Implementation of Finite Element Analysis into the Athletic Shoe Design Process

by

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Submitted to the Department of Mechanical Engineering
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Degree of

Bachelor of Science

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ABSTRACT

Finite element analysis is used by companies throughout the world as a substitution for manually testing prototypes. With the assistance of finite element analysis many companies and industries have decreased the time and cost of product production. Currently, the athletic shoe industry does not use finite element analysis in the shoe development process. The goal of this project was to implement finite element analysis into the athletic shoe design process with the intent of decreasing time to market and cost. This effort determined finite element analysis is not recommended to design and test an entire athletic shoe. The human factors and variability make simulation wear-tests on an entire shoe nearly impossible to accurately replicate via finite element analysis. Though human factors affect the entire shoe the most critical component, the heel cushion, is affected only slightly. Since a person's heel is in the shape of a ball, the variation of external forces caused by human factors is not significant. Thus, finite element analysis can be used to design and test the cushion of athletic shoes.

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1.0 INTRODUCTION

Finite element analysis is used by companies throughout the world as a substitution for manually testing prototypes. With the assistance of finite element analysis many companies and industries have decreased the time and cost of product production. Currently, the athletic shoe industry does not use finite element analysis in the shoe development process. The goal of this project was to implement finite element analysis into the athletic shoe design process with the intent of decreasing time to market and cost.

The athletic shoe industry is a very competitive business. There is an optimal shoe style for each sport yet five major styles prevail; basketball, running, cleats, tennis, volleyball. Currently, four different companies produce just over 50% of the world's running shoes. Though the top one or two companies remain the same over time many shoe companies see a fluctuation in market size over the years. This fluctuation is due to the large swing in popular shoe styles and advancement in design and technology for specialty shoes such as running shoes. In order for these companies to remain competitive they need to be able to take a new shoe design to the market before their competition or mimic their competitors quickly. Table 1 shows the percentage of sales for six companies in the running shoe business.

Table 1: Footwear-Running/Jogging: Percentage of Consumer Unit Purchases by Brand

Item		**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Nike		28.6	27.7	30.9	37.4	39.4	37.6	36.0	33.4	32.6	33.2
New Balance		4.9	5.7	6.1	5.9	6.1	7.0	8.7	11.0	15.0	16.7
Asics		19.0	19.5	18.3	15.7	15.0	11.5	12.1	10.4	9.5	8.6
Adidas		2.3	2.7	2.9	3.8	5.7	9.8	13.9	11.5	9.6	8.3
Saucony		9.0	7.0	5.5	5.3	5.9	6.3	7.3	6.9	6.5	6.8
Brooks		6.9	6.5	6.1	4.6	4.2	4.8	4.2	4.7	5.3	4.3

A potentially quicker method of shoe design includes the use of finite element analysis (FEA) in the design process. To evaluate FEA in athletic shoe design, the entire shoe design process will be inspected, as well as the design of a specific shoe component. In addition, a test case of shoe component design using FEA was completed to ascertain its applicability. Following the test, a method of integration of FEA into the existing shoe design process is proposed.

2.0 OVERVIEW OF FINITE ELEMENT ANALYSIS

Finite element analysis, or FEA, is a computer-based analysis used to predict the effect environmental factors will have on materials and structures. This is done by first generating a geometric model and specifying material properties along with boundary conditions. Next, the model is divided into smaller elements connected at nodes through a process known as meshing. This makes establishing stress-strain relationships easier to approximate. Then, environmental factors, such as force, heat and vibration, are input as equations and solved simultaneously by the FEA package. Finally, plots and numerical results are output to provide engineers with insights to the behavior of the model.

Finite element analysis is used by corporations around the world to simulate tests that, without FEA, would be performed on prototypes of components and systems. With FEA, engineers enjoy the freedom of testing and analyzing components and systems without having to create tangible prototypes; saving the company time and money. The goal of FEA is to accurately simulate tests and provide engineers with data. In order for FEA to be most effective the simulations must replicate the live tests performed on the prototype almost identically. In addition, a minimal number of finite element analyses should be run. For finite element analysis to be an effective and efficient substitution to live tests FEA, must be able to simulate live tests with a minimal number of analyses. When the amount of time and money spent running the finite element analyses is greater than or equal to the amount of time and money spent running the live tests it is no longer effective or efficient to rely on FEA for testing. An additional benefit of finite element analysis is the accuracy of the test results. However, this statement is only valid if the simulation input is accurate.

Potentially, finite element analysis can help companies in the athletic shoe industry create, model and analyze shoes, or their components, without having to create preliminary prototypes. It would also provide them with flexibility to adjust design, materials, or dynamics by changing numerical inputs rather than creating a new component.

The specific capabilities of finite element packages vary greatly to provide users with a package that fits their specific needs without adding unnecessary features. For example, some packages focus on mechanical dynamics while others emphasize thermal and fluid dynamics.

At this time the athletic shoe industry doesn't require a finite element package with the capabilities to analyze complex thermal or fluid dynamics. They could potentially benefit from a finite element package providing analysis for mechanical systems. Packages in the market that meet the specific needs of the athletic shoe industry include ADINA-AUI coupled with ADINA-M, ANSYS Structural, ANSYS Mechanical, COSMOSM, and ABAQUS/ Standard.

Though all the above packages meet their needs only one was selected for the use of this research. ADINA- AUI coupled with ADINA-M was selected to perform the analysis because of its ease of acquisition. Professor K.J. Bathe at the Massachusetts Institute of Technology developed ADINA, thus it was simple to acquire the proper license to use the package. ADINA- M can be used alone or coupled with any other ADINA package. ADINA-M, ADINA's modeling package, allows the design engineer in input sketches to the finite element package. When used alone, the engineer has the capability of modeling the sketch yet cannot perform tests on the model.

When coupled with any other ADINA package the engineer can create and analyze the model all in one package, the ADINA-AUI and ADINA-M combination. Having the ADINA-AUI and ADINA-M combination package allows the engineer to input the sketch of the model into the finite element package then perform tests on the model.

Similar to ADINA-M, ADINA-AUI can also be used independently. First, the model must be created within another system, for example a CAD package, and be imported into ADINA-AUI. Once the model has been imported to ADINA-AUI it can be analyzed and tested within the ADINA-AUI finite element package.

3.0 FEA USE IN OTHER INDUSTRIES

Other industries have already integrated finite element analysis into their design and production processes. In fact, many companies and industries find finite element analysis vital to their success.

Pratt & Whitney, a major player in the aerospace industry, uses FEA for most projects. With FEA they have been able to simulate the thermal response of a critical component of the Space Shuttle Main Engine (SSME) through an entire mission before a prototype is even created. To create and test the prototype without the use of FEA would have taken about one and half years, using FEA took only two months. Prototyping these components can also be very expensive, on the order of millions of dollars, thus finite element analysis helps companies like Pratt & Whitney save millions of dollars, not to mention time, that would be spent prototyping and testing the engine.

Finite element analysis is a useful tool for analyzing the performance of this component of the SSME for a few different reasons. First, it is very costly and difficult to create a prototype and send it into space to test it numerous times. Second, the external forces on the component and interactions with other components are known and can be simulated accurately. Finally, the total number of finite element analyses needed to fully simulate an entire mission can be run faster and cheaper than a live test.

An additional benefit to using FEA is quick optimization of the model or digital prototype. At 3M, the use of FEA was critical to designing a tennis racquet with maximum damping and minimal added weight. Using FEA, design engineers could vary the thickness and location of the material, along with the material itself, by changing numerical inputs. This process was much faster and cheaper, not to mention more accurate than creating multiple prototypes and making a decision without the precise data output by FEA.

For optimizing a tennis racquet FEA has proved useful for a few reasons. First, it is time consuming and costly to have racquets made with a different material after each set of live test results are analyzed. By using FEA, a change in material and design takes only a few hours. Second, the external forces and interactions (hitting a tennis ball) are known and can be accurately simulated. Finally, the total number of finite element analyses needed to fully simulate a live test can be run faster and cheaper than running a live test after each modification to the racquet.

Though finite element analysis is a useful tool in each of these industries it is for different reasons. Each company and industry has different potential uses for FEA including the athletic shoe industry. The main difference between these industries, which have already integrated finite element analysis into their production process, and the athletic shoe industry lies in one main area: human factors.

Human factors play a significant role in designing an athletic shoe. Human factors add variability and uncertainty in predicting the external forces and environmental interactions. Though human factors can also affect a tennis racquet the racquet being optimized by 3M needed maximum damping and minimal weight; both independent of human factors. The weight of the racquet and the vibration felt at the end of the racquet upon hitting a ball are independent of the person using the racquet.

Similar to 3M, the product of athletic shoe companies is subject to human factors. However, athletic shoes are not independent of these factors. The commonly tested characteristics of a shoe are very dependant on the person analyzing the shoe. It is this dependency on the individual person making the analysis that separates the athletic shoe industry from the previously mentioned companies and industries.

4.0 USE OF FEA IN THE SHOE DESIGN PROCESS

The first application to investigate is the application of FEA in the total shoe design.

4.1 Current Athletic Shoe Design Process

Though design processes vary slightly for each shoe there is a typically utilized process and duration for designing an athletic shoe. The process can be divided into four stages: sole design and testing, shoe design and testing, modifications and testing, and the final freeze.

The first phase in the athletic shoe creation process is the design and testing of the main component within the shoe sole. To start, industrial designers brainstorm ideas and begin concept sketches of the component; this stage usually lasts about two weeks. Once a design is chosen, the CAD Designer works with the Industrial Designer to create and fine tune the concept sketches in a 3D computer-aided design (CAD) package; this process takes approximately four days. The 3D CAD is sent to Taiwan where the prototype tooling is opened and samples are created; overall the turn around time is about 3 weeks. Concurrently, the Industrial Designer begins to work on the sole unit design. Again, once the concept sketches are completed, the CAD designer and industrial designer input the remainder of the sole unit into CAD; as the sole unit has greater detail than the component this process takes about 2-3 weeks. Once the sole unit is completed in CAD, a final design presentation to management occurs and the concept is reviewed.

This completed CAD for the sole unit is then exported to Taiwan where the files are reviewed and revised in 2D. The Asian supplier develops a silicone prototype and sends it to the company for review; this process takes about 10 days. The tooling for the sole unit is created after the silicone prototype is approved; this takes about 6 weeks. Once the shoe company has a functioning sole unit, a prototype upper is attached to the sole unit. The prototype is now wear-tested, engineers wear the shoes and an evaluation is made based on comfort and performance; this phase generally last about 20 days.

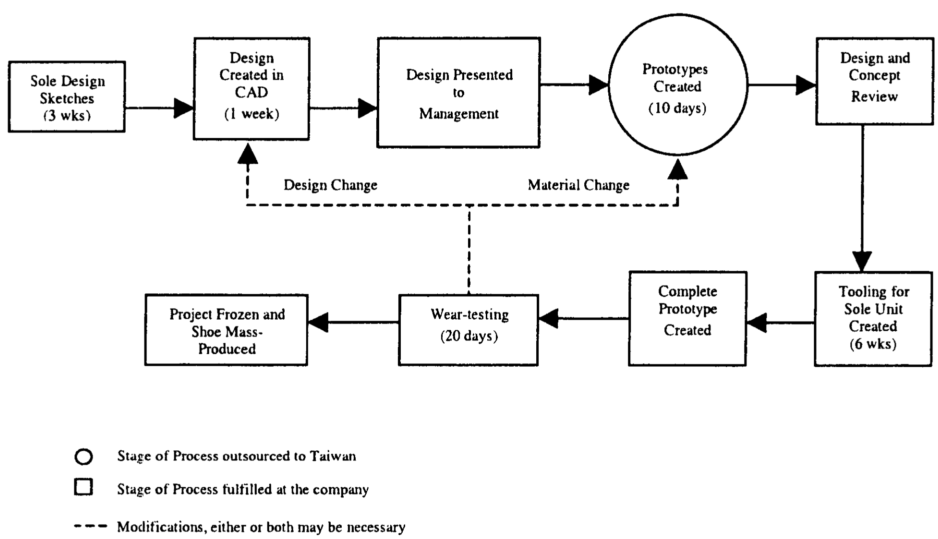


Figure 1: Current Athletic Shoe Design Process

Once evaluations are made the shoe is modified. Modification can include a design change, material change, or both. If a design change is made, the engineer makes the changes to the CAD model and again, sends the file to Taiwan to repeat the prototype acquisition process. If a material change is made, the CAD model does not need to be altered but Taiwan must be contacted for a material change request, again repeating the process. After each prototype is received from Taiwan it is wear-tested and, again, evaluated and potentially modified. This phase can be anywhere from four to six weeks depending on the number of modifications made and wear-tests. Once a final design is decided upon the project is frozen and the shoe is mass-produced and shipped to retail stores around the world. The entire processes, from initiation to project freeze, is currently about six months.

4.2 Difficulties of FEA Implementation

For the athletic shoe industry, the goal of finite element analysis implementation is to assist in quantifying wear-tests results with a minimal number of analyses performed on each shoe. Each wear-test examines the stability and comfort of the shoe. The term stability is used loosely because every company has its own tests and qualifications for what makes a shoe sturdy. Thus, there is no standard test to simulate via FEA to test for stability.

Like stability, every company has its own standards for what is comfortable. However, unlike stability, some aspects of comfort can be approximated with a single variable. While moving in a shoe, the softness or hardness of the sole can be quantified by equating the softness to the deflection of the sole. After numerous wear-tests the design engineers have an idea of the materials that people find comfortable and, in effect, the approximate deflection associated with the materials. If we could attain a numerical result via FEA by using the proper inputs to find the deflections when standing, walking, jogging, and running, an opinion could be formulated about the comfort level of the sole.

Companies in the athletic shoe industry would save the most time and money if FEA could be used to analyze the entire shoe. If this were the case, the number of prototypes and wear-tests would be reduced at each step in the total shoe creation process. To determine whether FEA should be implemented to analyze the entire shoe, the accuracy of simulation as well as results need to be considered. The more accurate the inputs and equations to the FEA package are, the more correct the output will be. Thus, the accuracy of the simulation is directly correlated to the accuracy of the results. In order to obtain accurate and useful results, variation must be limited.

It is assumed a model of the shoe, complete with accurate representation of material and mechanical properties, can be accurately produced within an FEA package. Following the creation of a model, a simulation of a wear-test, this includes a person standing, walking, jogging, and running needs to be performed.

The easiest simulation is that of a person standing. In order to accurately model a person standing the standing, 'style' and weight distribution need to be observed. For a single person, this simulation can be made fairly precisely. Though, every person has there own 'style' of standing and weight distribution the variation will be slight. Simulating standing could be done fairly accurately within FEA and the result could be assumed accurate with a fairly small degree of error.

However, walking, jogging, and running pose difficulties when attempting to simulate. Again, you could successfully model a single person with limited difficulties. Yet, we do not want to simulate a shoe, which will be available to people around the world under the assumption they each walk, jog and run in identical ways.

The differences in people's style of walking, jogging, and running vary in two main ways; gait and position of impact. The first way people's style can differ is gait. The term gait refers to the lateral position of the foot as it strikes the ground. A neutral gait describes a style in which the ankles are not leaning and the bottom of the tibia is parallel with the ground. A person with neutral gait will, for the most part, evenly wear the inside and outside of the shoe tread.

Pronation, sometimes referred to as over-pronation, occurs when the person's ankles lean inward and the arch flattens out. Besides causing discomfort in a person's legs, pronation can cause the inside of the bottom of a person's shoes to lose tread quicker. This is because the inside of the foot is the primary contact region while walking, jogging, and running for a pronator. Along with being the primary contact region, the inside of the foot will also bear most of the weight of the runner.

Supination, occasionally referred to as under-pronation, is the opposite of pronation and occurs when the ankles of a person lean outward. This tends to cause the outside of the person's shoe treads to wear faster. In addition, supinators tend to put the majority of their weight on the outsides of their feet.

Figure 2: The Three Most Common Gaits

Though there are three common gaits, the degree of each condition varies within each subgroup. It is this unpredictable variation in degree of gait, which makes it difficult to accurately represent the walking/ running pattern of most people. Even under the assumption that there exist only three distinct gaits, with no degree of variation, additional complexities arise when trying to standardize the inputs of the FEA.

As previously mentioned, the position of the foot upon impact varies for each person. For example, there are three common foot-strike and release patterns: heel-toe, flat-toe and toe-toe. The heel-toe pattern refers to a person whose initial impact is made with the heel of the shoe and released by pushing off the toe. A person with this strike-release pattern will use the entire length of the shoe to support their weight. Those with the flat-to-toe step pattern generally use the entire length of the shoe to support their weight. The difference to the heel-toe pattern lies in the initial impact. A flat-toe pattern results in the person's weight distributed over the entire shoe rather than the heel on impact. Finally, some people jog/run on their toes. This toe-toe pattern means that the initial impact and final push are made with the toes. Thus, a person with this style of running will support their weight only on their toes. The variations of point-of-impact further complicate an attempt at an accurate input for equation of motion for the shoe and, in effect, the primary weight bearing patterns of the person's foot.

This makes potential inputs to the finite element package extremely variable, producing specific results valid for only a very small population. Again, this is under the assumption we can categorize the population accurately into three specific gait types. The variability associated with gait and position of foot upon impact is too great, thus, too many tests would have to be run on each shoe to provide the company with accurate and complete wear-test data. This does not allow us to meet our goal of creating a minimal number of test scenarios. At this time, it is not recommended to analyze an entire shoe within an FEA package such as those listed previously.

5.0 USE OF FEA IN SHOE COMPONENT DESIGN PROCESS

Though FEA testing for an entire shoe is not recommended, the next step is to take a look at the components of a shoe and decide whether finite element could assist in their design and testing. The most critical component, the cushion in the heel of the sole, currently requires approximately six weeks to create. It is believed time, and in effect cost, can be reduced by using finite element analysis to design, test, and modify this critical component.

5.1 Current Design Process for Shoe Components

The design, testing, and modification of the main component within the shoe sole are currently a lengthy and involved process. To start, industrial designers brainstorm ideas and begin concept sketches of the component; this stage usually lasts about two weeks. Once a design is chosen, the CAD Designer works with the Industrial Designer to create and fine tune the concept sketches in a 3D computer-aided design (CAD) package; this process takes approximately four days. The 3D CAD is then sent to Taiwan where the prototype tooling is opened and samples are created; overall the turn around time is about 3 weeks.

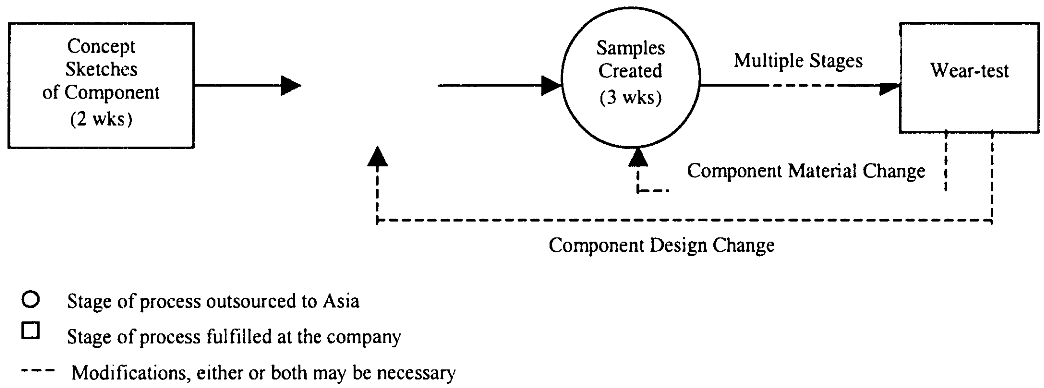


Figure 3: Current Component Design Process

The aforementioned process is referred to as the initial process; this encompasses the process up until the wear-test. Once the results of the wear-tests have been evaluated material and/or design changes within the most critical component may be necessary; these are the secondary cycles. One secondary cycle occurs when the wear-test results suggest an alteration to the design of the cushion. The design is then changed in the CAD program and the process again continues step-by-step through the initial process until the wear-test. With each design change that is made on the cushion an additional two to three weeks are added to the development process. Though material changes do not add as much time as design changes, one to two weeks, to the development process they are still costly and time consuming. When the wear-test results indicate a material change will be beneficial, the athletic shoe company contacts the company overseas and requests new prototypes with the new material.

Either or both of these changes could be necessary and may need to be repeated. Making iterations to the cushion is costly and time consuming. On average, each most component undergoes two to four rounds of changes. That could add an additional 10-12 weeks of production, depending on the modifications, along with the additional costs associated with each step.

5.2 Compatibility of FEA Implementation

In order to effectively utilize finite element analysis, a quantifiable result must be the goal of the analysis. Comfort, flexibility, and energy absorption and return are currently the main factors being tested during the wear-tests. As previously mentioned, comfort is difficult to quantify since everyone has his or her own definition of comfort. When it comes to the shoe cushion, the term comfort translates to engineering terms as deflection. Deflection describes the amount the top of the cushion deflects when a force is applied. In addition, deflection is quantifiable which allows FEA to output numerical results for analysis. Flexibility is also quantifiable. Again, most people have their own level of preferred flexibility, yet a single number can be agreed upon based on past acceptable cushions. Energy absorption and return can be best quantified by observing the characteristics of the deflection of the cushion over a cycle of impact, specifically noting the speed of recovery of the original condition of the cushion. Assuming this simulation, the most accurate representation of the wear-test energy absorption and return can be quantified accurately. Since each of these desired tests can be quantified, FEA can assist in analyzing the comfort, flexibility, and energy absorption and return of the shoe cushion.

In order to obtain an accurate quantification of the wear-test, knowledge of all external forces on the cushion and interactions with its surrounding components must be predictable. As previously mentioned, each person applied loads on a shoe in a unique manner. This, however, does not drastically affect the testing of the shoe cushion. The cushion is a small component taking up approximately the rear1/3 of the shoe in length. The heel of a person can be modeled as a pivoting point or a ball. If you apply the same force to a ball that cannot move on the horizontal plane, on a mattress vertically and at a slight angle the surface area, which the pressure is being applied will vary only slightly. This means the location of the force will generally be in the same location for every person, see Figure 3. Though the force is being applied at a different angle the contact surface varies only slightly depending on the person's gait. This slight variation still allows for the use of FEA testing with a high degree of confidence in the results.

Along with the slight variation in surface area the force on the cushion will vary similarly with the gait of the person. Force is typically represented as a three-dimensional vector with an X, Y, and Z component. The force from a person with a neutral gait can be represented as a force in the Z-direction (vertical) with no horizontal components. When the gait varies in either direction the force has both horizontal and vertical components. The total force vector is the position of the force vector where two of the three components are zero. The angle of the total force vector varies only slightly from its neutral vertical position among a vast majority of the population.

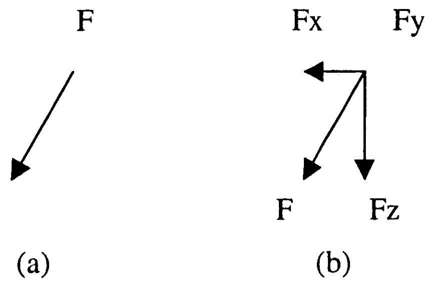


Figure 4: (a) F represents the magnitude of the total force. (b) Fx, Fy, and Fz represent the individual force vectors and magnitudes.

The deflection of the cushion is dependant on the vertical, Z-component of the force vector. The maximum deflection of the cushion will occur when the person standing on the cushion has a neutral gait (compared to other people of the same weight). This is because all of the force exerted on the cushion is in the vertical, Z-direction. Since the variation in angle of the total force vector is slight for the majority of the population, the variation in deflection will be slight as well. Thus, testing the cushion under the assumptions of a person with neutral gait will provide us with the maximum deflection.

The cushion of the shoe is in very tight contact with the surrounding components of the sole. Thus, we can model the sole as the meat of a sandwich, between the outer sole and upper sole. Since we are aware of the interactions the cushion will have with its surrounding components and the external forces being applied, we can analyze the cushion within FEA to a high degree of accuracy.

For each of the three main factors being tested, comfort, flexibility, and energy absorption and return, more than one finite element analysis will need to be run to accurately quantify the results. In order to test comfort, or deflection, analyses will need to be performed simulating the various weights of potential shoe wearers. In addition, separate tests will also need to be performed to simulate a person standing on cushion, walking, running, and jumping. Each of these will provide engineers with additional insight to the comfort while performing each of these activities.

To test for flexibility tests will need to be performed on the cushion, which simulates the addition of a load at one end while the other end remains fixed. In addition, adding a moment to each end of the cushion would also provide the engineers with useful data to assess the flexibility of the cushion. A final series of tests, which would aid in providing information to design engineers, includes a buckling test. This test can be simulated by fixing an end of the cushion while applying a load to the opposite end. One valuable piece of information would be the buckling point: the load when cushion first buckles. Once the material buckles the load can be compared to the deflection of the point of application.

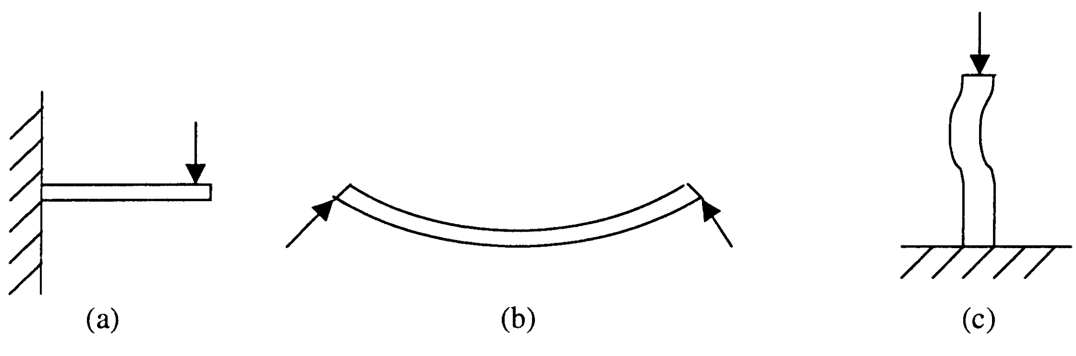


Figure 5: (a) Point-load with opposite end fixed. (b) Equal bending moments added to opposing sides. (c) Buckling test with fixed base.

The quantification of energy absorption and return can be found by observing the characteristics of the deflection of the cushion over a cycle of impact; specifically noting the speed of recovery of the original condition of the cushion. By noting the slope of the deflection versus time after simulation of a step input an estimation of absorption/return can be made. You can effectively perform the same simulations to gather energy data as deflection data, you would not necessarily have to prepare additional FEA tests. However, the deflection tests must be run in a cycle over time for simultaneous testing.

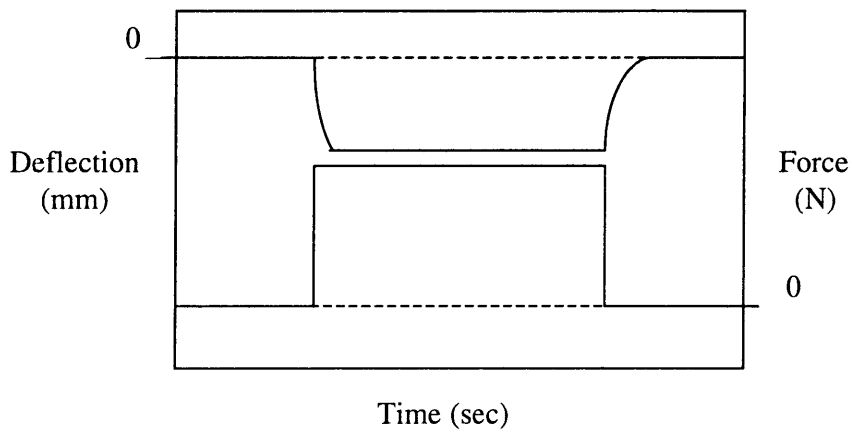


Figure 6: Sample plot of input and results to analyze deflection and energy absorption and return.

6.0 FEA IMPLEMENTATION

The shoe cushion wear-test is a good candidate for replacement by finite element analysis. First, the results of the wear-test are all quantifiable which allows for analysis of the output data. Also, the external forces on the cushion and interactions with its surrounding components are known and predictable with little variation. Finally, the numbers of finite element analyses needed to accurately represent a wear-test are minimal.

6.1 Component Details

To prove finite element analysis implementation is, in fact, a suitable replacement for current shoe cushion wear-test evaluations in the athletic shoe industry a sample shoe cushion needs to be tested within a finite element package. The sample selected is a two-piece heel cushion of a running shoe. Each component consists of an 18mm thick bladder filled with modified EVA-like foam. The foam is in contact with the top and bottom of each component leaving a gap on the sides for air.

6.2 Integrating the Component into Finite Element

As previously mentioned, ADINA-AUI can be used independently with the requirement that the model being tested is imported as an IGES file. Initially, I attained the IGES files of the experimental component from the athletic shoe company designing the cushion. After successfully importing the files to the ADINA-AUI program, an attempt was made to set boundary conditions: the first stage of analysis. ADINA-AUI was not responding favorably to the newly imported file. Setting boundary conditions within ADINA requires defined bodies comprised of defined faces. Within each face, ADINA requires defined lines while each line requires defined points. Difficulties in analyzing the imported IGES files were the effect of improperly defined lines and, in turn, undefined faces.

Rather than taking the time to define each line followed by each face of the component I opted to remodel the shoe cushion within ADINA-M. The athletic shoe company, which originally sent me the IGES files, sent me prototypes of the experimental cushion so I could generate an accurate model (Note: Sketches of the cushion that included dimensions could have been given to me and the resulting FEA model would be the same). By modeling the component I have the ability to define lines and faces much easier and quicker than sorting through the imported file and doing the same. Within ADINA-M each of the experimental cushion's subcomponents was created by utilizing the 3D capabilities of ADINA. Creating the subcomponents, and overall cushion, in 3D meant I could create each of the bodies without having to previously define points, lines or faces. By using 3D each was automatically defined within each body created (the two subcomponents).

Initially, each subcomponent was a box. Within the box and outer edges more boxes and 3D shapes were created that intersect with the original box. The intersecting regions of the original box and the additional 3D shapes were subtracted, along with the 3D shapes, to create each subcomponent modeled after the actual subcomponent. By creating each subcomponent in the accurate relative location it was not necessary to rearrange the location of the subcomponents after they had been modeled.

The finished component was not an identical replica of the experimental cushions given to me. The finished model was did not portray the cushion exactly to scale. In addition, only the inner foam was created for simplicity. My inexperience with ADINA and modeling handicapped the creation of a to-scale model of the cushion. An experienced finite element analysis engineer could create an exact replica of the cushion in approximately 15- 20 hours.

Creating the rough version of the component took a total of six hours. This includes an introduction to modeling in ADINA-M, a failed attempt at creating an accurate model of the cushion and the successful implementation of the experimental cushion into the finite element system.

6.3 Testing within FEA

Once the cushion is modeled the testing process begins. The simplest test to run is a deflection test, which simulates a person standing on the cushion. The following will describe the testing process for the aforementioned test. The process for running this test, like others, can be broken down into seven steps: applying boundary conditions, applying forces, defining material properties, defining element groups, specifying a mesh density, creating a mesh, and running the analysis.

The first step in the analysis is setting boundary conditions on the model. Boundary conditions enable the engineer to specify the range of motion for each point, line, face or body defined within the model. To test the cushion, the bottom face of each subcomponent is prohibited from all movement, including rotation. These faces are effectively glued to the floor while the rest of the cushion is free to react to the forces acting on the cushion.

Once the boundaries have been specified the external forces need to be applied. These forces can be input as a function of an independent variable, such as time, or simply as a number. To simplify this test the force is applied to the entire top surface of the cushion. This simplification is allowed because it does not affect the results whether whole or part of the surface is directly acted upon.

The next step in the analysis of the model is defining the material properties of the model. For a linear material the Young's modulus Poisson's ratio and other vital characteristics can be specified with a single number. However, for the more complicated, non-linear materials being used by the athletic shoe industry, the engineer will have to input equations of performance to specify how the material acts under various circumstances.

After the specification of material properties the element groups are defined. During this stage the engineer defines each element within the model. An element is another word for a subcomponent, of which the cushion has two. These subcomponents need to be defined as separate entities prior to meshing the model. By doing this, each subcomponent will be meshed separately and each will be treated as a separate object.

Following the defining of the element groups a mesh density for each element group is defined. Mesh density allows the engineer to specify the density of smaller elements that will be generated when the model is meshed. Analysis results will be more accurate as the mesh density increases. Once the mesh density has been specified the mesh is created. Upon creation, each subcomponent is no longer a single entity. By meshing the model, each element is divided into numerous adjacent pieces. Meshing is the equivalent to cutting up the model into differential pieces then reassembling the model by connecting the corners, or points, of each differential.

Creating the mesh is the final step in preparing the model for analysis. Now, the analysis takes place according to the previous specifications made on both the model and its environment. Once the analysis is complete the engineer has the capability of viewing many different results such as stress, strain, or displacement.

This process from setting the boundary conditions to data analysis took a total of three hours. This time includes learning the steps of analysis, implementing the analysis, and modifying the mesh to achieve more refined data. For an experienced ADINA user the time would decrease due to familiarity with the program.

6.4 Modifications to Model

Once the initial tests have been performed, the data is analyzed and appropriate modifications are made to the cushion. As previously mentioned the two main modifications made to the cushion are the design and material. For a design change in the model, the engineer would simply alter the model within the finite element package appropriately. Following the modification the analysis would be repeated. Depending on the severity of the modifications this process could take anywhere from a few hours to a few days.

Once the initial analysis is made within FEA, a material change may be necessary. Within FEA, changing materials can take minutes. The engineer simply has to pull up the materials options menu and enter the appropriate numbers for the new material. Once the new material has been specified the model can again be tested and the results for the new and old materials can be compared.

7.0 ADVANTAGES OF USING FEA

As previously mentioned, making the model, preparing for the initial test and running the initial test take approximately 10 hours for an inexperienced ADINA user. The costs associated with creating the model and wear-testing it are unknown. However, these costs include the cost of materials for the creation of samples, cost of labor, and opportunity cost. The opportunity costs associated with the current method is the loss of time, which could potentially be spent working on another shoe component. Since this process is more time consuming the athletic shoe company is missing the opportunity to produce more components. In addition, the company is forgoing revenue from the shoes associated with the components that could be produced.

The only costs associated with the proposed finite element method of production are labor costs and, initially, licensing fees for the appropriate software. Opportunity cost is not being incorporated into this analysis because the opportunity cost by using the current method of production is based on the difference in time between that process and the FEA process. Using finite element analysis is faster and more cost effective for the athletic shoe company.

Though using finite element analysis in the initial process sees benefit, the greatest benefit is to the modification stage. The amount of time needed to currently modify a cushion without the use of finite element analysis is on the order of 10- 12 weeks, as previously mentioned. Finite element analysis is the faster method of modification for the component. In addition to saving time, money is also saved. Currently, at the most basic level, redesigning the model incurs costs associated with outsourcing the design and creating a prototype. By using FEA, the only additional cost incurred with modifying the design of the cushion is the cost of paying the engineer.

FEA also allows the engineers to freely experiment with materials without taking up much time. In addition, using finite element analysis allows the engineers to compare the data between new and old material very easily because the data is stored in the computer. By comparing the use of FEA to analyze a component with the current method it is obvious the new, proposed method allows for greater flexibility, saves time and money.

8.0 NEW PROCESS INTEGRATION

Integrating finite element analysis into the current method of production for an athletic shoe cushion will take time. First, the proper computer equipment and finite element package must be purchased. Finite element analysis requires a computer with a lot of memory. The FEA package must also be selected to meet the current and projected needs of the athletic shoe company; suggested packages are previously mentioned. Second, an engineer with finite element experience must be hired or an engineer must be trained. Once the engineer and his/her equipment are ready they will begin work on the next component project. While the FEA engineer follows the newly outlined process the rest of the product development group will continue to create the component using the current method. The two will work side-by-side on the entire project. To save time CAD and FEA can be interfaced so the model is created within CAD then exported to FEA. This should be done for a few projects, until the FEA engineer and product development group become comfortable comparing the numerical results achieved via finite element analysis to the wear-test results. For example, the FEA engineer will learn the preferred deflection of the cushion by comparing his numerical data to the final cushion and those considered previously. Once the finite element engineer and product development group feel comfortable assessing the cushion based on its comfort, flexibility, and energy absorption and return the current process can be phased out.

9.0 CONCLUSION AND RECOMMENDATION

Finite element analysis was considered for implementation into various levels of the athletic shoe design and testing process. Implementing FEA on the macroscopic level, testing the entire athletic shoe, would be most beneficial. However, there are many human factors that affect the evaluation of an entire shoe. Finite element analysis tests very specific scenarios and thus would not accurately simulate a wear-test for an entire shoe.

Investigation of FEA implementation to the shoe sole development process was then investigated. Similar to the entire shoe, the sole of an athletic shoe has many external forces that can vary drastically from person to person depending on walking, jogging, or running style and the person's gait. With so much variation, numerous finite element analyses would need to be performed to capture data, which is representative of the athletic shoe purchasing population. The number of analyses would be so great finite element analysis would not reduce the amount of time spend developing the sole. Thus, the shoe sole is not a good candidate for finite element analysis.

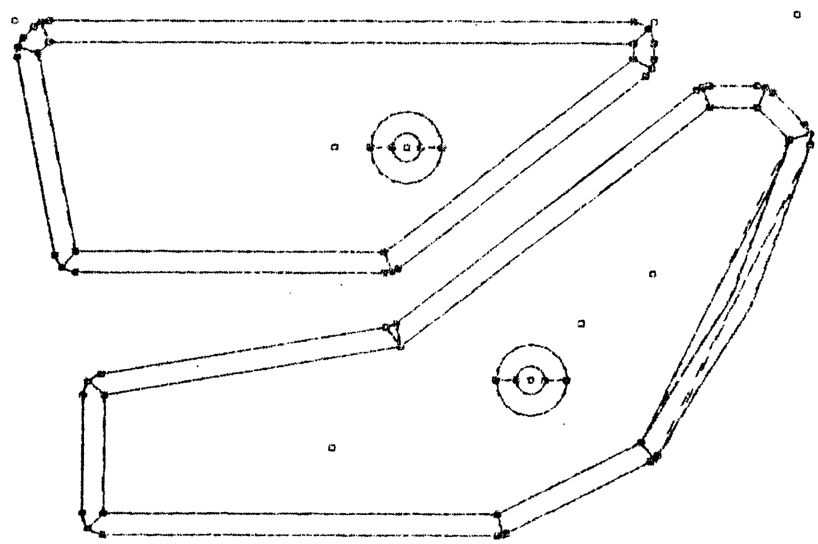
Within the sole of an athletic shoe lays the most critical component- the cushion. Investigation showed that the cushion is an excellent candidate for finite element analysis. The implementation of FEA is compatible with the cushion because the human factors do not vary much from person to person, thus keeping the number of FEA iterations minimal. Also, the external forces and interaction with the entire sole of the shoe are predictable.

At this time, it is recommended to use finite element analysis in the production of athletic shoes. Finite element analysis is a better method for producing an athletic shoe component than the current process. The current process of prototyping, testing, and repeating, if necessary, is very time consuming and expensive. By using finite element analysis time to market and cost decrease. In addition, finite element analysis provides more flexibility than the current method, especially with material selection and testing parameters.

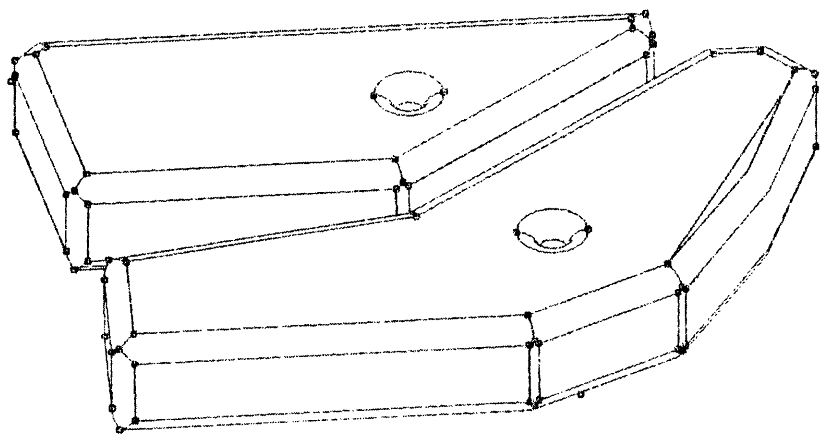
Many finite element analysis packages are available for purchase. In general, each finite element analysis company has packages for performing various types of tests ranging from mechanical to thermal. The athletic shoe industry currently does not require a FEA package with every capability. The mechanical packages from each company are best suited for the analysis of a component of an athletic shoe. These packages include ADINA-AUI (which can be coupled with ADINA-M as discussed), ANSYS Structural, ANSYS Mechanical, COSMOSM, and ABAQUS/ Standard. Through the use of ADINA I have become familiar with finite element packages and learned that the design of the component need not be done within the package. In fact, many packages allow the model to be imported from CAD.

Implementing finite element analysis into the shoe component production process will have various effects on the athletic shoe industry. First, time to market for the shoe will decrease. It is uncertain how drastic the decrease will be because the remainder of the shoe is still being produced using the current prototype and test method. Second, cost will decrease. Again the percentage of decrease is unknown (due to the same reasons the decrease in time is unknown) and will vary from shoe to shoe. The third benefit of implementing finite element analysis is potential consolidation of computer programs. Currently, the athletic shoe company uses various CAD programs, which are not all compatible with suppliers or each other. By using FEA all the models and tests will be performed in a single package. Data storage is another benefit of finite element analysis usage. The results of each finite element analysis will be on record and easy to refer to in the future. Another effect stemming from the integration of advanced technology into the shoe component process is the increase in the number of shoes being produced per year. As more shoes are produced the athletic shoe company implementing finite element analysis will have the potential to gain more market share. The gain in market share will be due to the fact the company can replicate ideas from other companies quicker and share in the specific market for that individual shoe faster. Finally, as engineers become familiar with using finite element analysis to produce the component of athletic shoes their knowledge will expand and perhaps, in the future, a method for testing the entire shoe within finite element analysis will surface.

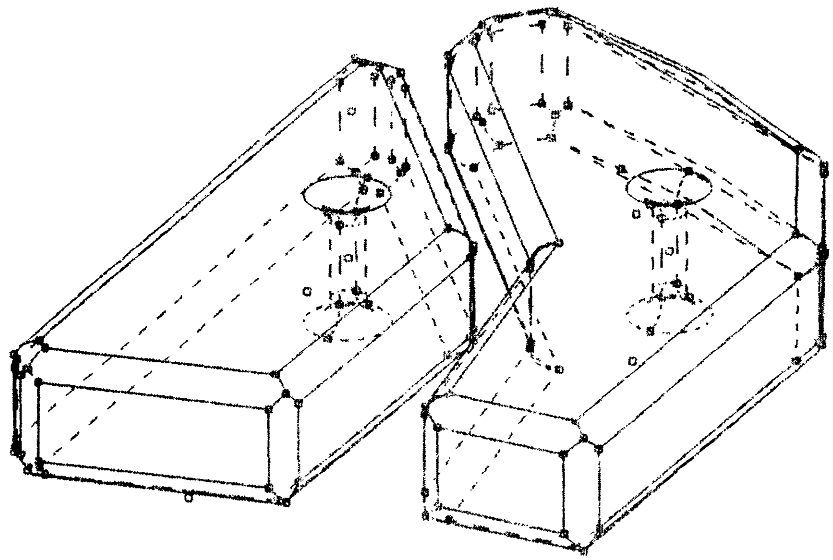
10.0 APPENDICES



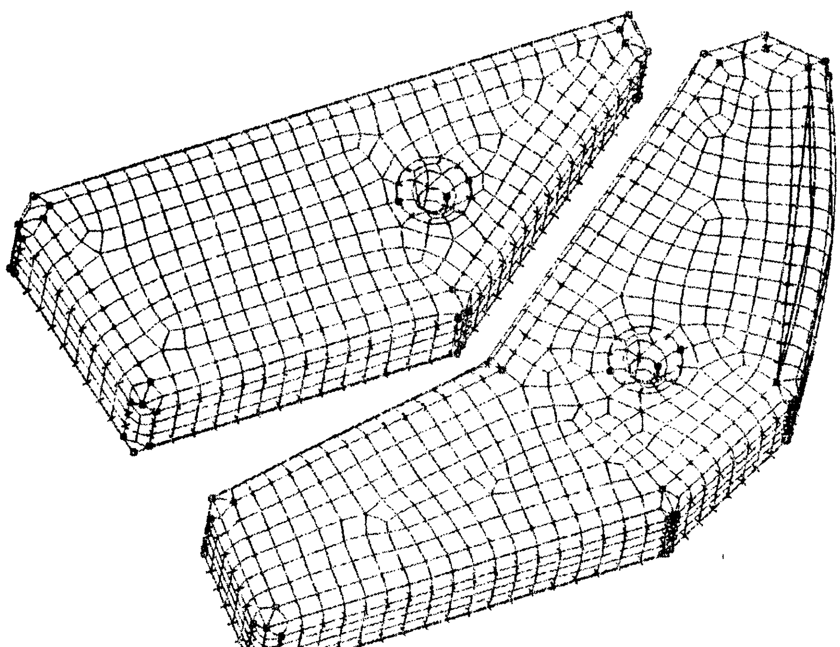
Top view of the cushion- interior lines represent beginning of curvature.



Three-dimensional view of the cushion.



3D model of the cushion showing internal structure.



Model of the cushion after being meshed.

11.0 REFERENCES

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