Finite Element Analysis of a Golf Driver and Golf Ball

Abstract: This paper performs a theoretical stress and frequency analysis of both a 2D and 3D golf driver head as well as a 2D analysis of a two part golf ball. The finite element model of the golf club and golf ball were created using ABAQUS. Frequency and stress analysis were performed on the structures to determine natural harmonics and the stress waves produced on impact. Theoretical conclusions are determined from the values obtained validating the models and proving them useful for future designs.

Keywords: Finite element analysis, stress waves, golf ball, golf club wood driver

1.   Introduction

The popularity of golf is currently on the rise. No longer is golf viewed as a game for old people, but as a sport embraced by young and old alike. Golf currently holds the record for the highest endorsement paid athlete in the world, Tiger Woods.

With the high endorsement deals and the upswing in participation, developing drivers and balls to out perform the competition is in high demand. Golf clubs evolved from the simple pieces of wood and iron used in Scotland in the 1450s to maple head steel shaft clubs of the 20th century to eventually the standard titanium driver we find today in many Pro shops. In less then 100 years, the shooting range of a professional golfer has increased from 200 yards to 400 yards.[1]

The golf industry has recently started testing equipment designs using Finite Element methods. This method greatly reduces cost while also improving the design capabilities of the engineer. Engineers can quickly enter in swingspeed, head loaf angle, head mass, center of gravity and head face material and quickly see the results.[2] Software suites such as MSC. Dytran are being made golf specific in order to provide easy to use FE programming.

In this study, the characterization of the golf club and ball is performed by the ABAQUS 6.5 FEA software. A quantitative analysis of the natural frequencies and stress wave as well as deformation geometry of a golf ball.

This paper adopts the Finite Element Method to perform model verification on the prescribed driver. The theories that are assumed are validated through the use of the method and practical comparisons with real life situations.

2.   Finite Element Analysis

The project has been separated into 3 distinct analyses. The first (1) being a standard load placement on a golf ball, the second (2) being a frequency analysis between a golf ball and two distinct driver configurations and the third (3) being an impact analysis on both a 2D and a 3D driver paying close attention to the phenomena known as the "trampoline effect."

- Golf Ball Load

During this analysis, I sought to determine the deformation placed on a golf ball due to impact from a driver. The tee shot requires the most force in golf and slow motion cameras have witnessed the golf ball deform under these loads.

Figure 1 Golf Ball Impact

The golf ball was modeled as a 2 piece type; an outer Ionomer resin and an inner core of Butadien Rubber (Fig. 2). The properties of the material are given in Table 1. The ball was made with 1600 4-sided elements made through shell meshing. The material properties were applied through partitioning the outer and inner radiuses of the model.

The ball was loaded statically with a load of 15000 N which is an average load put on a ball. The ball was dived into 8 equally spaced regions and a surface traction force was applied on the lower left hand corner i.e. 180˚ to 225˚ taking the +x direction as 0˚. The boundary conditions were placed 180 degree from that i.e. 0˚ to 45˚ where the surface was pinned. The reason for this was in order to apply the static load.

This analysis assumed that the ball behaved as a linear elastic material. This assumption is considered satisfactory model for characterizing the ball.[3] Attempts were made to characterize the ball as viscoelastic but these values were not available since certain journals were not available at Harvard.
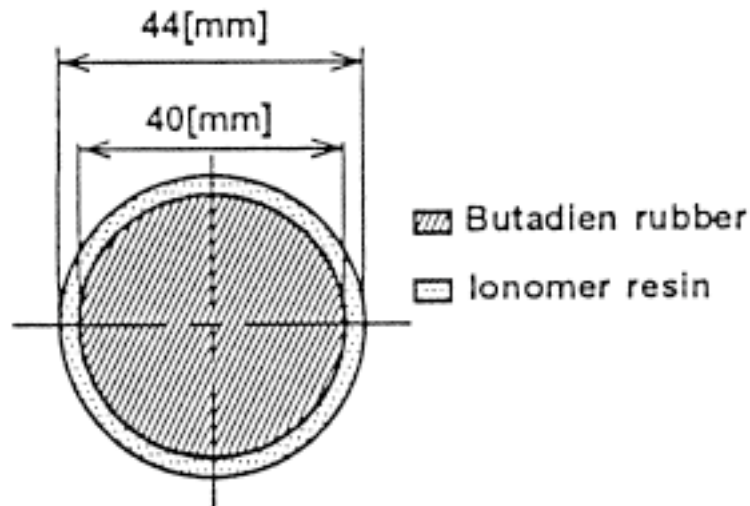
Figure 2 Golf Ball[3]

- Natural Frequency

The second part of the experiment dealt with determining the difference between hollow and solid golf driver heads. The sweet spot of the club is determined by the waves propagating through the shaft after it comes in contact with the ball.[4] By lowering the natural frequency, we can lower the discomfort felt by players hitting the ball. The analysis was done on two (2) 2D clubs, one being hollow and one being solid. The heads of the drivers were each meshed with 169 elements for the solid driver and 171 elements for the hollow driver. The golf ball was constructed of 124 elements in order to allow quicker calculations. For the purpose of this analysis we neglected the shaft since it we were only comparing the two.

For the purpose of this analysis, boundary conditions were put surrounding the ball and the boundary conditions for the driver were placed at the top where it would be connected to the shaft. The simulation was then run.

The material was assumed to be titanium compound (Ti-6Al-4V) and its properties are given in table 1.

Material	Youngs Moduls (GN/m^2)	Poissons Modulus	Density (kg/m^3)	Note
Butadien Rubber	0.0392	0.45	1150	Inner Core of Golf Ball
Iononer Resin	0.294	0.4	950	Outer Core of Golf Ball
Ti-6Al-4V	118	0.34	4507	Standard Driver Head Material
Carbon Fiber	17.2	0.31	1545	Standard of Shaft Material

Table 1

- Stress Analysis

   The final part was a placement of stress at different locations on both a 2D and 3D model of a driver head while changing between a hollow and solid driver head. The load was placed in as a traction to the surface for the 2D case and a circle of diameter 25 mm for the 3D case. The model was made with roughly 4000 elements with a circular traction stress placed on it and the magnitude of the traction pointing orthogonally to the surface.

   In the 3D case, three (3) points were examined to determine stress wave propagations in the driver head. The magnitude of the force acting on the face was analyzed and compared between cases. The trampoline effect was also analyzed the center loading case.

   The 2D case had the same amount of elements as the previous 2D study. The boundary condition was a pinned upper part (where the shaft would be inserted) and the bottom part parallel to the ground, which was stabilized in the XY direction since most of the inserts are placed to reinforce it and make it rigid. It was allowed to rotate.

   In the 3D case, a solid and an empty head were loaded. A corner of the shaft was pinned in order to represent the head being connected to the shaft. The bottom is again pinned in the XYZ directions due to the assumption of a rigid insert. The meshed units of the solid and the hollowed driver head were given by 6806 and 3906, respectively.

3.   Results and Discussion

- Golf Ball Loading

   The loading was used to explain the stress and the strain propagations in the impact of a golf ball that occurs during the .5 ms impulse. The ball deforms and produces a body wave going through the center of the ball.

   The exterior layer, being softer then the interior helps soften the impact the golfer feels. The core, being a harder material, allows for more energy from the golf club to be transferred to the golf ball at impact. This means the two piece ball deforms less during impact from the club than a one piece ball deforms and therefore conserves more of the energy from the club. The one piece ball can easily be imagines by neglecting the outer thin surface.[5] The fact that the compression differences is noticeable between materials validates the structure.
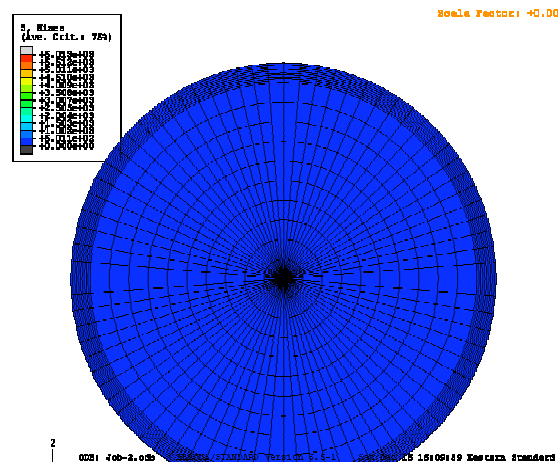
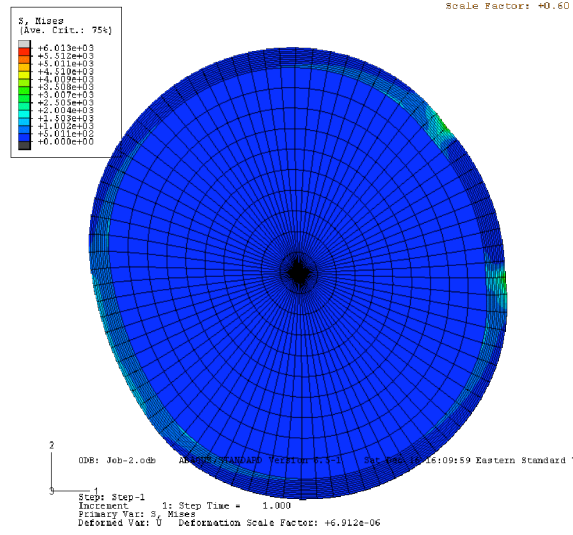**Figure 3 Initial Condition of Golf Ball**
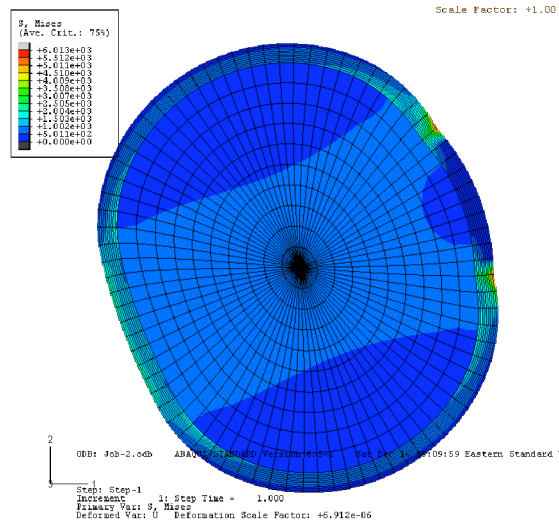

Figure 4 Stress at15000N at half time

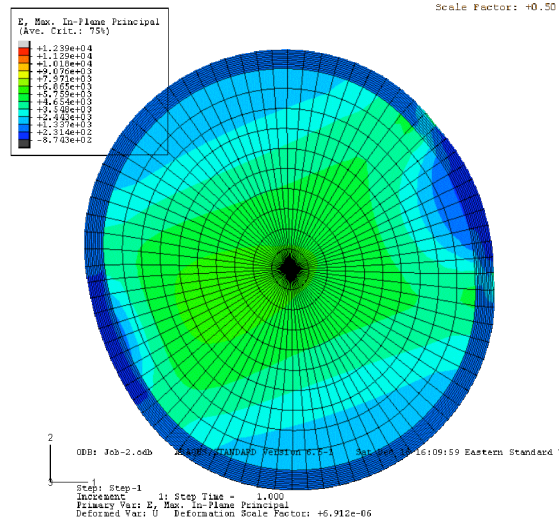**Figure 5 Stress at 15000N at full load**
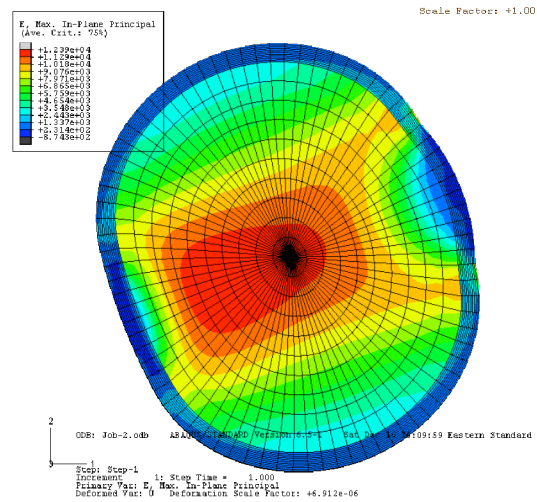
Figure 6 Strain Propagation half

Figure 7 Strain Propagation (full)

- Natural Frequency Measurement

Figures 9 and 11 show the difference in the natural frequency between a hollow head club and that of a solid club. The frequency difference shows that the hollow club has a lower natural frequency and therefore a closer match to those of the golf ball, which is imaged below. By matching frequencies, a driver transfer its energy better during impact and provide a better drive. Research is currently being done in order to tune golf balls to

certain clubs in order to maximize the properties between different clubs and different balls.[6]

The values of the fundamental frequency measurements are given in the table below.

Object	Fundamental Frequency (s^-1)
Golf Ball	0.00935
Solid Head	0.22367
Empty Head	0.00895

Table 2 Natural Frequency Values
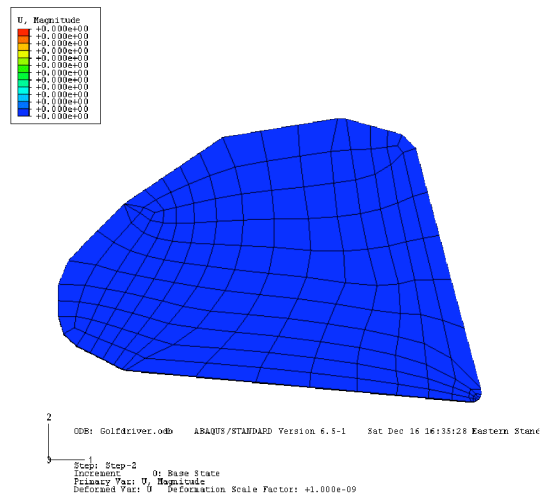
Figure 8 Initial Condition
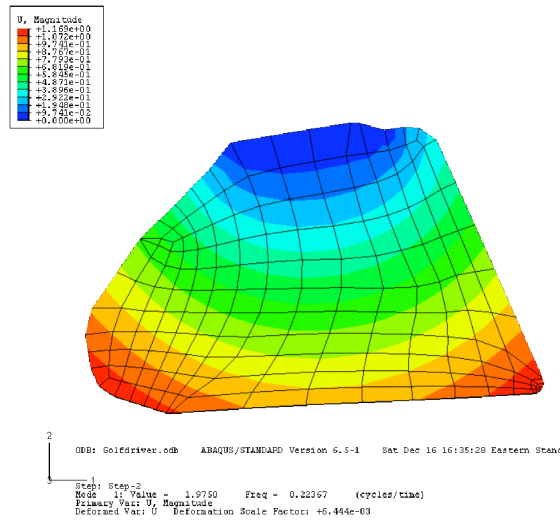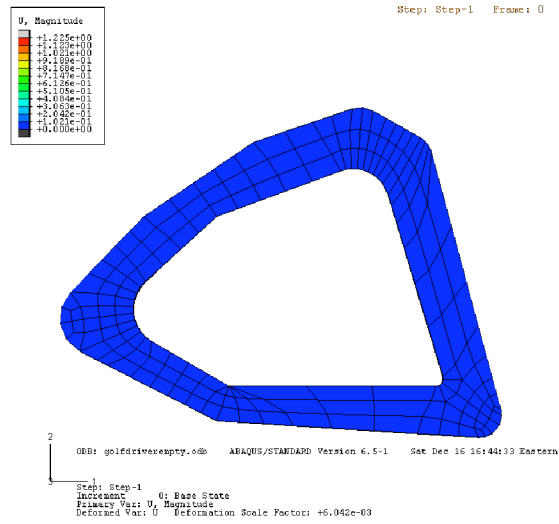

Figure 9 Natural Frequency of Solid 2D Driver

Figure 10 Initial Condition of Hollow 2D driver

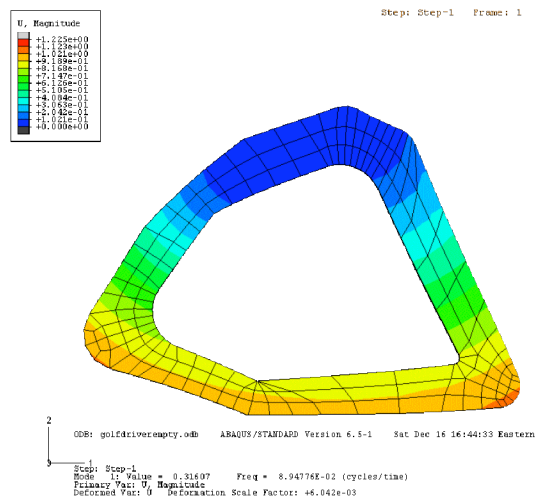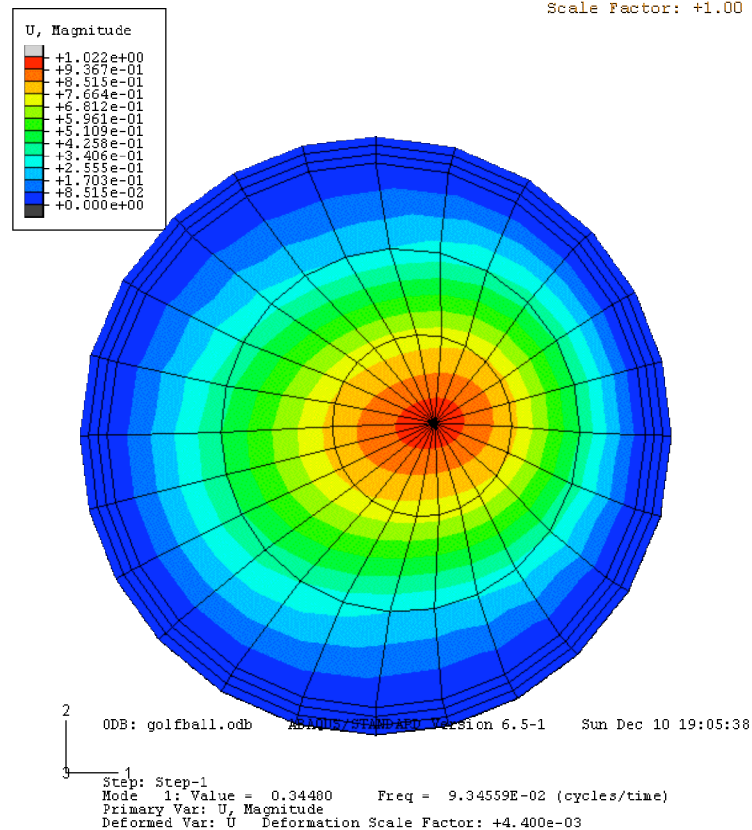**Figure 11 Natural Frequency of Hollow 2D Driver**

U, Magnitude
+1.022e+00
+9.367e-01
+8.515e-01
+7.664e-01
+6.812e-01
+5.961e-01
+5.109e-01
+4.258e-01
+3.406e-01
+2.555e-01
+1.703e-01
+8.515e-02
+0.000e+00

Scale Factor: +1.00

ODB: golfball.odb   ABAQUS/STANDARD Version 6.5-1   Sun Dec 10 19:05:38

Step: Step-1
Mode   1: Value =   0.34480   Freq =   9.34559E-02 (cycles/time)
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +4.400e-03

Figure 12 Natural frequency of Golf Ball

- Force loading on 2D and 3D Driver Designs

The first aspect of this analysis is that on the sweet spot of the club head.   In most analysis, the sweat spot is characterized as the point of contact where the golfer feels the least amount of vibrations.[7] These vibrations are generated by the propagation of the stress waves caused by impact through the shaft. The shaft and the club each have a separate natural frequency. The golf driver can be thought of as a cantilever beam with a weight attached to it at the far end and pinned at the other. The head is excited and propagates the wave through the shaft into the golfers hands.

This analysis shows that ideally, the golfer should hit the ball in the center of the driver since then the stress waves will not be reflected off the sides of the driver and causing higher vibrations. This is easily seen in the images where the waves are dissipated symmetrically in the center case but in the side loading cases, reflect off the boundary and will form interference and high vibrational modes.

The next analysis of this structure is the difference between the hollow and the solid driver head. For the sake of this analysis, the center loads shall be taken into account. It can be seen that the empty case exhibits more of a deflection in the center then the solid

as one would expect (both in the 2D and the 3D.) The impact this has is known as the "trampoline effect" which has been the center of much controversy in recent years.

The trampoline effect is a well-known phenomena in hollow drivers. The thin metal shell compresses during the collision with the ball and springs back resulting in much less loss of energy and therefore a higher ball speed. In the solid, this does not occur so readily and much of the energy is lost in the collision.[8] When the ball contacts the driver, it will compress less than it does when colliding with a rigid surface, and will turn to its original shape much quicker. This will allow for the golf ball, which acts as a visco-elastic material, return to its original shape faster and have a faster velocity off the driver thus equaling a farther drive.
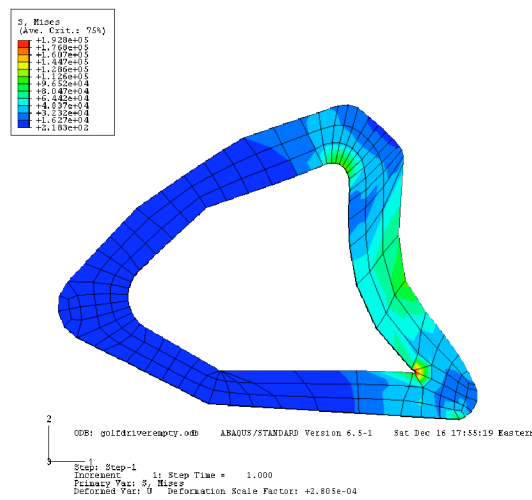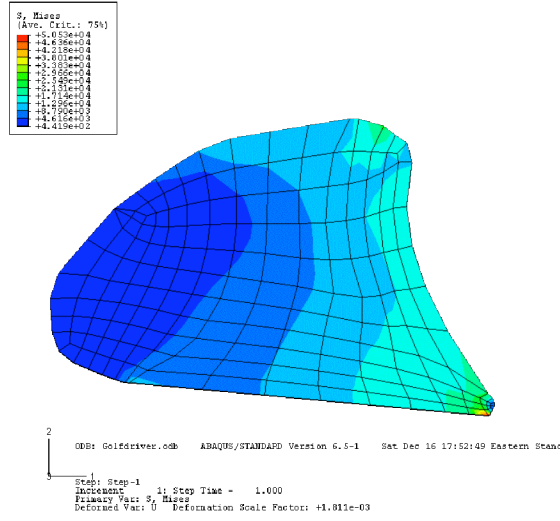

Figure 13 Surface Traction on Hollow 2D driver

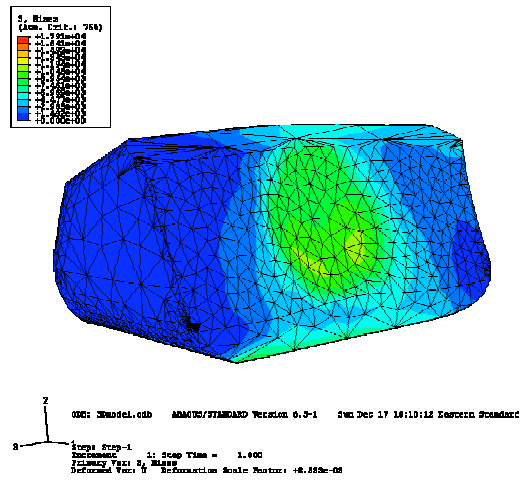**Figure 14 Surface Traction on Solid 2D Driver**

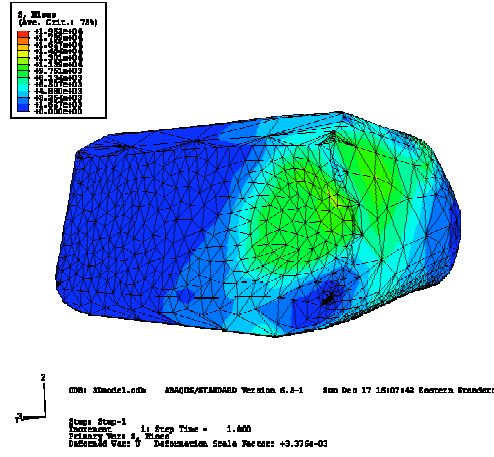**Figure 15 Center Stress on 3D Solid Driver**

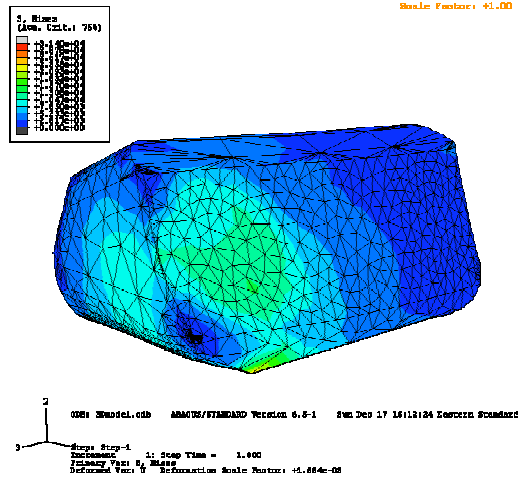**Figure 16 Stress on Shaft Side of Driver**

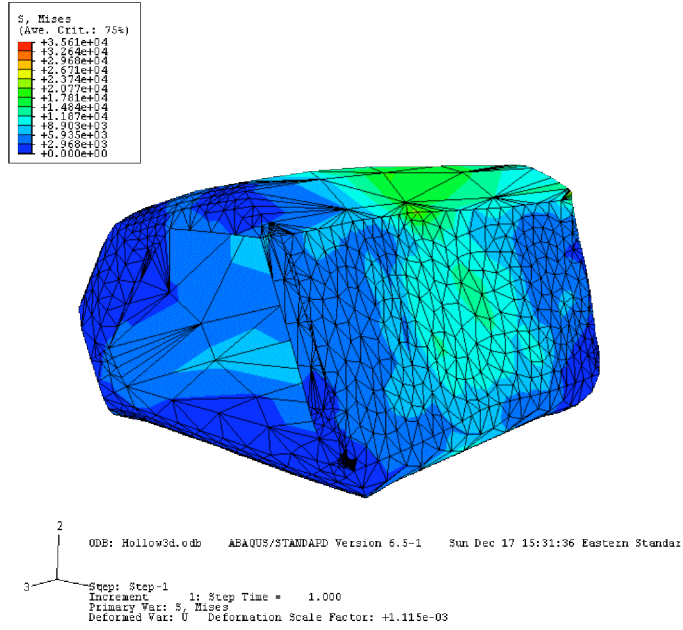**Figure 17 Stress on Far Side of Driver**

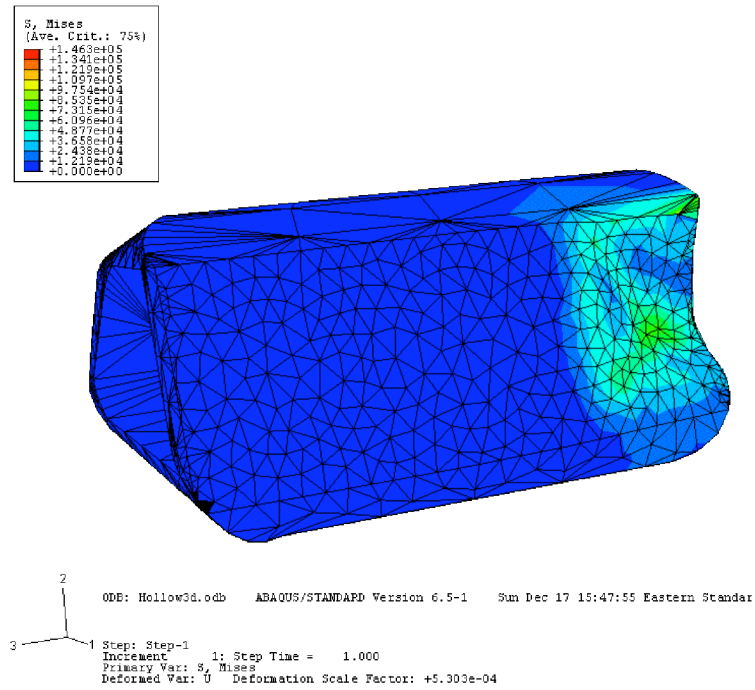**Figure 18 Center load on 3D hollow Driver**

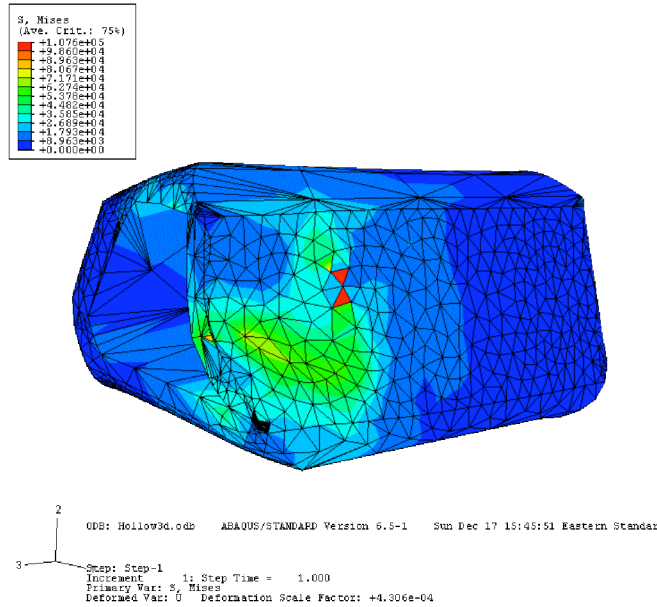**Figure 19 Shaft Side Load on 3D Hollow Driver**

Figure 20 Far Side Stress on 3D Hollow Driver

In looking at the drivers, it is a little misleading in comparing the colors since each has a separate scale with respect to the deformation scale factor. The values for the stresses of the center impact are given in table 3.

Object	Center Stress
Hollow	11,870
Solid	8,806

Table 3 Approximate Stresses at Center

The values displayed are given in pascals. This shows that the golf club is stressed more in the hollow case allowing it to spring back stronger and thus allowing for the trampoline effect to occur. The body is only elastically deforming so it will spring back and release the energy into the ball producing a better drive.

4. Recommendation for Further Works

This analysis was an introduction to the workings of ABAQUS and raises many issues that could be addressed in there own publications. Many of the shortcomings of the analysis lay in the inability to obtain proper meshing of my 3D driver design. It would mesh but the job would not run. With this solved, many more questions can be answered pertaining to a fully 3D driver. The failed 3D structure is given below.
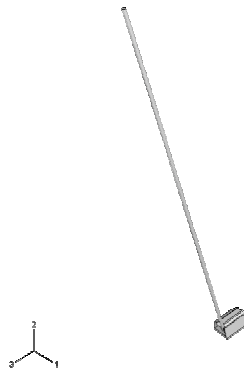
Figure 21 Failed Mesh 3D structure

Another shortcoming of this paper, which should be addressed in subsequent publications is the velocity and impact of the driver and ball on each other. Since I do not have much experience programming in ABAQUS, it was difficult to place dynamic loads on the structures and to deal with interaction parameters. This type of analysis would allow for more realistic results.

5. Conclusion

The analysis proved that Finite Element Analysis can be a viable method to design golf clubs and proves to be very effective with respect to energy transfer and stress wave propagations. The tool will surely revolutionize the way clubs are designed and will lead to farther drives and more accurate playing. This project validated assumptions that were currently being used in the design of golf clubs and golf balls.
This work was a first attempt at using ABAQUS as an analysis tool so faults and invalid assumptions may be present.

6. Acknowledgements

I would like to acknowledge Professor Suo for his guidance in Solid Mechanics through out this semester. I would like to thank Nanshu Lu and Xuanhe Zhao for there help in ABAQUS and showing me the tricks a beginner should know.

7. References

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[5] Josh Fritts. The physics of Golf
[6] Axe et al. The Vibrational mode structure of a golf ball.
[7] Hocknell et al. Hollow Golf Club Head Modal Characteristics: Determination and Impact Applications.
[8] Alan Nathan. The physics of Baseball