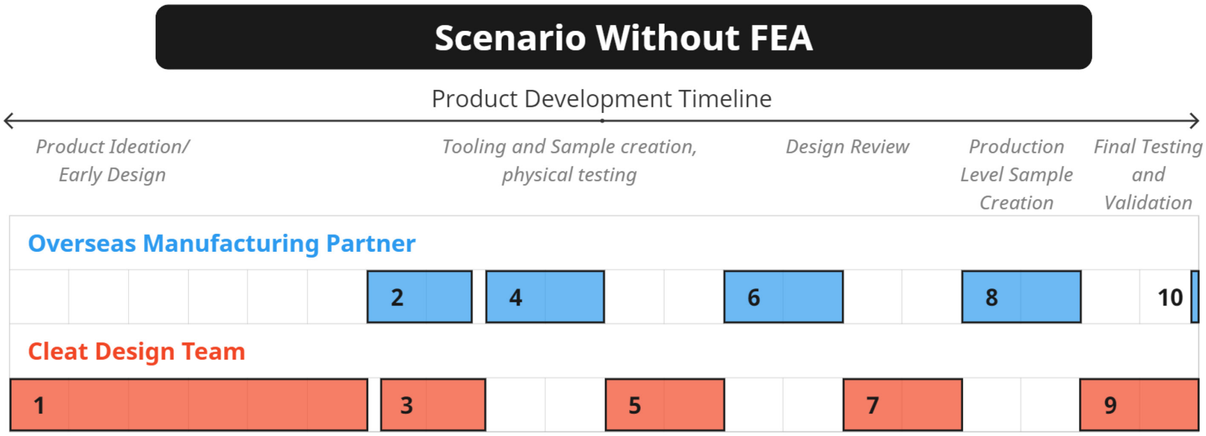
If a PCC were to commit to the investment of FEA, they will also need to commit to the upfront costs and reality that a fully integrated FEA process could take at least two to three years to build. This time includes the hiring and training of an FEA engineer for the PCC, and time spent selecting an appropriate FEA software, licensing and server system, as well as data management system. No digital system bought off the shelf will be a perfect fit for most companies, so it is also expected that teams will take time to modify the software for footwear needs. For FEA to run smoothly, there could also be added time in having to generate a 3D CAD model for all projects coming through the PCC, whereas in the past sampling projects in the PCC only required the 2D drawings from designers.

Ultimately, it may not make sense for a PCC to implement FEA given their specialty is in the ability to create visual and physical prototypes for design teams across a footwear company. Many of the benefits for increased product quality and better communication will be of more benefit to the design teams (such as those in cleated footwear development), than to the PCC whose sole purpose is to provide a shoe building service. However, while it might not make sense for a PCC with limited budget and resources to add a digital FEA capability, it could be more appropriate for footwear design teams of standard product lines to have an FEA engineering resource to serve them in early design phases. For example, it would make the most sense for a cleated plate bending capability to lie within the organization of cleated product design, not the onsite prototyping lab. The following section will walk through a simplified example of an analysis showing how the substantial benefit of time saved applies to a cleated footwear design team. Similar costs and benefits outlined throughout the above detailed framework will still apply, however, the use case of FEA is instead focused on integrating directly into a design team, not a PCC environment.

5.5 Simplified Business Case: Time Saved

The framework for a qualitative C-B analysis presented above is intended to provide all information possible to a decision maker, especially in a prototyping environment like a PCC. However, depending on the audience a simpler analysis could be warranted. For a standard design team of upcoming products, development time is its most precious resource, while dollars spent on development are considered expected R&D costs. What matters most to a footwear company is speed to market, since the longer it takes for a new product to hit the market the higher the risk that the company is no longer serving the constantly changing attitudes of the consumer. To address this, a simple business case is presented for the implementation of FEA directly into a cleated footwear design team as opposed to a PCC as discussed in the previous section. Traditionally, PCCs act as a service center for design teams to utilize, and whereas cost and time savings to the company are driven by the design teams themselves.

A simplified overview of the development timeline for a cleated product is outlined in Figure 36 . This example highlights a worst-case scenario in which the design created for the first round of sampling did not have expected stiffness behavior. In this case, the design team was forced to iterate quickly and do an additional round of sampling to assess different design options. More money is spent on the creation of secondary sample tooling, and the timeline becomes tight as the team waits on that next sample. Once the second samples are received, the team must do physical testing and wear tests with athletes to validate the design in less time than desired. In this scenario, the team is taking on added product risk by making an educated guess with the data and information they have from the shorter testing period.



1 Design created and ideated, 2D drawings generated

2 Create 3D file from drawings

3 Product engineer and team reviews 3D file, makes needed design changes without testing. Approves design for sampling.

4 Machines tooling and creates first round samples

5 Receives first sample. Immediately notices issues with performance (such as lack of stiffness). Team quickly ideates new design options.

6 Machines second tooling, makes samples for new design options

7 Tests new samples of design options. Iterates and modifies samples as needed for additional testing. Approves final design for production tooling.

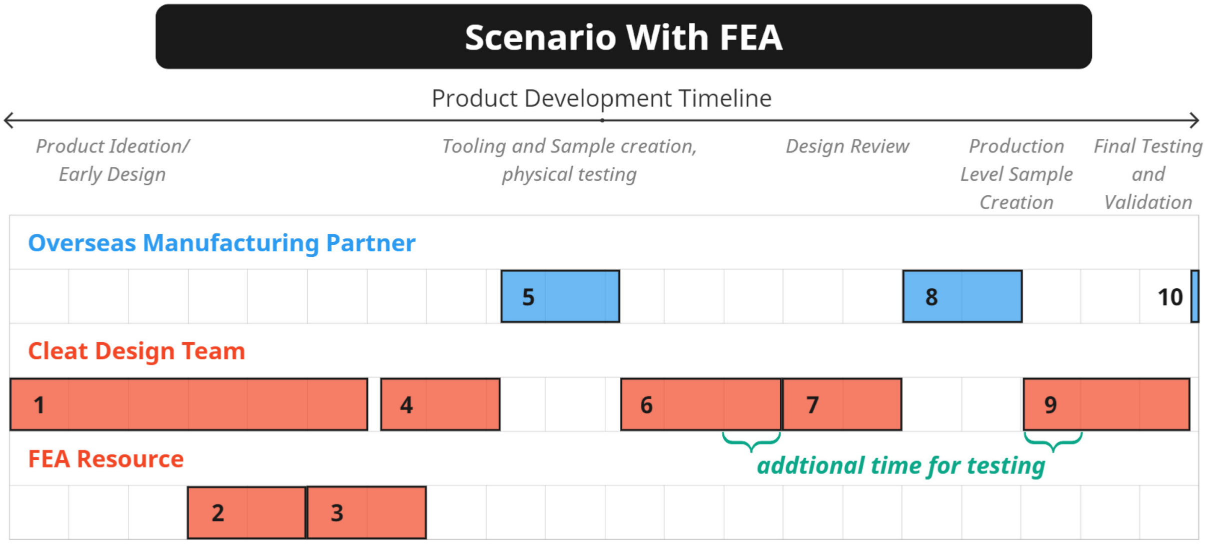
8 Machines and creates production level tooling for final samples

9 Final testing on production level samples. Approves for production.

10 Transfer to factory for production

Figure 36: Example development timeline for the current state in cleated footwear creation. This highlights the worst-case scenario in which no FEA is used and additional sampling rounds are required.

Now, consider a new timeline in which FEA is implemented into the team's design process (outlined in Figure 37). The development timeline and overarching deadlines remain the same, but there is more time available on the back end to use for physical testing with athletes to validate the design. Here, FEA is implemented early in the design process well before any sampling occurs. While more time may be spent performing the simulation and making design updates, the team has more confidence going into the first round of physical sampling. In this ideal scenario, the early engineering analysis helped produce a more robust first sample that did not require a major secondary round of sampling. Cost is saved by not having to purchase and machine new tooling, but more importantly time is saved by not having to wait two months for a second round.



1 Design created and ideated, 2D drawings generated

2 Create 3D file from drawings

3 FEA Engineer performs plate bending simulation in parallel with early design

4 Works with designers and FEA engineer to iterate on design until satisfied with design. Approves for samplling.

5 Machines tooling and creates first round samples

6 Receives samples. Tests physical samples to validate design

7 Minor design changes made (may iterate with small modifications, but no additional tooling needed). Approves final design for production level tooling.

8 Machines and creates production level tooling for final samples

9 Final testing on production level samples. Approves for production.

10 Transfer to factory for production

Figure 37: Example development timeline for a future state in which FEA is used for cleated footwear creation. This highlights the early iteration process of design using FEA, increasing confidence in the early design, and avoiding costly second sampling rounds

From a cost perspective, one round of tooling could cost shy of $100,000. Assuming the company works on fifteen to twenty new cleat models every two years, then this has the potential to save an average of $500,000 per year in added development cost for cleated footwear. For a large company making billions of dollars in revenue each year, this may not be significant to business leaders and is assumed to be the cost of R&D. On the other hand, looking at the time perspective, two months of development time can be created by implementing FEA. This could add up to thirty to forty additional months of development time across all cleated footwear design teams. Additional time could be used for further testing and validation as presented for the scenario in Figure 37, but it could potentially reduce overall product timelines. When speed to market is the top priority, FEA becomes a very advantageous capability to add to the footwear development process directly for design teams.

When assessing an entirely new digital capability, it is beneficial for leaders to take the time to fully assess all implications and factors through the framework presented in the beginning sections of this chapter. It is easy to make assumptions on the simplicity of adding new software tools, especially for leaders who are not directly involved in doing the work. Laying out all anticipated costs and benefits can help demonstrate the complexity of new digital capabilities and the startup time and costs to make them efficient. The goal of developing the detailed framework was to do just that, create a resource for leaders to become educated in all aspects of new capabilities. While it is critical that all details be researched and assessed, it is also critical to carefully consider the environment in which the digital capability will be implemented. The analysis does a good job of laying out the costs and benefits, but when considering the strategic goals of different groups within a footwear company, different conclusions may be drawn from the same list. If a PCC's top priority is to serve design teams through prototyping expertise, the costs of implementing FEA may not be worth it as the main benefits are not as well-aligned with providing better prototyping services to design teams. Yes, time could be saved and product quality improved, but it will be design teams realizing those savings, not the PCC. Through considering the same data and going through a simplified scenario for implementing FEA directly into a cleated design team instead, there is greater alignment between its benefits and the goals of the design team. A design team's top priority is to create high quality footwear products that get to the customer as quickly as possible. In this case, saving time means much more to the design team than it would to a PCC.

6 Limitations and Considerations for Digital Analyses in Footwear Design

So far, the focus of this thesis has been on one type of FEA simulation for footwear, that being the plate bending simulation. However, over the course of the research conducted for this work other possible opportunities for enhanced digital capabilities were identified for implementation into a PCC in a footwear development company. The following sub-sections will highlight the limitations of FEA in footwear product development as well as other opportunity areas that could be explored in future analyses or studies.

6.1 Limitations of FEA in Footwear Product Development

While the analysis presented above shows that FEA simulations can provide real benefits to footwear development teams, it is important to note that it should only be used as a tool for making relative design decisions. In other industries that utilize FEA simulation in their engineering processes, especially those that develop hardware with strict safety requirements (such as medical devices, aeronautics, or automotive industries), there is typically a set of standards or requirements that products need to pass to become certified for use by a customer. FEA simulations are carefully based off of these real-world requirements, and can be used as validation for adequate and safe designs. In the footwear industry, there is no comparable set of standards. It is possible in the future footwear companies may establish their own set of internal standards for simulation of their products, but that would require extensive testing and experimentation to establish the standards, and simulation capabilities must already be fully integrated into the company. However, as it stands, FEA can only provide additional information to design teams through relative comparison to known footwear behaviors from past designs.

In addition, simulation technology is only well-suited for the analysis of footwear bottoms at this point in time. Soft-materials and inconsistent manufacturing processes for assembly make it extremely difficult to simulate the performance of uppers. This implies that the simulation of entire footwear assemblies is also highly complex. While further research on upper simulation is warranted and could be valuable to the industry, footwear companies are likely far away from being able to completely simulate an entire shoe assembly. If only singular components of a shoe can be analyzed through FEA, then no single simulation can prove a final footwear product has adequate performance. Physical samples will still be the best option for understanding behaviors of an entire shoe assembly. FEA can only be used as a design tool, not an end-all solution for footwear design. However, if FEA is used smartly, it can provide valuable information to design teams that limit the total number of sample rounds required for the development process, even if it cannot eliminate sampling entirely.

6.2 Other FEA Simulations

Plate bending is just one example of a simulation that can be performed using FEA software for cleated products. FEA has the power to do other types of performance simulations as well. One large opportunity area is for cleat traction. As discussed in Section 2.3.1, a main test that is performed on cleats for athletes in the NFL is a traction study using “the Beast” testing machine. Proper cleat stiffness may protect the athlete’s foot by preventing overextension of the MTP joint and keeping the arch area stable. But another important safety factor is protecting an athlete’s ankles and knees by leaving enough traction with the playing surface to have aggressive movements on the field while also allowing the right amount of free movement so as not to lock out the joints. Simulating the effects of different cleat stud designs in various types of ground material could provide beneficial information to the design team.

For non-cleated footwear, there is also potential to assess the compression of different bottom materials and designs. For example, an engineer may be able to simulate the foam bottom of a running shoe to measure deflection in the material and ensure it adds proper underfoot cushioning to the athlete while not becoming over-compressed. Traction studies for non-cleated materials could also be investigated for various sports applications, such as running spikes on tracks, or different rubber sole designs on hard court surfaces for sports like tennis or basketball. Improving the performance of any sports footwear could increase perceived product quality desired by athletes of all levels and benefit a footwear company in the long run.

6.3 Simulation of Uppers and Pattern Engineering for Soft Materials

While upper simulation technology is not fully developed for industry as discussed previously, this makes it an interesting and impactful topic for future study and research. Patterning software programs do exist that footwear companies utilize for creating the flat patterns for the uppers. However, the ability to allow a designer to draw in 3D onto a shoe model and have that unwrap into a usable 2D pattern would be extremely useful. The opposite would also be useful, being able to take 2D pattern cut outs and wrap them onto a 3D CAD model of a shoe to check that the pattern is correct. Generally, the upper patterning process is handled by expert pattern designers who have years of experience and a developed intuition of how 2D shapes translate to 3D uppers. They know how the stretch and stitching of various materials requires special shapes to be made in 2D to match the final 3D design intent. For example, a designer may draw a footwear company’s logo onto the side of the upper in their sketch. The pattern designer will have to know how that logo will wrap in 3D dimensions and create a distorted 2D pattern that will look correct when assembled. Any improvements in digital design tools or simulation for uppers would make a large impact in footwear industry.

6.4 Manufacturing Simulations

All simulations discussed thus far have been on footwear components and address product quality or performance characteristics. However, there is a large opportunity area for simulating the manufacturing processes of footwear components. Many bottoms are injection-molded and require special tooling and manufacturing parameters such as heat and pressure tuned correctly to give the best final product. Thermal FEA simulations can be run to predict how a specific tool will fill during injection molding. Simulating new tooling designs prior to cutting and testing would be a huge advantage given the high cost and time required to make a new tool. Simulations can ensure the design is correct to allow the proper flow of material into the mold before the first prototype tool is cut. Many of these molds are also heavy and bulky, and are typically installed and moved around manually in a factory. Being able to make light-weight tooling designs that can still provide the proper heat transfer and pressure could be advantageous to companies that want to provide easier working conditions in factories. For large footwear companies with sustainability goals, this could have far-reaching impacts to reduce the machining energy and materials required to create bottom tooling, and make tools safer for the employees that handle them.

7 Conclusion

The purpose of this thesis was to investigate the implementation of simulation into the footwear creation process. Simulations such as Finite Element Analysis are common digital engineering tools in other industries as well as academia, but its implementation is not always straightforward. In a large footwear creation company, speed to market is critical due to the changing attitudes of the customer. There is always a risk that the customer may desire different trends or features in their footwear when a product is launched compared to what was outlined in the product brief one to two years prior. Given this, the goal is that integration of a digital tool such as FEA will reduce product development timelines by limiting the number of footwear samples and iterations that are required, provide associated cost and material savings, and make communication among team members more efficient. To evaluate this goal, this thesis began by exploring the background and literature surrounding the footwear development process and general implementation of FEA into industry. In order to give a detailed example of how simulation could be integrated and its associated technical complexities, a bending analysis of a cleated plate was used as a case study. Cleated products were chosen due to their high sampling round costs and lead times, and how vital it is for design teams to understand plate performance as it directly impacts athlete perception and injury prevention.

For the case study, three approaches to calculate the bending stiffness of a cleated plate were detailed and performed. In footwear design there is a focus on relative comparisons among multiple design features or to past models. The use case compared two different rib designs on a basic cleated plate, with the overall goal of the analysis being to understand the ratio of stiffness between the two options. All three approaches gave a similar stiffness ratio, all within 5% of one another. This work was able to prove that the relative results of each approach are similar, and ultimately it will depend on the project scenario for a design team to pick the most appropriate approach. The standard method of mechanical testing for plate samples is best suited for projects with quick timelines and little new design changes from previous cleat models. This is an especially quick method if tested prototypes are created through additive manufacturing. If a project has a short timeline but newer design features are being added, a simple bending calculation can be done by an engineer on the team without having to make any samples. While not completely accurate or representative of all possible product behaviors, this method may be sufficient in most cases to increase design confidence. Finally, the FEA simulation approach should be reserved for projects with longer development timelines or completely new design features with unknown behaviors. While simulation is still best for relative comparisons among design options, FEA will give more detailed information about the product that could influence the final design (including details on stresses, strains, deflections, and movement of the material).

Given that certain project scenarios could utilize FEA simulation, the work then analyzed the requirements and investments required to make this capability a reality. A qualitative cost-benefit analysis was developed to provide a framework for highlighting all potential costs, efforts, benefits, and opportunities of implementing FEA into a PCC environment. The analysis highlighted that the investment could be largely driven by financial costs and start-up time needed to hire and train FEA engineers, as well as to purchase and integrate FEA software and associated data management systems. The main benefits of FEA will not be directly measurable in terms of cost or time, but instead could be positive effects on product quality and the mindset of footwear design teams. Increased product quality perception may not be directly measurable without estimation and extrapolation, but it could lead to higher customer satisfaction, future sales, and brand loyalty, all of which provide great value to a footwear company in the long run.

FEA simulation as a service to be provided to design teams may not be appropriate for a footwear company's onsite PCC given the large dollar and time investment. Instead, PCCs should continue to focus on their expertise of physical building and creation for design teams. If FEA is implemented within a footwear company, it should be directly into the organizations that oversee the design teams. For the cleated plate example, this would mean that the global football organization within a footwear company should invest in their own FEA engineer to aid with cleat specific design throughout the development process. This holds true for other types of performance simulation as well, and could be implemented for other sports categories such as running, basketball, or tennis.

While simulation is an informative engineering tool, it becomes more difficult to run and implement the more complex the product becomes, and this is especially true for the footwear industry that deals with complex geometries and soft materials. However, if a company is willing to invest in the start-up time needed to implement efficient FEA methods into their product development process, they could create more robust products and the possibility to shorten development timelines. In a world where technology is constantly evolving, it would be in a footwear companies' best interest to pay the price now for integrating digital tools so that they are better set up to handle the next surge in footwear performance advances and technological trends. Digital tools can enable the company to provide their customers with desirable footwear, while also protecting them and providing the best performance.

Appendix A: Detailed List of Costs and Efforts for C-B Analysis

Cost / Effort	Value / Metric	Notes	Category	Relative Impact
Engineer hiring process	Weeks to months	The candidate needs the right mindset and interest to learn FEA, as well as help develop the new process. Applications, interviews, and creating offers will take time.	Time	Medium
FEA Engineer Salary	$80K – 130K+, new hire salary	Could be new hire, or transfer and training of existing engineer if they have the correct background for FEA	Financial	Medium
FEA Training Cost	$100+ per hour	Assuming 6-9 hours per week, 12-week training, works out to $72,000-10,800 minimum for FEA consultant	Financial	Medium
FEA Training Time	**4-12 months depending**	**Depends on skill level of engineer. FEA expert may need less time to learn footwear specific simulations, but could take much longer for an entry level engineer**	**Time**	**High**
Software licensing cost	$40K-60K a year for one engineer's use	Cheaper options likely insufficient for footwear deformations. May be good enough for simple analyses if it's metal/hard plastics)	Financial	Medium
Time to set-up and run simulation	1- 2 weeks	Assumes time for a trained FEA engineer that is working on multiple projects	Time	Low
File Storage System	$ for system, cloud storage, and servers	Possibility to upgrade existing systems, but may need to buy new package with external company	Financial	Medium
File Storage System set-up time	**1-2 years**	**This takes into account time to select and purchase system, work with IT to set-up within company, and time to learn and organize the process for using it**	**Time**	**High**
Plan to create 3D models for each project	1 week to 1 month	Dependent on project complexity and modeling resources available. FEA engineer needs a watertight CAD model, it will not be responsibility of FEA engineer to create model from 2D drawings.	Time	Medium
Buy-in from managers and leadership	N/A	Leaders need to allocate time to engineer training and process development. Will have to accept slower project times as the process ramps up	Mindset Shift	Low
Still need to make samples and conduct physical tests in later design iterations	N/A	Simulation results cannot predict feel or aesthetic look, final designs will still need samples to be tested	Product Quality	Low

Appendix A Continued

Cost / Effort	Value / Metric	Notes	Category	Relative Impact
Adoption by design teams to utilize FEA early in process	N/A	Design teams may be used to current processes and reliability of samples from overseas manufacturing partners. They need to shift their process mindset to incorporate and plan for FEA	Mindset Shift	Medium

Appendix B: Detailed List of Benefits for C-B Analysis

Benefit / Opportunity	Value / Metric	Notes	Category	Relative Impact
Eliminating sampling round	**Weeks/Months**	**Time saved or time gained for further testing and validation of project**	**Time**	**High**
Eliminating tooling from sampling round	~$100,000	Cost of tooling material and machining	Financial	Medium
Material cost saved from less samples	~$0	Negligible cost savings since material cost is not priced per sample during development, design teams have general preset R&D budget for this	Financial	Low
More robust final product	Varies based on desired behavior or performance metric, ex. stiffness (N/mm) for plate bending simulation	Varies based on project or performance metric being assessed. Robustness could also be a subjective measure.	Product Quality	Medium
Higher athlete satisfaction	Positive reviews from user testing	Could come from athlete testing, or word of mouth reviews once in the market. Increased satisfaction has potential for more footwear products being purchased in the future and customer loyalty	Product Quality	Medium
Additional time for athlete wear testing and validation	**Weeks or months added**	**Time gained from in the product development process by better upfront design using FEA. This increases confidence in the final product, and reduces product risk**	**Time**	**High**
Increased design flexibility	Additional number of design variations	FEA and similar digital tools allow for quicker testing on more iterations as opposed to having to select specific designs for sampling. More variations tested should lead to a better-informed design	Product Quality	Medium
Learnings to improve future projects	Time or design steps saved	Lessons learned from previous simulations could influence first round of design concepts for future products, making them more robust upfront, or saving teams time by needed less time for initial design	Time / Product Quality	Medium
Development of best practices	N/A	Overtime FEA can go quicker and designs can be made more thoughtfully as results from footwear simulations are documented	Mindset	Medium

Appendix B Continued

Benefit / Opportunity	Value / Metric	Notes	Category	Relative Impact
Positive sustainability impacts	Less material and energy used to make samples	While less material usage could have a small cost impact, it is more of a commitment to the footwear company's sustainability goals	Mindset	Low
Eliminates costs of mistakes	Unplanned costs (additional tooling rounds or modifications to designs)	Mistakes add cost to make new tooling, or through doing additional testing.	Financial	Medium
Grows engineering community or network within the company	N/A		Mindset	Medium
Better communications between design team members	**N/A**	**FEA gives visual aids and results to help engineers communicate needed changes with designers**	**Mindset**	**High**

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