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Numerical Analysis of Bat-Ball Collision Performance in Cricket

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***Abstract*—** Experimental tests in the case of bat performance in some sports like baseball and cricket is costly and tedious. In this paper a three dimensional modeling of ball and bat is generated and computational finite element method used to predict the performance of baseball bat. This could be useful for bat designers to use from these results achieved by computational soft wares in order to reduce cost and time spending. A finite element modeling is done in software ANSYS/LSDYNA version 971 R.4.2 that is used to explicit dynamic problems. The ball is created by viscoelastic material and using an orthotropic material for baseball bat the ball exit velocity should be then quantified. Performing modal analysis to bat, the region indicated between first and second fundamental modes of vibration and where the ball has maximum exit velocity is compared. The results will be shown graphically in the case of stress exerted to the bat and modal analysis in transient mode, and graphs will show the ball exit velocity for six different points on bat as the contact locations.

***Keywords*—** Collision Performance, Bat-Ball, Cricket, Finite Element Method, LSDYNA

I. Introduction

BALL exit velocity (BEV) is an important quantity related both to offensive production by the batter (such as home runs), and also to the risk of ball-impact injury to defensive players. Bat performance is tested experimentally using hitting machines at which bat is rotated in a horizontal plane at 29.3 m/s (66 mph) against a ball dropped at 31.1 m/s (70 mph). The current BEV recommendation of 43.17±0.4 m/s (97.71 mph) is based on the average BEV from a professional-quality wooden bat, (NCAA news release). Such test protocols, however, do not account for important factors in the dynamics of the impact such as bat mass and moment of inertia, and the variation of pre-impact velocities. In this paper, explicit finite element analysis (FEA) was used to approximate the impact response of the ball and the maximum obtainable BEV. In using FEA, the need for simplifications used in previous analysis of bat–ball impact, such as linear elastic material properties and assumptions of planar motion, were obviated. The purpose of this research was therefore to develop a model of bat–ball impact based on the three dimensional kinematics of bat and quantify BEV due to different contact locations on the bat. (See references [1-6])

The impact between bat and ball is the one in which bat exerts a huge force to the ball thereby causing it to change directions and gain speed. The force that the bat exerts on the ball is not constant during contact, but it follows more of a sine-squared time history, starting and ending at zero and peaking approximately half way through the duration of contact. Although this collision maybe considered as one-dimensional only, but n reality, most collisions between bat and ball collisions require a two-dimensional analysis.

Linear momentum is the product of the mass and velocity of an object. If the net force acting on a system of objects is zero then the total momentum of the system is constant. While the bat and ball are in contact, the player is exerting a force on the bat that is the force needed to swing the bat. However, for a completely correct analysis, momentum is not constant because of this force exerted by the player swinging the bat. However, the force on the bat by the player is very much smaller than the forces between bat and ball during the collision, and the contact time between ball and bat is very short (less than one millisecond). Three-dimensional models for bat could be created in modeling soft wares such as CATIA or SOLIDWORKS then input; but here this model was developed for a wooden bat using spline to avoiding discontinuities resulting from stepped cross-sectional properties in LSDYNA. It has total length of 33.25 inch and different diameters as shown in Fig. 1.

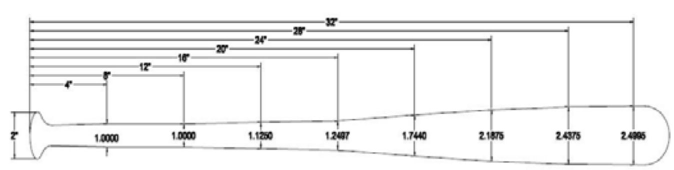

Fig. 1 Dimensions of modeled bat in 2-D

The wooden bat was modeled as a homogeneous solid, and discretized into SOLID186 element. These elements were used to prevent meshing and analysis time problems for contact region, and reasonable accuracy in solution. The reason for choosing this element shape instead of SOLID164 is curvilinear faces exists in mesh. It seems to be suitable for a round shape of bat. Structural mesh has been used for model. These models are assigned to each other in LSDYNA, see reference [7].

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Bodies are 4 mm apart from the other one at the first in order to reduce the computational time for explicit analysis and initial penetration has not defined for LSDYNA too. In this analysis, the baseball was approximated as a homogeneous solid sphere of radius 36 mm, meshed with 2000 SOLID164 hexahedral elements. A linear viscoelastic model was used to account for the time-dependent response of the ball against to impact which follows Eq.1.Properties chosen for material used are presented at Table I according some articles in literatures.

$$G(t) = G_\alpha + (G_0 - G_\alpha)e^{-\beta t} \quad (1)$$

TABLE I
MATERIAL PROPERTIES OF BAT AND BALL

Bat		Ball	
Property	**Value**	**Property**	**Value**
Density	450 (kg/m^3)	Density	150 (kg/m^3)
Elastic Modulus	9.8 (GPa)	Bulh Modulus K	69 (MPa)
Shear Modulus	6.7 (GPa)	Shear Modulus G_0	41 (MPa)
Poisson Ratio	0.3	Shear Modulus G_α	11 (MPa)
		β (Material Constant)	9000

At the impact instant, the diameter of ball considered one fourth of uncompressed mode; so its diameter will be 9 mm at this time. Two approaches are investigated here:

a) Consider bat as a cantilever beam.

b) Consider bat as a free body in the space.

The initial conditions for each case are different in displacements constraint definition for the bat. For case (a), bat should be fixed at the end contacts with batsman's hand; so in nodal solution there is always one node at the fixes end. Nevertheless, for case (b) nodes can be represented freely along the bat. The results will show graphically.

Three considered assumptions to this problem are as follow:

1) Deformation of bat is negligible compared to its overall motion.
2) The duration of collision is much shorter than the time taken for an impulse to propagate to the hitter's hands and back.
3) All material behavior considered linear, if unless, ANSYS will assign this property to the bodies in analysis.

As mentioned in assumption number 2, during a high-speed impact, the ball may be in contact with the bat for as little, say 1ms, therefore, BEV is highly dependent on the linear velocity of the bat impact point, which in turn is affected by the distribution of mass along the long axis of the implement (swing moment of inertia). Results are based on 0.005 sec that involves one millisecond for impact instant only. Initial boundary conditions like velocity, acceleration, displacement are very important for stress and modal analysis. If bat considered as cantilever, the end contacts with hand should be considered fix. In this study, the mass and damping effects of the player's hands were not modeled, with both ends of the bat free to translate and rotate. This assumption was appropriate given the very short impact time (assumption number 2) if the vibrational waves arrive back at the point of impact after the ball has departed, ball motion cannot be affected by how the handle is secured.

To determine maximum BEV, the incident trajectory of the ball supposed to be perpendicular to the point of greatest momentum transfer on the bat. In this analysis, six impact locations on the barrel were simulated. The LSDYNA general surface-to-surface contact algorithm was used, because it is suitable for arbitrarily shaped contact areas with large values of relative sliding. The nodes near by contact area on the bat and ball were designated as contact and target components, respectively. The value for coefficient of friction was determined as 0.2 from the relative velocity of the surfaces in contact, this proved by following the guidelines literatures. Due to the transient nature of the problem, large deformations and nonlinear response during bat–ball impact, explicit FEA procedures were used. The solution time step was automatically determined by LSDYNA from the relative difference in contact surface stiffness between two bodies. The adequacy of meshes for each shape is a critical factor in the accuracy of the FEA solution in this software. If the level of discretization (i.e. the number of degrees of freedom) is too small, the model resolution will be too low to accurately represent the dynamics of the structure. A meshed model is represented in Fig. 2 for bat in 2-D and bodies together in 3-D.

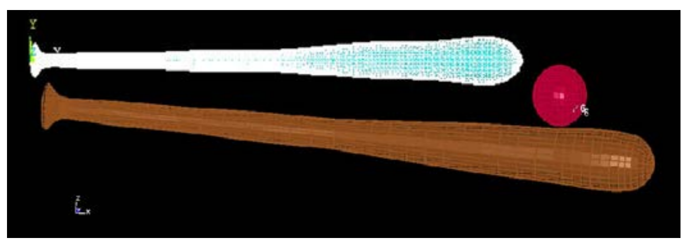


Fig. 2 Representation of meshed model for bat in 2-D and both bodies 4 mm apart in 3-D

II. Modal Analysis

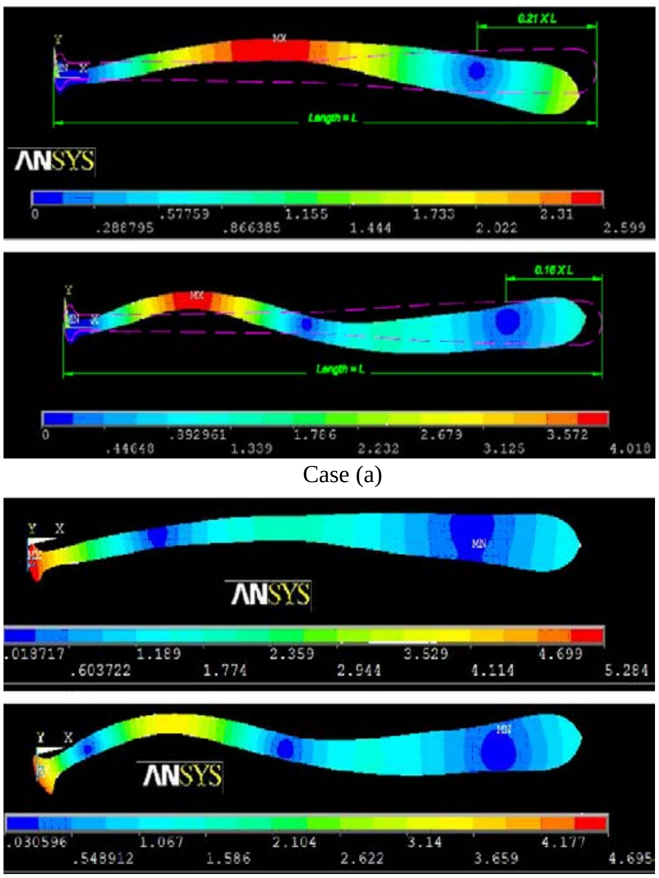
As mentioned before large deformation of bat is neglected for modal analysis. The formulation for this part, referring to ANSYS HELP is as Eq.2.

$$K \times \Phi_i = \lambda_i \times m \times \Phi_i \quad (2)$$

Where Φ_i is displacement vector of nodes, and K is stiffener matrix, m is mass matrix and λ_i said to be specific value that is a constant. This formula is used to buckling calculations. By twice derivation of this equation, modal analysis will be achieved.

Graphically results are shown in Fig. 3. For case (a) in which bat is levered at its knob, this is acceptable that always one node will be at this end because of zero displacement definition initially as boundary condition. Although the two first lateral fundamental frequencies are enough, here vibrations in longitudinal and lateral directions are supposed too. Anyway, just two first are shown.

Stress due to contact appeared on the bat is calculated by LSDYNA but simulated in ANSYS, because of its colorful representation. The two first fundamental frequencies of bat in case (a) are 149.328 and 574.719 respectively. Maximum stress exerted to the bat when exit velocity of ball be the highest. In this problem as shown in the results for BEV graphs, this velocity occurs when contact location is 0.19 of bat length apart from its top. This means if the knob considered as horizontal direction reference then contact location is computed by (Length of bat) – [0.19*(Length of bat)], for more details see Fig. 3 and its magnitude by colorful image in that when initial velocities for ball and bat is equal to 40 m/s.



Case (a)

Case (b)

Fig. 3 Modal analysis for a and b cases and position of maximum contact stress for initial velocity 30-30 and 40-40 m/s from top to down for each cases

III. Ball Exit Velocity

Results of the analysis are given for nodal locations in the one end fixed baseball bat. Center of ball is assumed to be in contact with centerline of bat this causes a perpendicular impact. Here, BEV was measured 0.005 s after separation of the ball from the bat, to prevent post-impact ball vibrations affecting the result. Compressed ball diameter at impact instant is 0.25 of its original size that is large deformation. In Table II, the values of BEV by considering six different points on the bat as impact location, which are measured from top of the bat, are shown. These values have given in Table II. It has seen when ball and bat both are subjected to 40 m/s linear velocity the maximum ball exit velocity of 73.3 m/s is obtained, and when ball and bat both are subjected to 30 m/s linear velocity the maximum ball exit velocity of 55.5 m/s is obtained. In Table II, the percentage impact location versus ball exit velocity BEV is shown.

Table II
BEV with respect the various percentage impact location on the bat

Percentage Impact Location	Initial velocities: 30-30		Initial velocities: 40-40	
	Ball Exit Velocity m/s			
	Present Work	Ref. [1]	Present Work	Ref. [1]
0.1	49.3	43.5	66.87	76
0.13	50.96	52	66.39	76.5
0.16	55.5	49	70.09	77
0.19	53.97	48	73.3	78.5
0.22	50.41	48.5	71.34	78
0.25	51.53	46	67.11	77

IV. Summary

BEV is a measure of bat performance of interest to both hitters and defensive players. The momentum a batter can impart to the ball affects both the distance and trajectory of ball flight, and the time available to field the ball. Similarly, BEV determines the time available for an infielder to take evasive action against a ball hit directly toward him. The numerical model developed in this research accounts for the kinematics of bat motion and the time dependence of ball behavior, and provides further insight into the performance capabilities of bats in the field. For our wooden bat, initial and boundary conditions have been defined. Using this computational method the ball exit velocity is quantified. Ball exit velocity has been determined for six different locations on the bat.

Modal analysis is carried out to locate the node points. Relationship between the nodes and the region, which produces maximum Ball Exit velocity, is established. It is found that region between the two nodes produces the maximum ball velocity. This region is called as sweet spot. This region is lies between the 0.16 m and 0.21 m from the bottom of the bat. This value is very nearer to the location of the ball exit velocity at different impact condition as shown in results.

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