Dynamic Analysis of Impact of Ball on Cricket Bat and Force Transfer to The Elbow

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***Abstract*— A number of games like cricket, tennis, baseball, etc. have developed a lot due to the extensive research done in the sporting equipment. The main aim of this research is the evaluation of stresses in the hands of a cricket batsman. Very less literature has been found to attempt such an analysis, although it can be of great use, like predicting the location of injury, predicting the performance of the safety wear being used by the batsman, etc. One of the aims of this work is also to study in detail the variation in the ball exit velocity with respect to the impact location on the blade. Finite Element Modeling is used as an approach to predict the exit velocity of the ball. Three situations with various velocities of bat and ball are considered and simulated. The results confirm the existence of sweet spot, and indicate the same location where minimum amplitude of vibration is expected. A study on the reaction forces on the hand due to both the bat swing as well as ball impact is done. It is seen that reaction forces are minimum for sweet spot impact. The load on the hand is observed to be a dynamic load, occurring for a period almost five times the impact period of ball. A study is also performed on the stress distribution in the hand of the batsman, due to these reaction forces.**

Keywords—impact of ball on cricket bat, Finite Element Analysis, stress in hand while batting.

I. Introduction

Cricket is one of the sports, where the constantly evolving rules, do not allow much scope for use of technological advancement to improve the game. For instance, in baseball the bats can be either made up of solid wood or hollow aluminum barrel, where latter gives an increased ball velocity upon impact. In 1979, when Dennis Lillie walked onto the pitch using an aluminum bat, named ‘the ComBat’, a few overs into the game the opposing English captain complained to the umpire that the bat was damaging the ball. The bat was replaced with its orthodox wooden counterpart. And soon a new rule was into place, the bat must be made of wood [1]. These and many such constraints on the bat are aimed at protecting the integrity of the game. However, within the parameters enforced by the rule, there is still a scope for technological research to improve the design of the bat. A design variation in the cricket bat will improve the efficiency of the shot as well as reduce the effort the player has to put into playing the shot. Presently, other than personal experience and preference, there is no method for the batsman to select an appropriate bat for an appropriate version of the game, or situation within the same game [2].

Much of the previous literature referred to for this study concerns itself with baseball. Many researchers like Van Zandt [3], Alan Nathan [4], have confirmed the role vibrations play in an impact of bat and ball. The exit velocity of ball as a function of impact location as studied by these researchers confirms the existence of a region of higher impacting efficiency. David Thiel, et al [5], have confirmed these physical analysis by experimental work for a cricket batsman, showing that for sweet spot location impacts, the wrist mounted accelerometers show considerably lower readings. H Singh [6] studied the effect of mass distribution and composite reinforcements on a cricket bat’s performance.

One of the parameters of paramount importance is the ‘sweet spot’. Sweet spot is a location primarily identified by the batsman as the best location on the bat with which the ball can come in contact. The sweet spot has three physical interpretations [7]. It is a location on the bat which produces maximum batted ball velocity. It is also understood as the location on the bat which produces minimum sting on the batsman’s hand. A third interpretation is the location on the bat which produces minimum amplitude of vibration. Hariharan and Srinivasan [8] found that two of the three interpretations of the sweet spot correspond to a similar location on the cricket bat.

II. Finite Element Modelling of Bat

A. Modelling of Bat

The modeling of the bat is carried out using ANSYS Workbench, version 12.0. The data points on an actual bat are measured to obtain their co-ordinates. Thus a solid model of the bat is obtained. Bat material is taken as English Willow wood, which is a linear elastic orthotropic material with the material properties as shown in Table 1. Before the model can be used for impact simulation it is calibrated with the actual wooden bat used for modeling purposes. This is done by comparing various parameters like mass, location of center of mass, moment of inertia and the fundamental frequency of the first mode of

TABLE I. MATERIAL PROPERTIES OF ENGLISH WILLOW WOOD

Density (kg/m^3)	Young's Modulus (GPa)			Poisson's Ratios			Shear Modulus (GPa)		
P	E_x	E_y	E_z	ν_{xy}	ν_{yz}	ν_{xz}	G_{xy}	G_{yz}	G_{zx}
650	13.3	0.883	7.06	0.015	0.6	0.16	1.33	0.133	1.33

vibration, for free-free boundary condition. All these values are experimentally measured for the actual bat and calculated for the Finite Element Model using ANSYS. The table 2 draws up this comparison. It can be seen that the physical properties being compared are approximately equal, thus verifying that the FE model closely represents the actual bat.

B. *Use of Modal Analysis to Predict Sweet Spot*

The modal analysis carried out on the cricket bat serves an additional purpose of revealing the location of the sweet spot, according to one of the interpretations presented previously. The amplitude of the vibration is always zero at the nodes. When the ball impacts the bat, the impact lasts for roughly 0.001 s [9]. During this time, the ball is able to excite the bat only in the two lowest fundamental modes of vibration, for a free-free boundary condition on the bat. The values of the natural frequencies for these two modes as obtained using FEA were, 218.45 Hz and 733.54 Hz. The excited modes are as shown in Fig. 1. Fig. 2 shows the region of minimum amplitude when both the

TABLE II. CALIBERATION OF FE MODEL AND ACTUAL BAT

Property	Unit	Experimental value	FEA value
Mass	(kg)	1.360	1.347
Location of Centre of mass	(mm) from the shoulder	220	241
Moment of inertia	(kgm^2) about center of mass	0.058	0.044
First mode of vibration	(Hz) Free-Free boundary	225	218.45

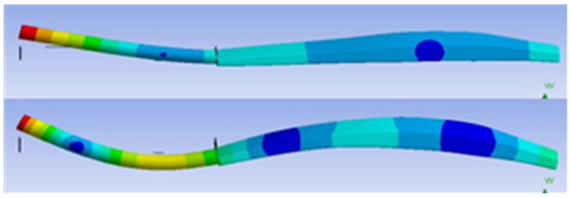

Fig. 1. (Colour Online) Two lowest modes of vibration of bat

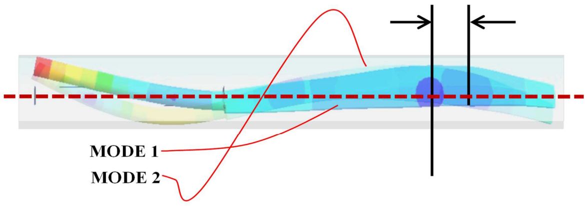

Fig. 2. (Colour Online) Superimposed image of the two modes, showing the sweet spot

modes are excited simultaneously. This would be the region we call the sweet spot. Thus the location of the sweet spot is obtained as 0.324 m to 0.388 m from the shoulder of the bat.

C. *Impact Simulation*

A cricket ball is simply modeled as a sphere, such that its radius and mass are in the range permitted by the MCC laws of cricket [10]. The ball is considered to have visco-elastic properties, with the parameters shown in Table 3.

Three situations have been simulated. They are, (a) ball moving at 35 m/s towards a stationary bat, a 0-35 impact, (b) ball moving at 40 m/s towards a bat moving at 40m/s, a 40-40 impact, and (c) ball moving at 35 m/s towards a ball moving at 17 m/s, a 17-35 impact. Fig. 3 shows the stress propagation in one of the impacts being simulated.

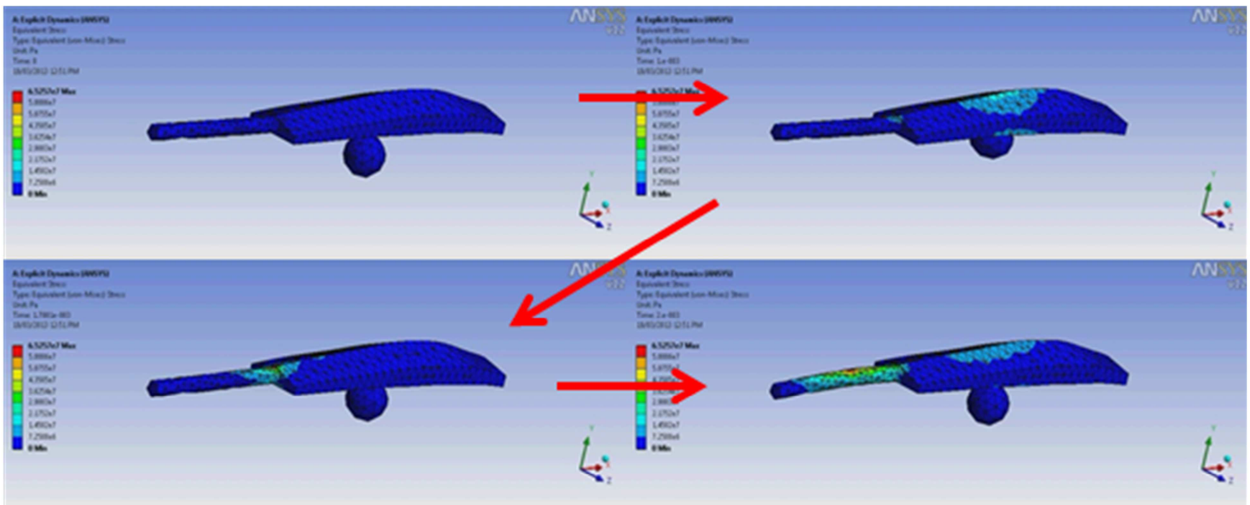

Fig. 3. (Colour Online) Impact of the ball with stationary bat and post-impact wave propogation in the bat.

TABLE III. MATERIAL PROPERTIES OF THE BALL

Density	(kg/m^3)	814
Instantaneous shear modulus	(MPa)	41
Long term shear modulus	(MPa)	11
Bulk Modulus	(MPa)	69
Decay Constant	(s^{-1})	10500

Before moving ahead, a justification as to why these particular velocities are selected. The stationary bat represents a simple defensive stroke being played. In general the shot being analyzed throughout the research work is a pull shot, where ball bowled by a medium pacer typically reaches velocities of 35 m/s. There is no clear data of the bat velocity during a pull shot. However work done by Cross, as discussed later, reveals that in a baseball shot, which is very similar to a pull shot, the center of mass of bat can reach a maximum velocity of 17 m/s, towards the end of the swing, when the ball is just impacting it. Hence this value is taken for bat velocity. The 40-40 situation is an exaggerated situation for representational purpose.

In each of the impact situation considered, the impact location of the ball on the bat is varied from 0.2 m to 0.45 m from the shoulder of the bat.

D. Results of Impact Simulation

The maximum stress developed in the bat due to the ball impact and the maximum exit velocity of the ball, are recorded for different impact locations. The resulting data is plotted graphically. Fig. 4 to 7 show the variation in maximum stress and ball exit velocity for 0-35 and 17-35 simulations respectively. Clearly there exists a region towards the lower end of the bat; around 0.35m from the shoulder, where the exit velocity would be maximum and the stress produced on the bat will be minimum. This corresponds to the region of minimum amplitude of vibration, 0.324 mm to 0.388 mm, as predicted above. Thus it is seen that two of the three definitions of the sweet spot, basically denote the same region.

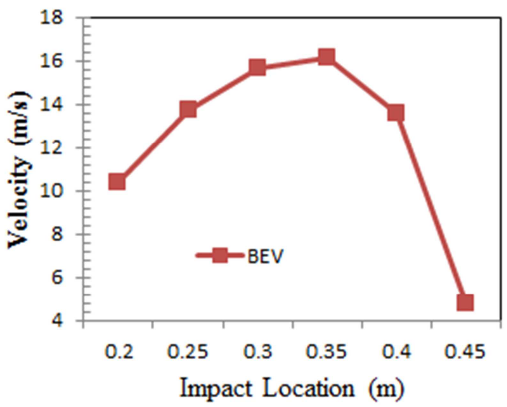

Fig. 4. Ball Exit Velocity for 0-35 impact

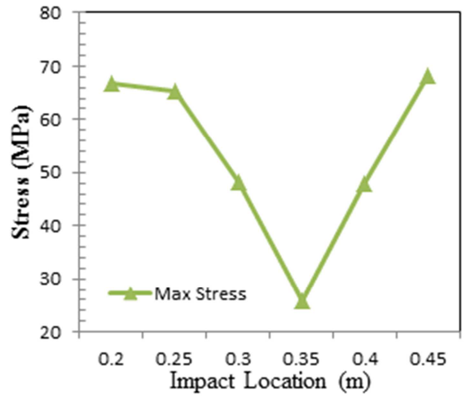

Fig. 5. Maximum Stress developed in 0-35 impact

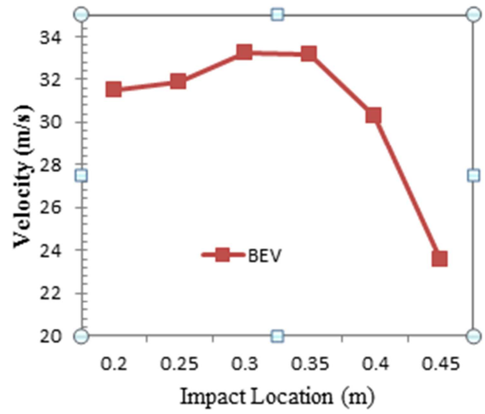

Fig. 6. Ball Exit Velocity for 17-35 impact

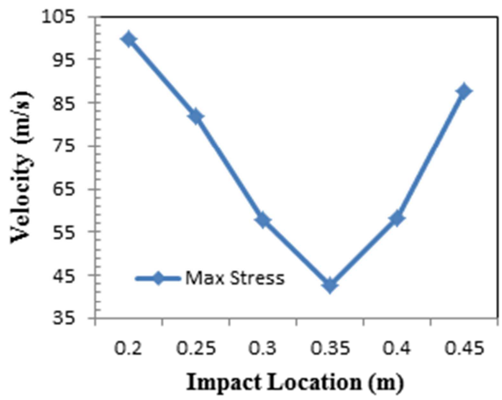

Fig. 7. Maximum Stress developed in 17-35 Impact

E. Verification of Impact Simulation

In order to not to put blind faith in the results obtained using FEA, a verification of the same is done using Rigid Body Model. Rigid Body Model assumes the bat ball impact to be impact of two rigid bodies. It applies the conservation of angular and linear momenta, and conservation of energy, considering coefficient of restitution. It is to be understood that Rigid Body Model gives approximate values only, and the 'sweet spot' loses its existence. For a rigid body model the maximum velocity will be when the ball strikes the center of mass of the bat. Previous researchers have studied this model and have found it to be of 'limited' use [11], and a good tool for first approximation [2]. Here, it is used only as a verification tool for the FEA analysis.

The model used is as follows [12]:

$$v_{1a} = \frac{-v_{1b}\left(e - \frac{m_1}{m_2} - \frac{m_1 B^2}{I_0}\right) + (1+e)(v_{2b} + B\omega_{2b})}{1 + \frac{m_1}{m_2} + \frac{m_1 B^2}{I_0}}$$

Where,

v_{1a}	=	Velocity of ball after impact
v_{1b}	=	Velocity of ball before impact
v_{2b}	=	Velocity of bat before impact
m_1	=	Mass of ball
m_2	=	Mass of bat
B	=	Impact location of ball from the Centre of mass of bat
I_0	=	Moment of Inertia about center of mass
e	=	Coefficient of Restitution
ω_{2b}	=	Angular velocity of bat before collision.

Fig 8 and 9 show the comparison between FEA results and rigid body model results for 17-35 and 40-40 impact situations respectively.

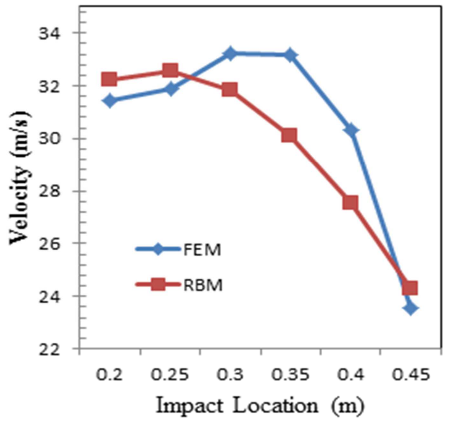

Fig. 8. Comparison between RBM and FEA for 17-35 impact

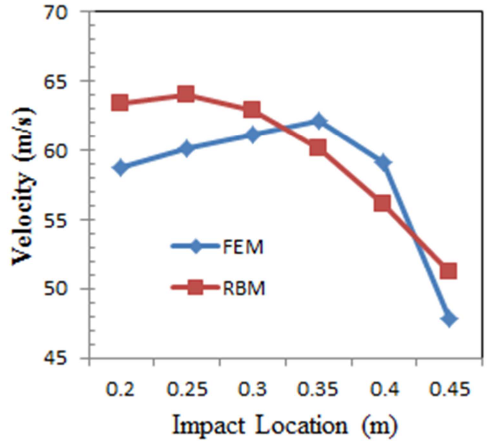

Fig. 9. Comparison Between RBM and FEA for 40-40 Impact

There is an excellent correlation between the two models, and thus the Finite Element Model is verified.

III. Reaction Forces on Hand

The next step in the study is to analyze the reaction forces on the wrist of the batsman while executing the pull shot being studied. It is to be noted that the batsman has to apply forces for two purposes. One is to bear the impact of the ball on the bat, and the other is to swing the bat itself. The force experienced by the batsman on the hand will be the sum of these two forces, the impact force and the swing force. In this section both of these will be calculated.

A. Calculation of Swing Force

As the batsman swings the bat, he has to apply some force on it. The calculation of this force can be done by applying simple kinematic analysis on the bat swing. A similar study has been done for a baseball bat swing, which is very similar to the pull shot in cricket, in great detail by Cross [13]. To measure the forces on the bat due to the hand, a high speed video of a swing of baseball bat was taken and analyzed by Cross. The results obtained can be used with some minor modifications to suit the requirements of the current study on cricket bat. Table 4 shows the comparison between the baseball bat used by Rod Cross and cricket bat used in this study.

It can be seen that most of properties of cricket and baseball bats are similar, except for the mass. Cricket bat weighs almost 1.5 times the baseball bat. Keeping this in mind, the reaction forces are calculated for the cricket bat in the same lines as done by Rod Cross in his research. For a swing speed of 17 m/s, the forces obtained are 641.77 N on left hand and 530.37 N on right hand, for a cricket player.

B. Calculation of Impact Force through Simulation

The impact between cricket bat and ball has already been simulated. The simulation is run again with minor changes in the model. Fig 10 shows the new model, wherein a small addition of clamp like structures is done, so as to measure the reaction forces at the contact surfaces of bat and the clamps. The clamps represent the left and right palms of the batsman and are placed accordingly.

TABLE IV. Comparison of Baseball and Cricket Bat

	Unit	**Cross's Baseball bat**	**Cricket Bat**
Mass	(kg)	0.871	1.347
Location of CM	(in mm, from knob)	560	541
Moment of Inertia	(in kgm^2, about CM)	0.039	0.044

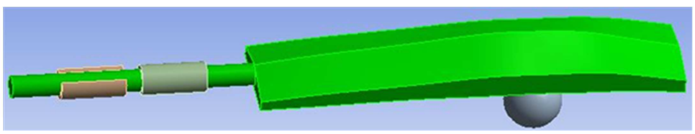

Fig. 10. (Colour Online) New Model to Measure the Reaction Forces due to Impact

The simulation is carried out over a period of 5 ms. The simulation gives the results in form of dynamic values of reaction forces on both left and right hands over the compete period of simulation. This process was carried out for both 17-35 and 40-40 impacts.

C. Total Force Obtained on the Hand

The total force on the hand is calculated as the vector sum of the impact forces and swing forces. The values obtained over a period of 5 ms are plotted for both left and right hands. Fig 11 shows the reaction forces on the right hand for various impact locations of a 17-35 impact. Fig. 12 shows the reaction forces on the left hand for various impact locations of a 17-35 impact. The maximum reaction forces borne by both left and right hands varying with impact location for a 17-35 impact is shown in Fig. 13. Fig 14 shows the same variation for a 40-40 impact.

It can be seen from Fig. 11 and 12 that right hand shares more load than the left hand for a right handed batsman. This is as expected. From Fig 13 and 14, it is very clear that impacts at around 0.35 m to 0.4 m from the shoulder of the bat result in much lower values of forces. This is the same spot which was earlier located as the region of minimum amplitude of vibration as well as the maximum value of exit ball velocity. Hence there is an excellent correlation between the three interpretations of sweet spot.

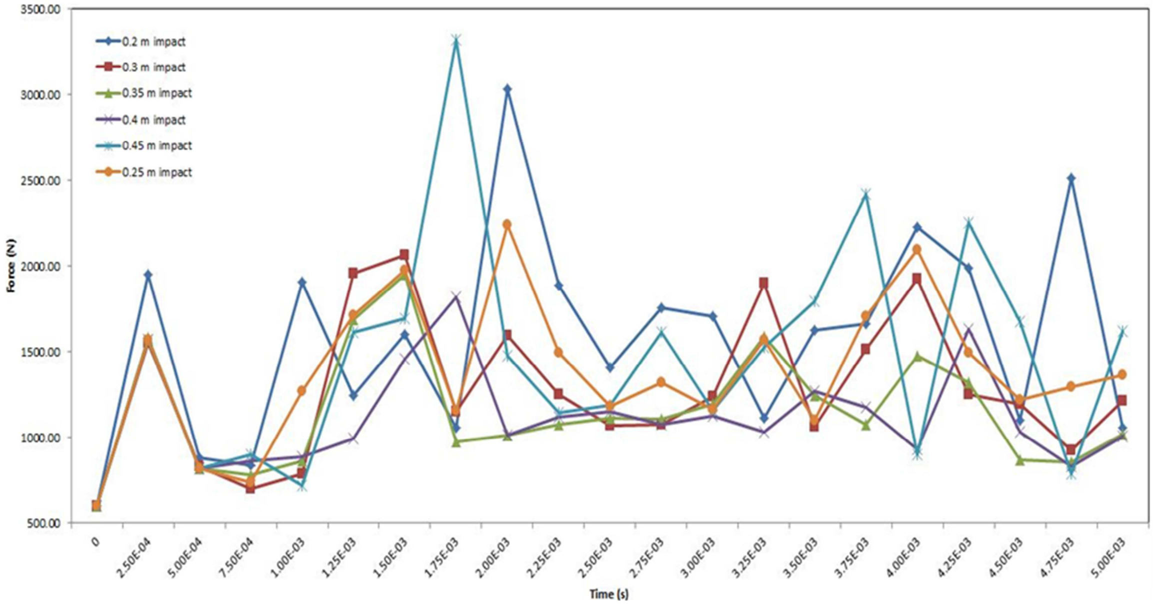

Fig. 11. (Colour Online) Reaction Forces on the Right Hand for Various Impact Locations of a 17-35 Impact

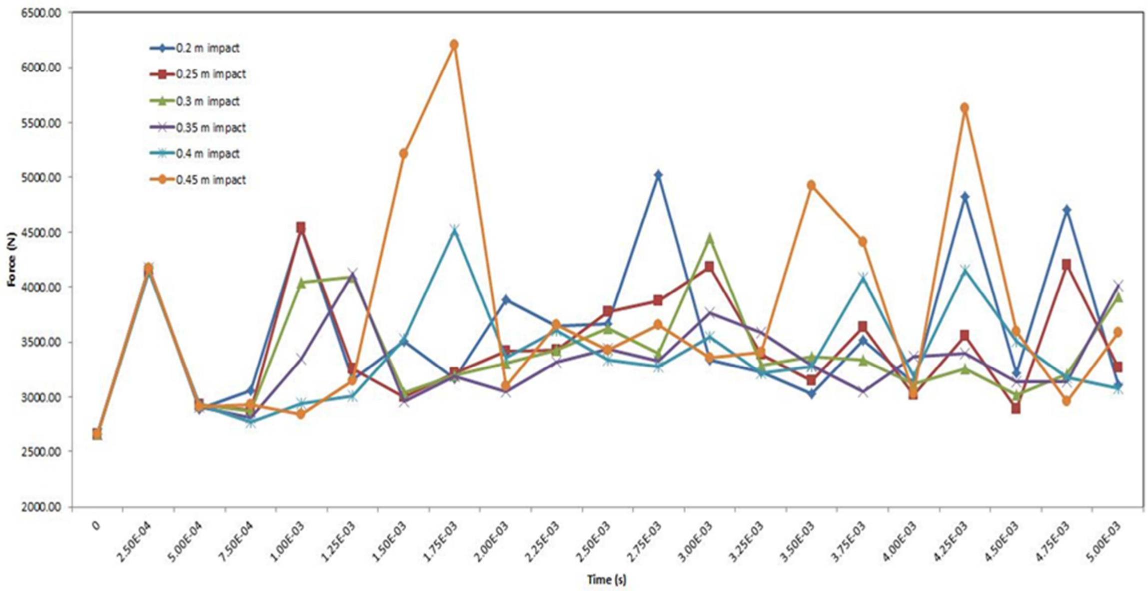

Fig. 12. (Colour Online) Reaction Forces on the Right Hand for Various Impact Locations of a 17-35 Impact

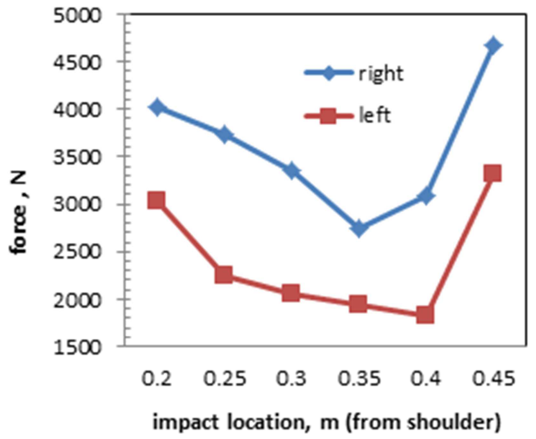

Fig. 14. Maximum Force Experienced on Left and Right Hands (17-35 Impact)

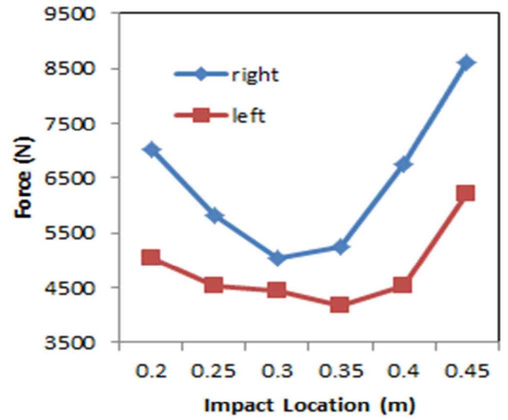

Fig. 13. Maximum Force Experienced on Left and Right Hands (40-40Impact)

IV. Stresses Induced in Hand

Now that the reaction forces on the wrist of the batsman is known, the next step is to find out what are the stresses that will be developed in the hand of the batsman. For this purpose a modeling of the internal structure of the hand needs to be done. Before proceeding ahead, it is desirable to do a simple analysis so as to get an idea of what range of values can be expected. For this purpose, consider a beam as is shown in Figure 15. The beam represents a forearm of a batsman, i.e. a bone from the wrist to the elbow. The end of the beam is assumed to be fixed, i.e. at the elbow. An average load of 3KN is being applied at the wrist end. The beam is assumed to behave in pure bending.

Section modulus,

$$z = bh^2/6 = 20*50^2/6 = 8333.33 \text{ mm}^2$$

Where,

b = breadth of beam,

h = height of beam.

Then,

Maximum bending stress

= bending moment/section modulus

= (3000*275) /8333.33

= 99MPa

An actual analysis of the structure of the hand should give a much lesser value of stresses than this, because arm will actually never be arrested at the elbow, but will be allowed some displacement. Moreover this is a static analysis, in the actual case, the force will not be constant, but will be varying about this value, most of the time being well below it. And most importantly there is no single bone connecting the wrist to elbow, there are two of them and they will both share the load.

Keeping this in mind, it is possible to move towards the modeling of the hand's internal structure. A human hand is a very complex structure, consisting of various bones. The wrist alone has 7 bones called the carpals. Due to computational limitations, this study is limited to a very crude approximation of the actual structure. Also the bones will be considered to be connected to each other through ligaments, in a very simplistic way, not in the way the connections actually exist. The model of the human arm which is considered for this study is shown in Fig 16.

The next complexity is addressing the material properties of the bones and ligaments. The bone is known to be a complex tissue, consisting of various components. Primarily, the bone is an inhomogeneous composite material having anisotropic material properties, depending not only on its composition but also distribution within a structure. All bones have a dense cortical shell and less dense cancellous inner component. The bone surface is surrounded by perisoteum, a membrane providing a network of blood vessels and nerves. The bone, like any good composite material, has strength higher than either of the two main components, the softer component prevents the stiff one from cracking and the stiff one prevents the softer one from yielding [14].

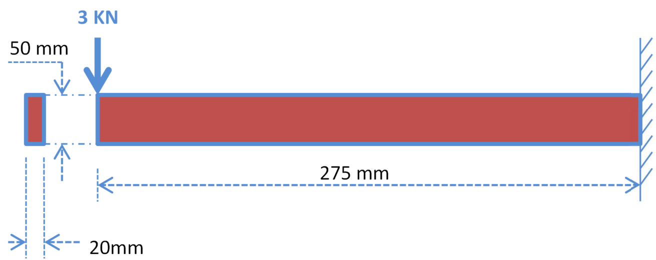

Fig. 16. Beam Representation of the Forearm to Estimate the Stresses

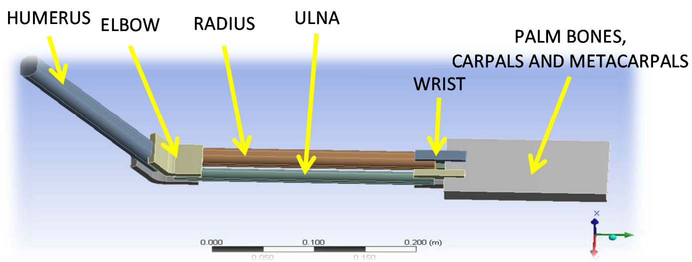

Fig. 15. (Colour Online) An Approximate Model Representing the Human Arm

However, again due to computational incapability, the bone is considered to be an isotropic homogenous system, having material properties of the harder component, cortical bone. These properties are listed in table 6. The ligament is generally taken as a viscoelastic material, which supports only tensile loads. Most of the material properties available in research papers are regarding Anterior Cruciate Ligament, (ACL), present in the human knee. However, an isotropic homogenous material for ligament is considered with properties listed in Table 5.

Once the material properties are assigned, the load obtained above is applied normal to the palm in the form of pressure, varying with time. The results are obtained in the form of the stresses and are shown in Table 6. The table lists out the maximum stress that occurs in the structure of arm over the period of the simulation, from the point of start of impact, for three different impact locations. The time listed in the first column is the time after the impact of ball on the bat. The Table 7 lists out the maximum stresses, their locations, and the maximum stresses in the ligaments and wrists over the entire period of simulation for three different impact locations.

TABLE V. MATERIAL PROPERTIES OF BONE AND LIGAMENT

		Bone	Ligament (ACL)
Density	(kg/m^3)	1900[15]	1027[15]
Young's Modulus	(GPa)	20[16]	0.1[17]
Poisson's Ratio	-	0.3	0.3[18]
Yield strength (tensile, long.)	(MPa)	120[14]	-
Fracture strength (tensile, long.)	(MPa)	140[14]	38[14]

TABLE VI. MAXIMUM STRESS DEVELOPED IN HAND

Stress in MPa	0.3 m Impact	0.35 m Impact	0.4 m Impact
2 ms	7.2268	8.2843	7.33
4 ms	20.469	19.009	16.67
6 ms	41.116	31.727	31.12
10 ms	83.415	58.449	57.585

TABLE VII. STRESSES IN VARIOUS PARTS OF ARM FOR DIFFERENT IMPACT LOCATIONS

	unit	0.3 m Impact	0.35 m Impact	0.4 m Impact
Overall Max Stress	MPa	83.415	58.449	57.585
Location of Max Stress	-	Elbow end of Radius		
Max Elbow ligament stress	MPa	24.727	16.997	16.598
Max Wrist Ligament Stress	MPa	8.55	5.94	5.92

It can be seen that stresses are minimum when the impacting region lies between 0.35 m to 0.4m from the shoulder of the bat. Thus it can be said that sweet spot impacts produce a lesser stress in various parts of hand when compared to other impacts.

V. CONCLUSION

Finite Element analysis is used as a tool to examine the effects of impacting a ball on a cricket bat. The existence of a high performing region, called sweet spot, is verified using various methods. The region where the minimum amplitudes of bat vibration occur is identified through modal analysis. Balls impacting in this region are found to result in maximum exit velocity after the impact. A study of reactions forces on the wrist involved in hitting the ball is done. Forces due to both, swinging of bat as well as impact of ball on the bat are considered. Sweet spot impacts are found to result in lower reaction forces. These reactions forces are used to study the stresses developed in the hand. It is found that stresses obtained using the analysis are quite feasible, though may not be experimentally verifiable, as far as the authors could presently see. Although it may not experimentally verifiable, it can be physically experienced by a batsman, though can't be quantified. It is known that players often experience pain in the back portion of the elbow. This is precisely the location of maximum stress, as predicted by the analysis.

The stresses obtained in the bone and the ligaments are found to be much lower than their yield stress values. This shows that the stresses are within an acceptable range.

It is also observed that for sweet spots impacts the stresses in bones and ligaments is least.

Another important observation is that since a right hand batsman is being considered, the right hand is the one that experiences more forces as compared to the left hand. This observation is also validated by the experience of right handed batsmen.

VI. FUTURE SCOPE

The research that has been carried out as described here, has been successful in answering some questions, such as discussed above. However, when it comes to actual application in a cricket scenario further work needs to be carried out. The assumptions made in this study need to be reduced to improve the accuracy. The handle of the bat needs to be assigned a proper material, cane, to be precise. One more very important component which has been overlooked is the effect of gloves. Also the hands need to be modeled more realistically, structurally, as well as the material definitions of bones and ligaments. These components would be difficult to model but would give an accurate representation of the stresses developed in the hand.

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