HARVARD UNIVERSITY

School of Engineering and Applied Sciences

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ES 128 - Finite Element Analysis

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Mechanical Analysis of Golf Club/Ball Impact

Authors:
Matheus Fernandes
Jeffrey Fischer
Ryan Simpson

Professor:
Katia Bertoldi

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1 Introduction

In today's growing sports industry, engineers are constantly working, trying to discover new ways to improve equipment durability and efficiency. In 2011, it was estimated that the sports industry accounted for over 422 billion dollars of revenue. Athletic gear and equipment accounted for 40 billion dollars of the 422 billion dollars. This is why engineers have been working so hard. After the digital revolution, engineers were able to increase an athlete's performance by creating lighter and stronger equipment at a lower expense, using finite element analysis.

In golf, engineers and club designers are constantly changing the shape and material of club-heads and shafts in order to give golfers optimal performance on the course. Because golfers have an assortment of clubs for various shots around the golf course (drivers, irons, and putters.) concepts such as physics, engineering, material properties, and manufacturing processes all have to be taken in to account when creating the various components of a golf club.

1.1 Goals

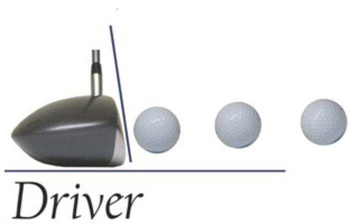
The goal of this particular project is to analyze the performance of existing clubs and to make suggestions on how to improve the design of these golf clubs. In this paper we will analyze the design of three different clubs: Driver, Putter and 7-Iron.

In the analysis we will looking at the stress distribution across the club geometry and comparing it to known material properties such as Yield Strength.

Additionally, we will be modeling different impact speeds for the Putter by parametrization and will analyze the effect of impact speed on the maximum stress of the club. In this analysis, we will also provide visuals on the strain strain distribution throughout the clubs which we will be able to compare to other known material properties. Through this analysis we will be able to make recommendations on improvements in the club design as well as predict failure locations.

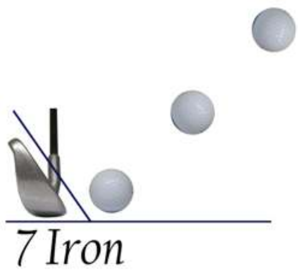
2 Background

2.1 Driver



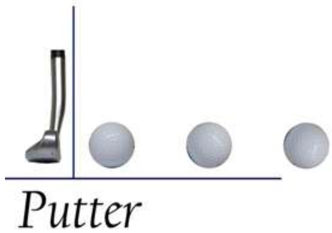
Drivers are made with large club heads and long shafts in order to hit the ball very long distances. Drivers have relatively low angled club faces because for golfers, the distance of the driven shot is of more importance than the height of the driven shot. Drivers used to be made of wood, but in today's modern game of golf, golfers use drivers made out of titanium or metal composites.

2.2 Irons



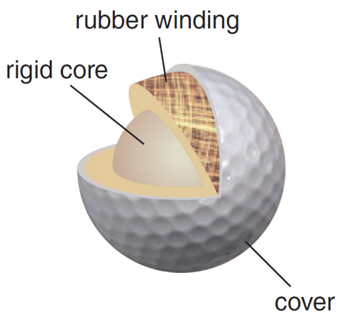
Irons have a large angled club head like the driver but the club face itself is relatively flat. Also the shaft of the club is shorter than that of the driver, decreasing power but increasing accuracy, which is critical for lofted shots that must be placed on the green. Irons are typically made of iron but more recently these clubs have been produced with alloys of steel. Irons having varying angles on the club face, giving golfers the ability to choose a different iron for different distanced shots on the course.

2.3 Putter



Putters are a unique type of golf club that gives golfers the ability to roll the ball along the green toward the hole. These clubs are typically used for shots that are very close to the hole, either on the green and sometimes on the fringe. The face of club is almost perpendicular to the ground, but contains a bit of an angle to get the ball over grass or any indentation the ball has created from the previous shot.

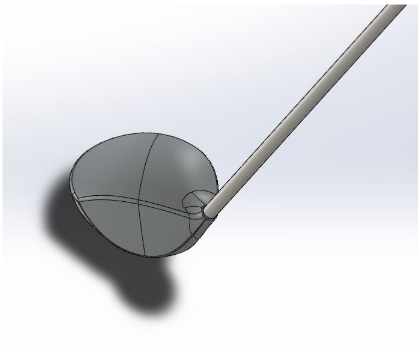
2.4 Golf Ball



Since the origins of golf, the size and the materials of golf balls have changed over time. Golf regulations state that balls must not weigh more than 45.93 grams and the diameter must be larger than 42.67mm. Golf balls started as wooden spheres but the more modern version of the ball is made out of a rubber composite. Dimples are added to the ball for aerodynamics, giving the ball the ability to spin as well as resist wind. Golfers use balls with different patterned dimples allowing them to hit the ball farther or spin more than a non-dimpled ball.

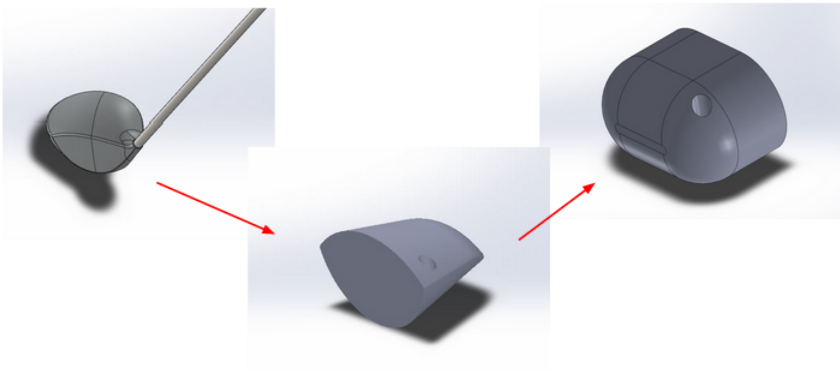
3 Creating and Cleaning CAD

3.1 Driver

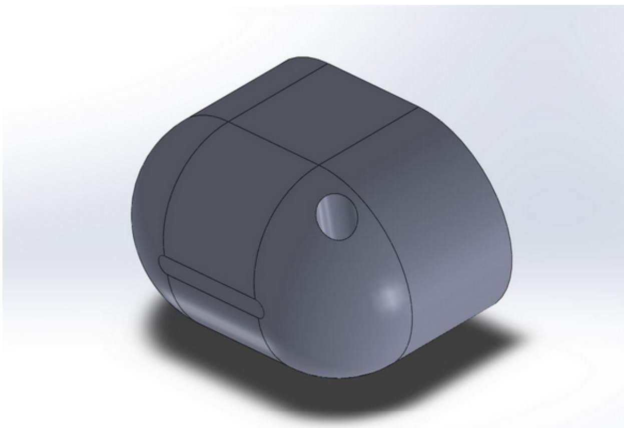


The design for the driver model began with a downloaded SolidWorks file found on the internet. The first model was a very accurate representation, both in size and dimension, of modern day drivers. However, problems were encountered when the model file was imported in a .sldprt format to ABAQUS. (More detail about problems with the models will be included in later sections)

Unable to clearly identify the problem, a new model was created from scratch in SolidWorks with a simpler geometry. While the second design had fewer complex contours and design elements, it was still designed with some realistic elements in order to produce a more accurate analysis of the real-life scenario. Upon importing however, problems were again encountered and no obvious solution was made apparent.



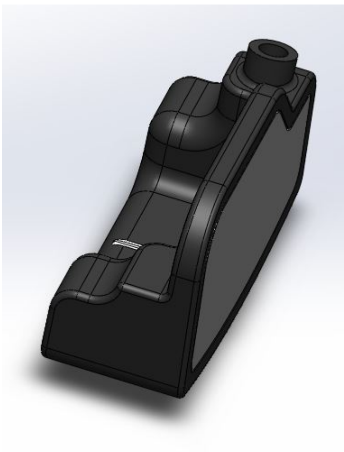
For the third design iteration, another from-scratch model was created. For this iteration however, very little attention was paid to designing a realistic representation of a driver. Instead, only the basic geometry of a driver was considered and the design was made to be as simple as possible. Finally, after importing the third model, ABAQUS was able to successfully read and upload the model file.



3.2 7 Iron

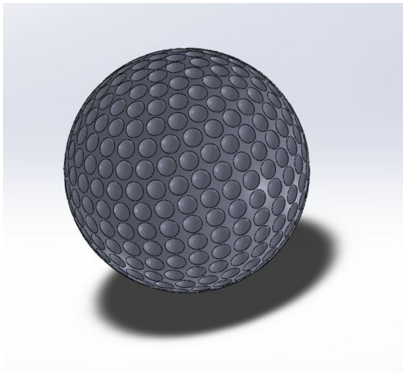
The design for the iron model began with a downloaded SolidWorks file of a Titleist 7 iron club found on the Internet. The first model was an actual representation, both in size, dimension, and brand, of modern day Titleist 7 iron. Using SolidWorks, we removed any markings, engravings, or grooves on the club that may have caused any problems when we meshed the part on ABAQUS. Additionally, the removal of sharp corners or tight contours would eventually help to decrease the computational cost of running the model resulting in quicker more efficient analysis results.

3.3 Putter



The design for the putter model began with a downloaded SolidWorks file found on the Internet. The first model was a very accurate representation, both in size and dimension, of modern day putters. Using SolidWorks, we removed any markings, engravings, or grooves on the club that may have caused any problems when we meshed the part on ABAQUS. Additionally, the removal of sharp corners or tight contours would eventually help to decrease the computational cost of running the model resulting in quicker more efficient analysis results.

3.4 Golf Ball



The golf ball was the easiest model to create/clean. Originally, a realistic SolidWorks model was downloaded from the Internet but upon importing errors were encountered that were not easily solved. For this reason, a ball was modeled from scratch in SolidWorks.

The modeling simply consisted of performing a revolution in order to produce a single smooth sphere. The dimples on the ball were purposefully omitted because their inclusion would have greatly increased the complexity of the problem and the computational cost. Furthermore, the dimples only serve an aerodynamic purpose and have no structural significance, meaning their inclusion would contribute little in the structural analysis of the ball.

4 FEA Analysis

4.1 Model Assumptions and Simplifications

In the interest of computational resources and convergence many assumptions and simplifications had to be made. Clearly one assumption is the simplification of the geometry and CAD models. For instance, for the ball the dimples were removed and for the 7-Iron the engravings such as the logo and the grooving in the front were removed.

Damping effects were also ignored as it was computational burden was not worth the additional small information it provided. This was analyzed in the 7-Iron by making it a very course mesh and comparing the model with damping versus without damping, no discrepancy in the Maximum stress was found when performing this sub-analysis.

Frictional forces along the interface between the ball and the face of the club were also ignored as it would only affect the final trajectory of the ball.

This provides us very little useful information with respect to the goal of the analysis.

The boundary condition also contains an assumption, in that the club shaft is infinitely stiff. This assumption can be valid although not entirely correct as the bending stiffness of the shaft is really high compared to the stiffness of the club. Most likely this assumption will yield the same result in the the highest stress will be located at the junction of the club and the shaft.

Another assumption made was in the geometry of the Driver. As we all know driver these days are made of hollow titanium, however our model assumes that the Driver is a solid club. This as we know will yield a very different result than from the actual club. This assumption was made in the interest of time in order to avoid the problems mentioned in the "Funny points" section.

We also assume that all body forces are negligible and that the impact of the ball is under a perfect hit; meaning that the golfer hit the ball with the club at full velocity and at the perfect location at the club.

4.2 Simulation Properties

For this simulation ABAQUS Explicit module was used. In it, we defined the dynamic step with an initial velocity field for the ball and a boundary continuous boundary condition for the shaft. As mentioned previously, this boundary condition assumes an infinitely stiff shaft. The simulation will consider a fully elastic collision under the conservation of energy law. The simulation is viewed from the golf club reference frame in that the ball has the initial velocity and the club is stationary.

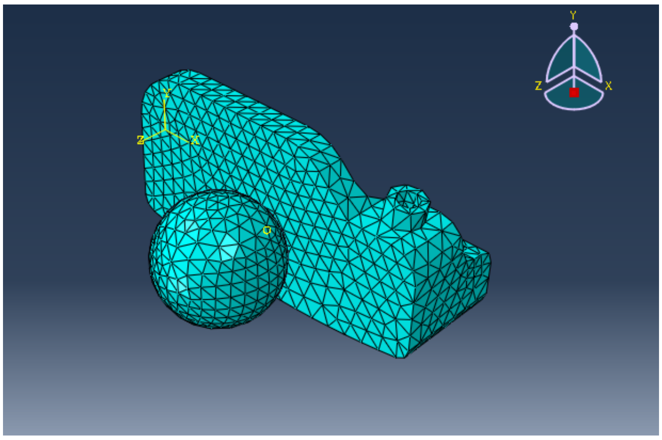
For the step we requested information such as: Stress, strain, displacement, velocity, acceleration, contact, energy and reaction forces. We requested these outputs in order to get a very broad overview of what is going on during each time step. Having this information helps us make conclusions and recommend improvements for the club performance and strength.

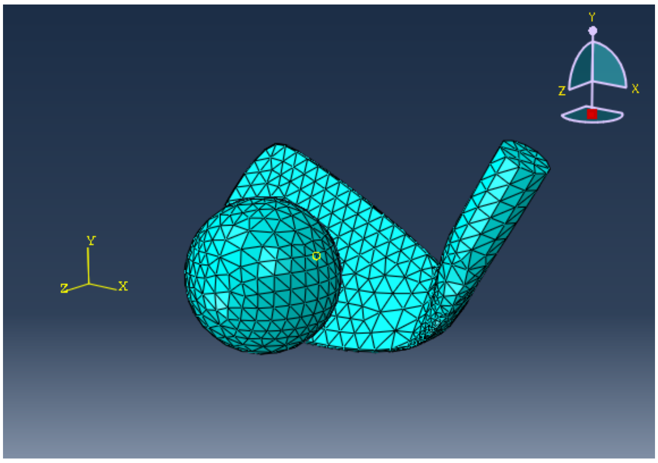
The model step is mainly driven by the time stepping error and 100 output increments are requested for the above mentioned information.

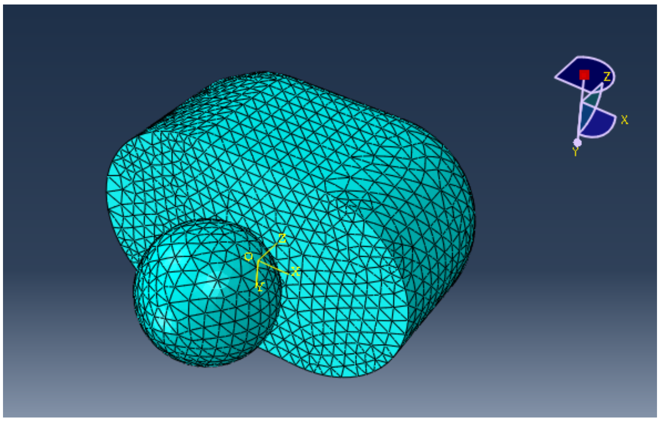
4.3 Meshing

The elements used for all of the models is free tetrahedral 3D elements. The elements are linear as requested by the Explicit module. Thus the ABAQUS element code for the elements are C3D4R. In order to increase efficiency we created a very course mesh for all models. This allowed us to change small parameters and get results in timely manner. Once we had the model running appropriately we created a finer mesh throughout the body and ran the simulatlion again to get the more accurate results.

The following figures illustrate the fine meshes for the models:





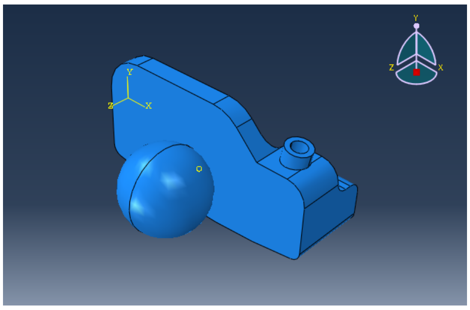
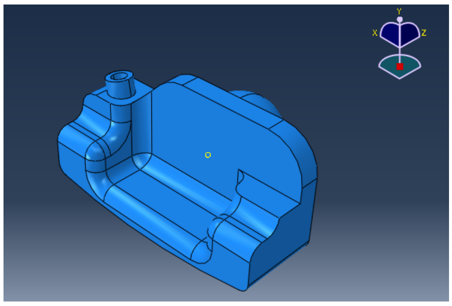


4.3.1 Issues with Ball meshing

The meshing for the ball required some more attention in that the stiffness of the ball seems to have been impacted by the meshing strategy used. At first we had an organized mesh where the ball was meshed equally top to bottom. This created a numerical artifact in the stiffness of the ball making it stiffer than it should have been. Changing the mesh to the current free Tetrahedral mesh portrayed in the figures above we were able to overcome that issue and achieve the desired correct results for the stiffness of the ball.

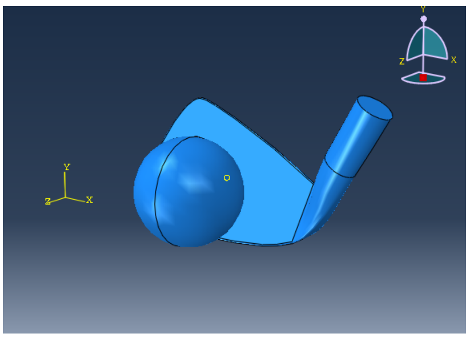
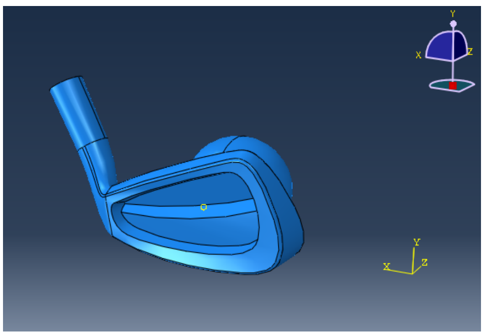
4.4 Golf Club Properties and Definitions

4.4.1 Putter

The material selected for the putter was 304 stainless steel and the model was defined as a homogeneous solid. 304 stainless steel has a yield tensile strength of 215 MPa and a ultimate tensile strength of 505 MPa. Additionally, 304 stainless steel has an elastic modulus of 200 GPa and a Poisson's ratio of .29.

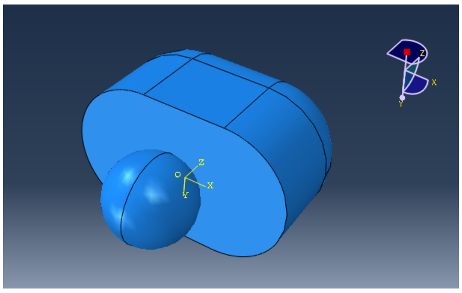
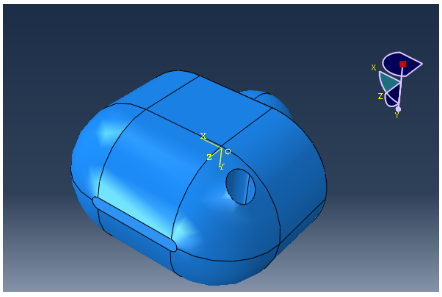
4.4.2 7-Iron

The material selected for the 7 Iron was Malleable Iron (ASTM A47) and the model was defined as a homogeneous solid. Malleable Iron (ASTM A47) has a yield strength of 880 MPa and an ultimate tensile strength of 950

MPa. Additionally, it has an elastic modulus of 165 GPa and a Poisson's ratio of .27.

4.4.3 Driver

The material selected for the Driver was Titanium and the model was defined as a homogeneous solid. Malleable Iron (ASTM A47) has a yield strength of 228 MPa and an ultimate tensile strength of 359 MPa. Additionally, it has an elastic modulus of 116 GPa and a Poisson's ratio of .32.

4.5 "Funny Points"

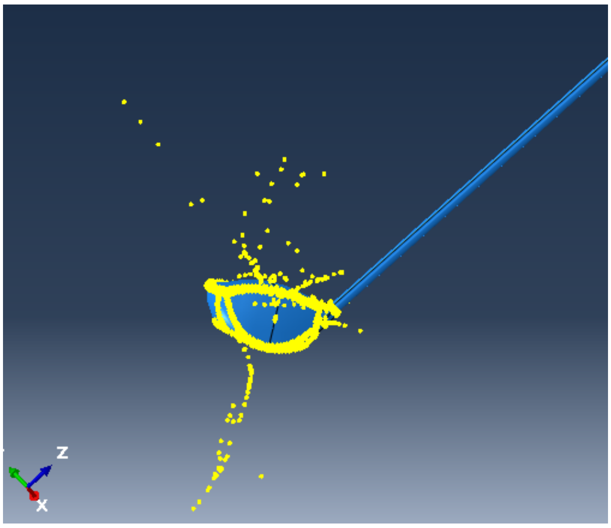
4.5.1 1st Problem

While importing, as well as creating our driver model, we ran into some problems that would cause difficulties when we tried to mesh the part as well as submit the job. The first problem that we ran into occurred in ABAQUS when we tried to make our driver a shelled part rather than a homogeneous solid part. Today's "real-world" drivers are constructed with hollow metal clubheads made out of some type of metal usually titanium, steel, or other metal composites. When we downloaded the SolidWorks of an actual driver model as well as created a model from scratch in SolidWorks, we noticed floating nodes when we chose the "shell option" while making a section in ABAQUS. It became apparent that floating nodes were unnecessarily generated when ABAQUS tried to hollow out the solid, Solidworks imported model. These floating nodes lacked element connectivity and property assignments and because of this we were unable to delete them or get the model to converge.

4.5.2 Solution

To solve this problem, we stopped trying to create a shelled part on all of our models and simply assumed a homogeneous material when creating our section in ABAQUS. By doing this we were able to eliminate any of floating nodes that were generated. As mentioned previously, today's "real-world" drivers are constructed with hollow metal clubheads, but for our purposes we assumed that clubheads are solid homogeneous structures.

4.5.3 2nd Problem



The second problem that we ran into with "funny points" came specifically from importing CAD files from SolidWorks to ABAQUS. When creating a model on SolidWorks we had to use tools such as fillet and extrude which were the source of our problem. We found out the ABAQUS incorrectly registers and assigns nodes to material that we had stripped away using the fillet and extrude tools. These floating nodes, similar to the previous problem, lacked element connectivity and property assignments and because of this we were unable to delete them or get the model to converge.

4.5.4 Solution

To solve this problem we simply experimented with the various types of file formats we could use in order to import our SolidWorks files to ABAQUS. We found that the VDA file format was the optimal format to removed these floating nodes that lacked element connectivity and property assignments.

4.6 Error Analysis

While running the analysis on the three models in ABAQUS two errors were encountered. Luckily, both errors were numerical in nature and the magnitude of each error was negligible compared the the values the problem focused on. The first error was the pre-impact vibration of the golf ball. As the ball was initially approaching the club-face it exhibited small vibrational deformations. This was occurring before any forces had been imparted on the ball and thus was clearly a result of computational noise.

The second error was the pre-impact stresses that existed in the ball and club face. Before either object had imparted a force on the other, both exhibited stresses within their respective bodies. However, the magnitude of these pre-impact stresses were several magnitudes lower than the magnitudes of stress at impact and so, could easily be neglected and removed from the analysis.

4.7 Steps for Creating Model

1. Import from/create club and ball in SolidWorks
2. Translate part(s) to correct position
3. Seed/mesh part(s)
   (a) Use Tetrahedral elements
   (b) Linear
4. Define material properties
5. Assign material to section
6. Create step
7. Select output variables
   (a) Stress
   (b) Strain
   (c) Disp/Vel/Acc
   (d) Forces/ Rxn
   (e) Contact
8. Create interaction property
   (a) Normal behavior
9. Assign global property
10. Create Boundary Condition
    (a) Rigid boundary condition at shaft
11. Assign predefined field
    (a) Set velocity and direction of ball
12. Create and submit job
13. Repeat steps for different clubs

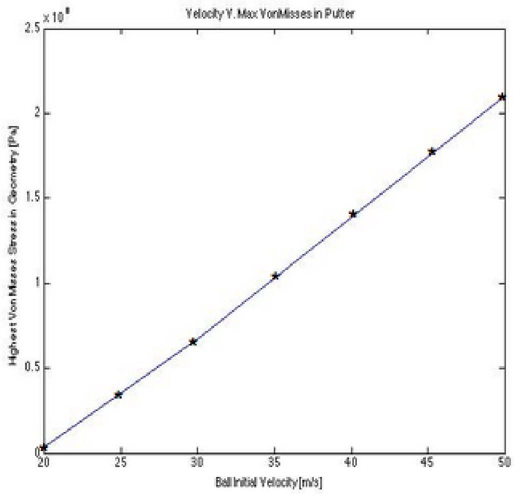
5 Results, Discussion and Design Recommendations

5.1 Putter

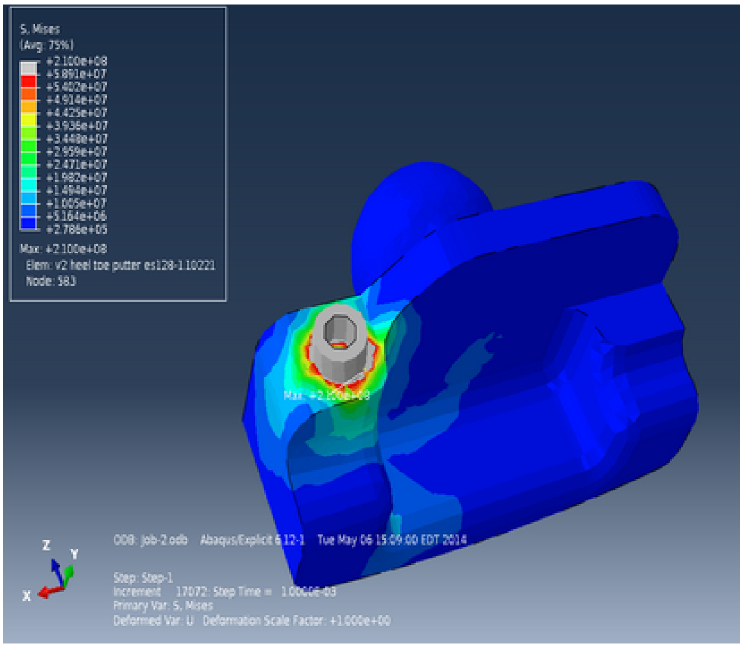
5.1.1 Parametrization

When analysing the putter, three different impact speeds were used separately in order to produce tree different stress/strain results. While the three speeds were above typical values for a shot with a putter, the extreme values were used in order to produce significant stress/strain distributions that could be more easily visualized and analyzed. Furthermore, by parametrizing for three different speeds, a relationship was created between stress values and impact speed, which was found to be nearly linear.

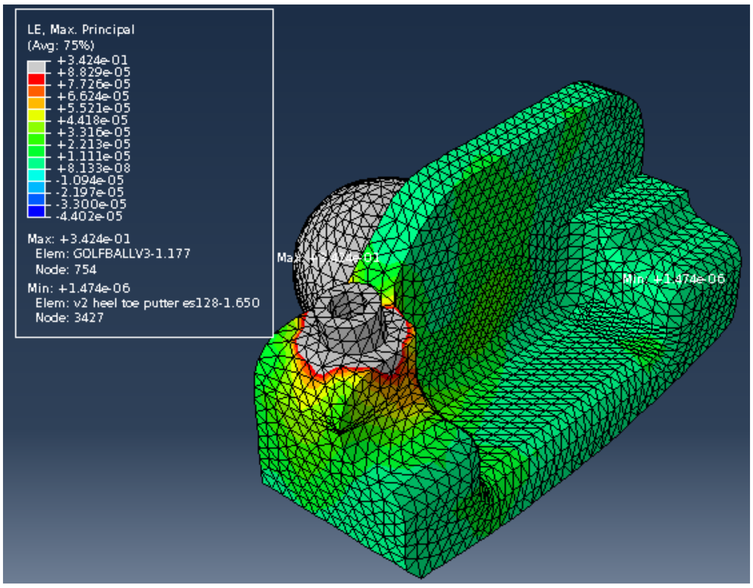
This relationship is particularly useful as it allows for the prediction of stresses for slower, more typical impact speeds a putter would experience. Additionally, it can be reasonably assumed that the other two clubs also exhibit linear relationships between stress and impact speed where the only difference is the slope of each line which is dependent on the relative stress each club experiences which is in turn determined by the differing material properties of each club.



5.1.2 Stress Distribution



5.1.3 Strain Distribution



5.1.4 Overall Design

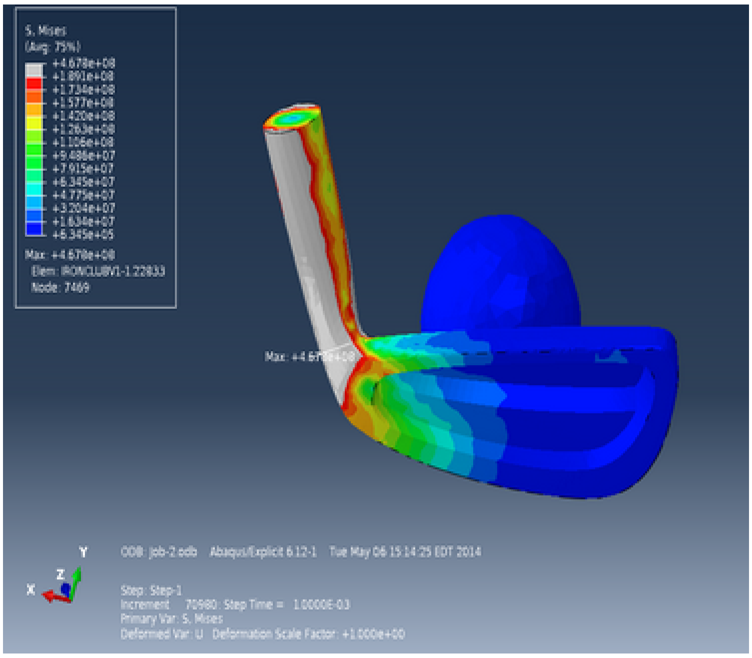
While the stresses experienced by the putter in our model are unrealistic and likely would never occur in a typical game of golf, there are still significant concentrations of stress in the region where the shaft connection is made. This is in contrast to the majority of the putter body that experiences relatively low stresses and is in no danger of failure. However, for all intents an purposes very little consideration needs to be given to structural constraints when designing a putter. Instead, consideration is mainly given to weight distribution of the club such that it is easier to mimic pendulum motion in a swing.

5.1.5 Design Recommendations

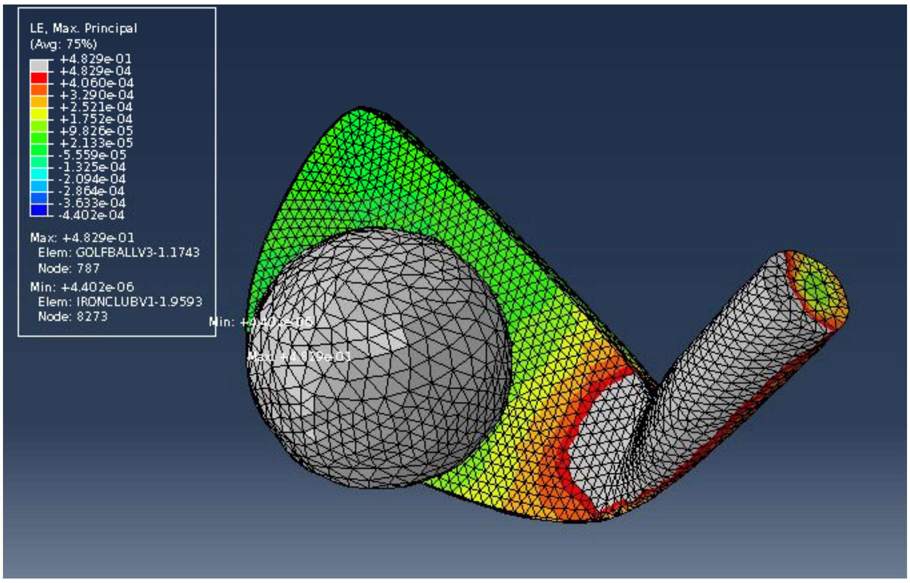
If design recommendations were to be made for the putter experience high velocity impacts with the golf ball the two main suggestions would be to add material to the area surrounding the shaft connection and to the eliminate the extruded hollow cylinder that holds part of the shaft. This extruded hollow cylinder experiences the greatest concentrations of stress to due its relatively small amounts of material that exist to distribute the stress. Instead, the shaft should simply be placed directly into the body of the putter.

5.2 7-Iron

5.2.1 Stress Distribution



5.2.2 Strain Distribution



5.2.3 Overall Design

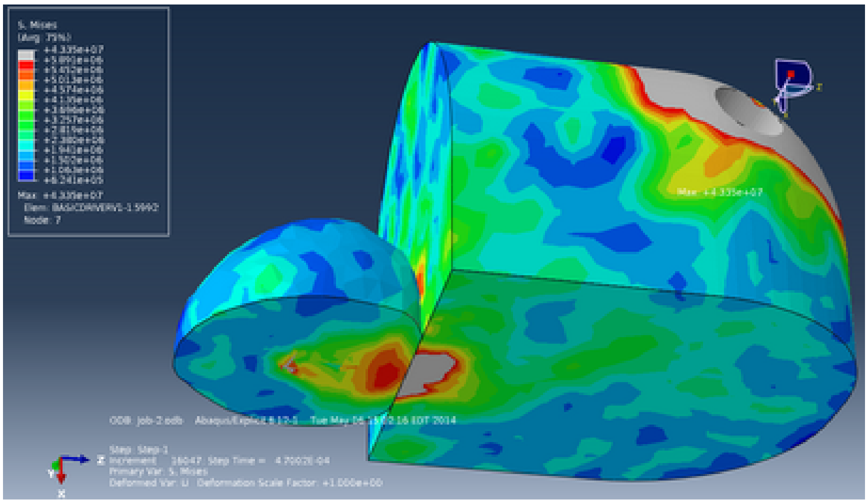
Our results showed us the the Titleist 7-Iron model is a very sound design and this makes sense because the design is modeled after a real modern golf club. Our results show us that failure will occur at the connection between the shaft of the club and the head of the club. This club is also probably the easiest to repair because when the head flies off during failure, it can easily be reattached using appoxy.

5.2.4 Design Recommendations

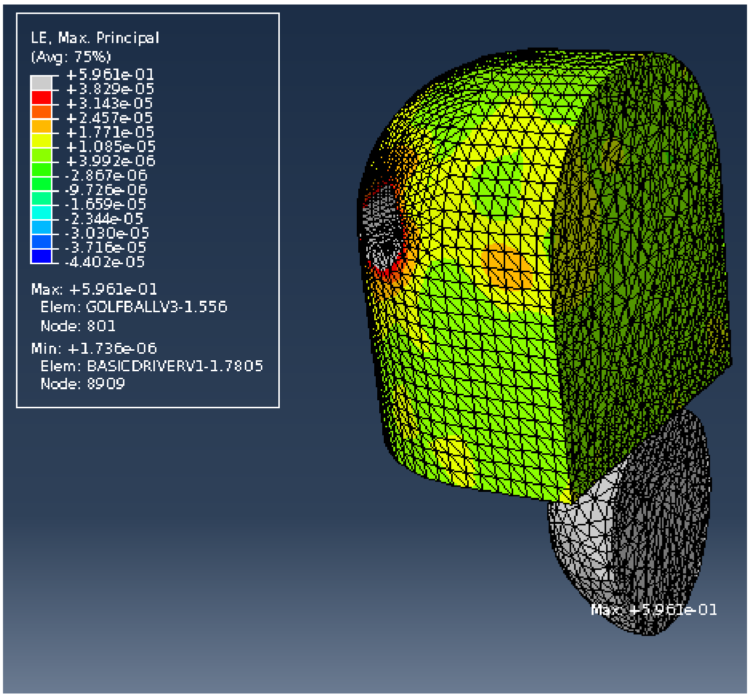
The Titleist 7-Iron model is a sound design and we do not have any recommendations to improve the model.

5.3 Driver

5.3.1 Stress Distribution



5.3.2 Strain Distribution



5.3.3 Overall Design

As you can see from the above figures, the design for this club is over-strengthened. There is a lot of redundant material all throughout the club and you can see that the stress everywhere is very low compared to Titanium's yield strength of 228 MPa and ultimate strength of 359 MPa. This is a result of the simplification and assumption we made previously in order to avoid the "Funny points" issue. From this we conclude that the overall design is strong although not efficient. It will work for impact speeds much larger than any human's swing which obviously is not a necessary atribute.

5.3.4 Design Recommendations

From these conclusions we would recommend to remove some of this redundant material from the back of the club or from a layer at the top. We would also recommend to make the junction between shaft and the club a little more smooth in order to avoid some of the stress concentration seen. From

6 Conclusion

Our analysis of our various clubs, both created as well as imported, proved that the use of Finite Element Analysis is a valuable method when creating lighter and stronger equipment. Finite Element Analysis allows engineers to virtually test equipment without actually creating the material, making the whole process very cost beneficial. With the continued use of Finite Element Analysis, the sport of golf will continue to see improvements in a golfer's performance all around the course.

7 Appendix w/ Links to Files

Please find all of the CAE files for this project at:
`http://people.seas.harvard.edu/~fernandes/DOC/ES128_CAE_FILES.zip`

The Final presentation for this project can be found at:
`https://docs.google.com/presentation/d/1ux7SKZ9ln1kp9M1bpWxxrFMZmW--1v_xOYS4YKXalUQ/edit?usp=sharing`