Baseball Bat Swing Analysis Using Finite Element Methods

Chaemoon Lee, Ruthie Sellers, Yong Hau Boo, Dr. Roberto Cammino, Dr. Aiman Shibli

Illinois Institute of Technology, Chicago, Il.

Abstract: This paper builds on previous undergraduate research done on the analysis of a baseball bunt. In that situation the bat was held stationary, while the ball was launched at a given velocity. In this research, the bat is allowed to swing with the swinging motion controlled by the user. The end result is a determination of the optimal position to hit a ball during a bat swing on an approaching ball as well as the optimal swing pattern. The ball's exit velocity and direction is obtained after the impact with the bat. The results will not only show the direction the ball will travel, but how far it will travel as well. Bat stresses are also determined for each impact. For simulation purposes the ball was designed to have material properties similar to that of the official ball used in Major League Baseball, while the bat was designed specifically to use the material white ash wood and aluminum. The bat was also designed to have a rigid grip. The primary goal of this research was to show the advantages of utilizing finite element analysis applications in sports. The results will show that accurate results can be attained if the simulations mimic that of the real case. In this manner, guidance can be provided to players on the optimal swing pattern to apply for different approaching ball launches. All simulations are run using Abaqus/Explicit.

Keywords: Abaqus/Explicit, Baseball, Exit Velocity, Finite Element Analysis

1. Introduction

Argued one of the best sports to see live and play; baseball has long been considered a favorite sport by many. Major League Baseball (MLB) is North America's highest level of play, where players can be seen every summer competing for a spot at the coveted World Series, in which one team will be crowned the best for that year. The major premise behind the game is to score runs. To score runs a team must hit the ball and the farther the ball is hit, the more likely the hitter can get to a base and thus score a run. ("Official Rules", n.d)

There are many elements to consider when hitting the ball. These include vibrations, maximizing exit velocity, minimizing stress, and impact positions. A baseball bat exhibits flexural bending modes depending on the material properties, weight, length, and contour of the bat. (Russel, 2012) Previous research has shown that every bat has an ideal impact position approximately seven inches from the edge of the bat that doesn't vibrate, called a node. (Cross, 1998) The node is generally considered where the sweet spot is. This is also where the bat does not bend or vibrate. (Cross, 1998) Typically the bat vibrates when struck by the ball. When it is struck, it utilizes energy and the more energy the bat utilizes, the less energy is transferred to the ball, the less energy transferred to the ball the slower it travels. The more energy that is transferred to the ball, the faster and farther it goes. (Phallon, 2002) There is about a two-inch range that is ideal for impact. (Cross, 1998) If an impact occurs in that range it's not going to excite that bending pattern, thus maximizing the exit velocity of the ball. Knowing the ideal impact positions, a player can consistently hit the ball farther and increase chances of getting a run.

One of the aims of this work was to study in detail the variations in the exit velocity and stress with respect to the impact location of the ball on the bat. Finite Element Modeling was used as an approach to analyze the exit velocity of the ball and stress at the grip of the bat. Six situations with various impact positions of the ball were considered and simulated. In this case, a typical swing angular velocity is applied, but this can be varied further to determine the effect of different swing parameters as well. Abaqus/Explicit lends itself very well in allowing these types of simulations to be run, given its versatility in applying prescribed rotation angle over time functions to the bat. This is normally data that can be measured experimentally, allowing to further use this work in conjunction with experimentation.

2. Methods

2.1 Material

Finite element models of the aluminum bat, wood bat, and ball were built from profiling measurements. The mesh for the bat consisted of tetrahedral meshes. Ash wood and aluminum were the materials of choice for the bat. Similar to the one used in MLB, cork (the core of the ball), leather (the outside layer of the ball), and wool (center layer in the ball) were the components of the multi-layer baseball as shown in Figure 1. ("Official Rules", n.d.) Both the bat and ball were modeled as purely linear elastic and isotropic materials, because the model was assumed to be perfectly elastic and have mechanical properties that were the same in all directions.

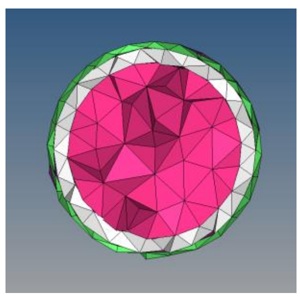

Figure 1. Baseball material layers.

Before the model could be used for impact simulation, the material properties of the bat and ball were obtained to not only ensure accurate results from the analysis but to ensure the FE simulation closely represented that of actual bat swing. The material properties for the bat and ball are shown in Tables 1 and 2 respectively.

In addition, a rigid handle is modeled at the area of the bat that is typically held by the players. The rigid handle is controlled through a reference node at which rotational speed and translational speed profiles can be applied to mimic the actual player's impact. These can be easily optimized to result in further optimized hits and then players can be trained to hit based on these findings, rather than intuition.

Table 1. Bat material properties.

Material	Density (g/mm^3)	Young's Modulus (MPa)	Poisson's Ratio
Ash Wood	6.5e-4	12000	0.059
Aluminum	27e-4	69000	0.33

Table 2. Baseball material properties.

Material	Density (g/mm^3)	Young's Modulus (MPa)	Poisson's Ratio
Cork	8.811e-4	40	0
Leather	9.98e-4	200	0.4
Wool	1.05e-4	100	0

2.2 Impact Simulation

As shown in Figure 2, six random hitting positions were simulated, where the ball was moving at 41.13 mm/ms (92 mph) toward a bat moving at 31.29 mm/ms (70 mph). The swing motion was analyzed over a 15ms time frame around the moment of impact. The time from the initial start to the moment of impact was analyzed starting at the time frame from 0 to 10ms. The post-swing motion was analyzed over the next 5ms interval. The entire motion was idealized by simplifying the swing pattern from a 3D motion to a 2D planar motion to reduce computational time.

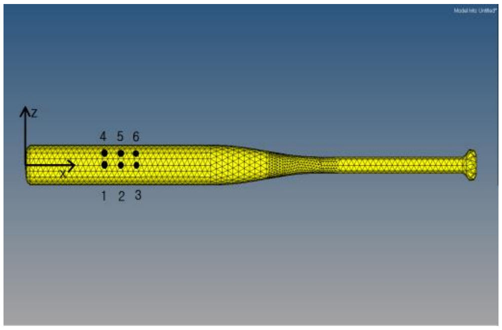

Figure 2. Impact positions.

Table 3 shows the x, y, z coordinates of the impact positions with respect to the edge of the bat as shown Figure 2. The dimensions in the x direction are measured from the left origin. The Dimensions in the y and z directions are measured from the center.

Table 3. Bat impact position.

Impact	x (mm)	y (mm)	z (mm)
Position 1	152.4	0	0
Position 2	177.8	0	0
Position 3	203.2	0	0
Position 4	152.4	11.3	37.2
Position 5	177.8	11.3	37.2
Position 6	203.2	11.3	37.2

3. Results

Table 4 shows the magnitude of the ball's exit speed at each position. It can be seen from the table, that the aluminum bat has the fastest exit speed. It can also be seen that position's 1, 2, and 3 have faster exit speeds than position's 4, 5, and 6.

Table 4. Ball exit velocity.

Position	Exit Velocity [m/s]	
	Ash wood	Aluminum
1	77.7	90.2
2	74.7	91.4
3	69.5	86.4
4	62.2	84.6
5	60.6	76.0
6	64.0	77.2

Due to the swing motion and the effect of gravity on the model, the speed of the ball was considered as a 3 dimensional vector to understand the actual movement of the ball. Table 5 depicts the speed in each direction. It can be clearly seen that the speed in the y-direction is fastest, since several speeds in the x and z-directions have both positive and negative signs, to determine the direction of the ball. The data in Table 5 also suggest for positions 1, 2, and 3, the ball moves directly to the ground, but the ball can travel into the sky at positions 4, 5, and 6.

Table 5. Ball directional exit speed.

Position	Speed [m/s]					
	Ash wood			Aluminum		
	x	y	z	x	y	z
1	-3.6	77.6	-0.4	16.8	88.6	-3.2
2	-1.6	74.6	-3.0	-0.4	91.4	-2.2
3	-4.2	69.0	-7.0	-0.4	86.2	-5.5
4	7.3	44.1	43.2	8.0	64.9	53.6
5	7.0	42.1	43.1	8.3	57.9	48.5
6	-6.2	46.3	43.8	-9.1	59.1	48.8

Table 6 shows the displacement of the ball from impact up until the ball hits the ground. For cases 1, 2, and 3, the ball traveled in a downward trajectory towards the ground, similar to an infield grounder; however, when the ball hit the upper point of the centerline, the ball travels over 300m. For this trajectory calculation, the BEV (ball exit velocity) is used as the initial velocity. All other factors were ignored such as wind and different heights of baseball stadiums.

Table 6. Estimated ball displacement.

Position	Displacement [m]			
	Ash wood		Aluminum	
	x	y	x	y
1	-1.3	28.2	3.2	17.1
2	-0.3	15.1	-0.1	21.8
3	-0.4	7.4	-0.3	11.2
4	64.0	388.4	87.5	709.1
5	61.5	369.7	82.1	572.6
6	-55.8	413.3	-90.4	588.4

Table 7 depicts the maximum stress of the bat at the moment of impact and Table 8 depicts the maximum stress post impact from 10ms to 10.5ms. It can be seen from tables 7 and 8, the stress analysis on the bat show different trends for each material. In the case of the ash wood bat, the highest stress on the bat is at position's 3 and 6; the closest positions from the center of swing. However, for the aluminum bat the same position has smallest maximum stress.

Table 7. Maximum stress at moment of impact.

Position	Max Stress [MPa]	
	Ash wood	Aluminum
1	10.83	196.2
2	8.257	191.3
3	16.34	117.4
4	11.12	257.7
5	9.994	258.8
6	15.09	142.4

In all cases, there were stress propagations from the initial impact. After the impact, the stress on the bat grip continuously changed. Table 8 shows the largest stress values overall on the bat. Similar to table 7, position 3 and 6 had the largest maximum stress values for the ash wood bat; however, the same positions had the smallest values for the aluminum bat.

Table 8. Maximum stress post impact.

Position	Max stress [MPa]	
	Ash wood	Aluminum
1	21.07	283.8
2	21.58	310
3	27.05	148
4	17.49	409.7
5	20.96	459.7
6	26.69	238.8

Further evidence depicting the stress on the bat can be seen in Figures 3 and 4, where several consecutive still frames capturing the swing motion as the bat swings and the ball moves towards the bat are shown. (See Appendix A) It can be seen from these frames the bat experiences some deformation near the grip area through out the swing, but experiences the greatest at the moment of impact as shown by the stress contours in the last frame. It can also be seen by the stress contours, leading up to impact that some energy is stored in the bat as it bends and deforms. Abaqus/CAE is very easy to use and allows for a quick evaluation of all results and presentation of results.

4. Analysis and Discussion

The exit velocity shows that the difference of material and position could affect the velocity of the ball. Generally, the aluminum bat had faster exit velocities than the ash wood bat and positions 1, 2, and 3 had faster exit speeds than position 4 and 6. This is expected because the center of the ball is hit along the center of the bat at these positions, thus minimum energy loss during impact.

Each component of the velocity led the direction of the ball's movement. Positions 1 to 3 could possibly result in an infield grounder but after impact with the ground, it is difficult to predict the motion of the ball because of the likelihood of an uneven ground, effects of grass, etc. For positions 4 through 6, the results show ideal ball trajectory. In particular the data in table 6 suggest reasons why professional players do not use aluminum bats. It can be weird that the distance is much longer than the real situation, the reason is only the initial speed is used to estimate the flying distance in this calculation. When the ball speed is calculated, both initial speed and the final speed are measured and the special equation with some constants, that is how the average ball speed is measured, but in this case, there is no way to get some constant for the equation, and the running time for the input file was more than 6 hours for each case, which is 15ms analysis. Thus, there was no chance to run the motion analysis until the ball hit the ground.

The stress comparison table shows that the stress at the moment of impact had large differences by material. Additionally each material had different areas where the smallest maximum stress on the bat was located. The stress propagation was shown on table 8. After the impact, the stress propagation continued on causing higher stress values than those at impact. These values suggested that there were super-positions of stress waves. These high stress values were located between the grip and the neck of the bat. These high values further confirm why bats are often broken during real baseball games.

The swing simulation shown in figures 3 and 4 correlates previous findings, further confirming when the ball collides with the bat, some energy is stored in the bat as it deforms due to impact. (Phallon, 2002) From this it can be concluded that the amount of energy stored in the bat and how it is transferred back to the baseball contributes to the exit velocity of the ball.

Compared with the bent motion analysis, this dynamic bunt motion analysis can show the entire motion of the baseball after the hitting point. Also, it is able to estimate a flying distance, which is really hard to get estimated distance from 2D motion analysis, by using the exit speed. Even though the set up time is less than 5hours since I understand this problem, I was not able to run the entire swing motion because of not enough time for each case, even I just had analysis for 15ms but it took more than 50 hours to finish the all the analysis when the inp file was fully developed.

5. Conclusion

This research has proven a Finite Element Model can simulate a real sports event. Abaqus/Explicit was critical in solving this problem. The model can estimate the ball's exit velocity, the ball's trajectory, and how far the ball will travel when hit at various positions on a bat. In regards to the swing motion, the results show that 1-inch can cause a huge difference in the ball's movement and in the stress on the bat at the grip. It also shows how the energy stored in the bat from impact is transferred to the ball. The Finite Element Model provides an excellent alternative to investigating not only material properties of the bat, but determining the best bat swinging techniques for batters on the baseball field.

6. References

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7. Appendix

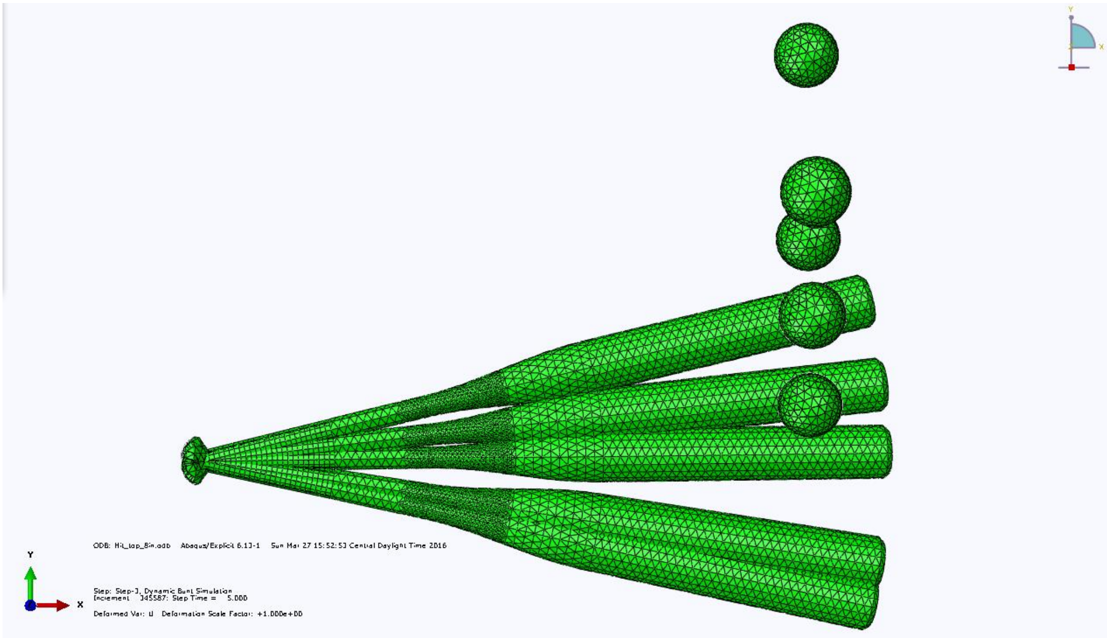

Figure 3. Swing simulation in x-y plane.

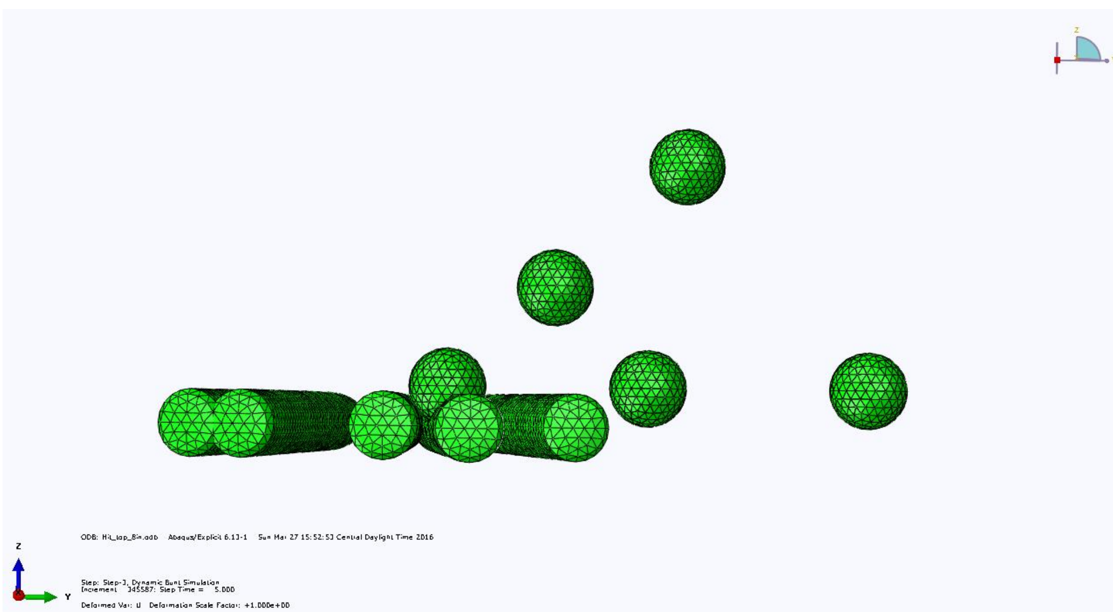

Figure 4. Swing simulation planar motion in y-z plane.