Sheffield Hallam University

Finite element model of a cricket ball impacting a bat

ALLEN, Tom, FAUTEUX-BRAULT, Olivier, JAMES, David and CURTIS, David

Available from Sheffield Hallam University Research Archive (SHURA) at:

http://shura.shu.ac.uk/8205/

Published version

Repository use policy

The 2014 conference of the International Sports Engineering Association

Finite Element Model of a Cricket Ball Impacting a Bat

Tom Allen[ab]*, Olivier Fauteux-Brault[a], David James[a], David Curtis[a]

[a]*Centre for Sports Engineering Research (CSER), Sheffield Hallam University, Collegiate Campus, Sheffield, S10 2BP, UK*
[b]*Department of Engineering and Maths, Sheffield Hallam University, City Campus, Sheffield, S1 1WB, UK*

Abstract

Finite element analysis is often applied to further our understanding of the mechanics of sports equipment. The aim of this research was to develop and validate a finite element model of a cricket ball/bat impact. The ball model was independently validated against experimental data for normal impacts on a fixed rigid surface, at speeds up to 35 ms⁻¹. Finite element models were produced for two bat geometries, with ball/bat impact simulations compared to experimental data. A rigid body model was also applied to each bat. The validation experiment involved projecting a ball at 30 ms⁻¹ normal to a freely suspended bat, at a range of locations on the long axis. The finite element models were in good agreement with the experimental data in terms of apparent coefficient of restitution. The rigid body model failed to accurately predict apparent coefficient of restitution for all impact locations along the length of the blade. The finite element modelling techniques presented here could be applied to aid the design and development of cricket bats.

1. Introduction

Cricket is a popular sport with a rich history, and the first rules were laid down in 1788. Despite the sport's popularity, cricket bats have seen relatively little technical development in comparison to other sporting implements, such as tennis rackets, golf clubs and field hockey sticks. The lack of development is due to the rules restricting alteration to materials, Law 6 states that the blade and handle shall be made solely of wood (Marylebone

* Corresponding author. Tel.: +44 (0)114 225 2255
  E-mail address: t.allen@shu.ac.uk

Cricket Club). Willow is selected for the blade, with cane for the handle. Wood is an orthotropic material which means the mechanical properties change in the longitudinal, transverse and radial directions (Kretschmann, 2010). For a cricket bat the longitudinal axis of the willow is aligned with the longitudinal axis of the blade to maximise strength and stiffness (Subic and Cooke, 2003). As a consequence of material restrictions, most cricket bat developments are geometry related. An accurate model could aid developers in predicting the effect of changes to the design of a bat.

A number of authors have developed cricket ball/bat impact models of varying complexity. James et al. (2012) presents a rigid body model of a cricket bat based on Newtonian mechanics. Smith and Singh (2008) present a finite element (FE) model of a cricket ball/bat impact. A linear viscoelastic material model was applied to the ball, with material coefficients selected to provide agreement with a load-time curve for a ball impacting a load cell at 27 m/s. A linear elastic material model was applied to the handle of the bat and a linear orthotropic material model was applied to the blade. The FE model for the ball/bat impact was shown to be in good agreement with experimental data, in terms of the rebound speed of the ball. However, despite independent characterisation of the ball for an impact on a fixed rigid surface, the material coefficients applied to the ball required further adjustment to achieve the level of fit presented for the ball/bat model.

The aim of this study was to develop and validate an FE model of a cricket ball/bat impact. Models were developed for two cricket bat designs. A rigid body model was also applied to both bats.

2. Methods

2.1. Bat properties

Two Gunn & Moore cricket bats were used in this study, one with a concaved profile on the rear of the blade (Icon[TM]) and the other with a flatter profile on the rear of the blade (Flare[TM]) (Table 1). A bifilar pendulum arrangement (Walker, 1991) was used to measure the moment of inertia (MOI) of each bat. The structural properties of the bats - when suspended from a long string - were measured by means of modal analysis. The experiment consisted of 'tapping' the bats with a hand-held cricket ball and sampling the frequency response with an accelerometer (4.2 kHz piezoelectric transducer), placed away from any nodes of vibration. The signal was sampled at 2,000 Hz and then converted from the time to the frequency domain using the Fast Fourier Transform (FFT) function in MATLAB (MathWorks, MATLAB R2012b). The blade was also struck at small intervals along its length while the signal was observed to locate the point which excited the lowest amplitude vibrations in the bat, defined here as the Nodal Sweet Spot. The Nodal Sweet Spot was located ~0.225 m from the toe, for both bats.

Table 1 Inertial and structural properties of the two bats used in this study.

	Mass	Distance of Centre of Mass from Toe	Moment of Inertia	Mode 1 frequency	Mode 2 frequency
	(kg)	(m)	(kgm^2)	(Hz)	(Hz)
Icon	1.074	0.335	0.0464	153	460
Flare	1.202	0.332	0.0505	139	454

2.2 Ball and bat impact experiments

Cricket ball (Reader, Club Training ball) elasticity was assessed by measuring coefficient of restitution (COR) for normal impacts on a fixed rigid surface (Figure 1a). In this instance, COR is defined as the ratio of rebound to inbound ball velocity. The ball was fired from a bowling machine (BOLA, UK) without spin, at velocities from 10 to 35 ms^{-1}. Impacts on the ball's seam were discarded as they result in a lower stiffness in comparison to impacts away from the seam (Carre et al. 2004).
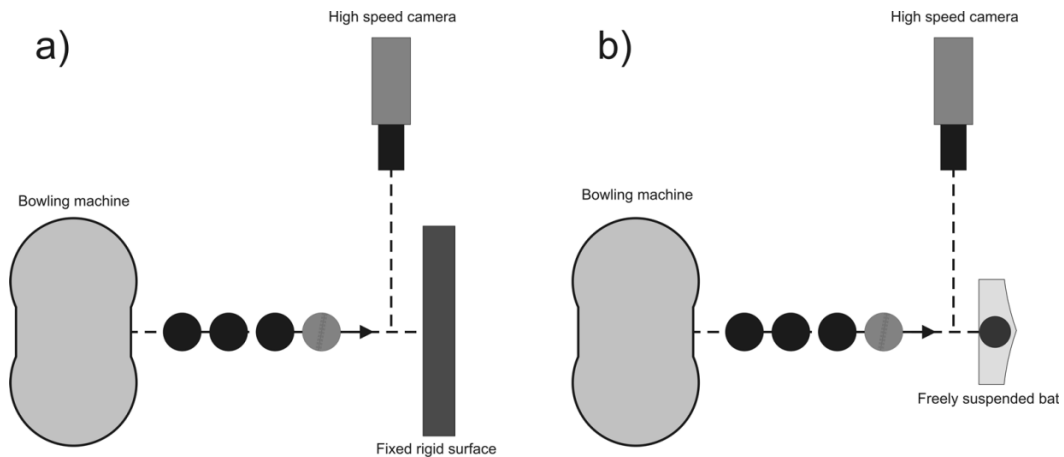
Figure 1 Experimental setup for impact testing a) ball/plate and b) ball/bat (view from above)

Bat performance was assessed by firing a non-spinning ball against the freely suspended bat while measuring apparent coefficient of restitution (ACOR) (Figure 1b). ACOR is defined as the ratio of rebound to inbound ball velocity; it represents the intrinsic power of the bat and is a simpler measure than ball/bat COR as the recoil speed of the bat is not required (Cross, in press). Freely suspended conditions were selected as the frequency response is comparable to when handheld (Brooks, Mather and Knowles, 2006). The mean inbound ball velocity was 30 ms^{-1}, with a standard deviation of 1.1 ms^{-1}. Impact position was varied along the longitudinal axis of the bat, from 0.1 to 0.5 m from the toe.

Impacts for both experiments were filmed with a high-speed video camera (Phantom V4.3, Vision Research), operating at 1,600 Hz. The acquired footage was manually digitised using in-house software (Centre for Sports Engineering Research) to obtain the inbound and rebound velocity of the ball. The uncertainty associated with manual digitisation was likely to be up to 0.2 m/s, based on previous work (Allen et al., 2009, Wiart et al., 2011).

2.1. Finite element models

Three models were developed using ANSYS/LS-Dyna i) Ball/plate impact, ii) Ball/bat impact (Flare model) and iii) Ball/bat impact (Icon model). A viscoelastic material model (MAT_VISCOELASTIC (LSTC, 2012)) consisting of a bulk modulus k and a time dependent shear modulus was applied to the ball

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

where G_0 and G_∞ are the instantaneous and long-term shear modulus respectively, β is the decay constant and t is time. The viscoelastic model has previously been applied to model solid sports balls (Smith and Duris, 2009 Allen et al., 2012), including cricket balls (Smith and Singh, 2008). Starting with the material coefficients applied by Smith and Singh (2008) the values were systemically adjusted to provide good agreement with the experimental data in terms of COR (Table 2).

Table 2 Material coefficients used in the finite element ball models. Plate-tuned 1 corresponds to the coefficients in Smith and Duris (2009).

Ball model	Density (kg/m³)	Bulk modulus (MPa)	Instantaneous shear modulus (MPa)	Long-term shear modulus (MPa)	Decay constant
Plate-tuned 1	851	134	43.4	11.5	10500
Plate-tuned 2	851	134	62	11.5	13000
Bat-tuned	851	134	37	11.5	13000

The ball was meshed with 10,976 8-node brick elements, following a convergence study that indicated relatively low dependency of COR on mesh density. A fully constrained rigid material model (MAT_ RIGID (LSTC, 2012)) was used for the plate which was also meshed with 8-noded brick elements. Ball/plate impacts were simulated at velocities from 10 to 30 m/s at increments of 5 m/s, resulting in a total of 5 simulations.

Computer Aided Design (CAD) geometry for the bats was provided by the manufacturer. The majority of the bat was meshed with quadrilateral elements. Tetrahedral elements were applied to the far ends of the blade and sections of the handle. A linear orthotropic material model (MAT_ORTHOTROPIC_ELASTIC (LSTC, 2012)) was applied to the blade and a linear elastic material model (MAT_ELASTIC (LSTC, 2012)) was applied to the handle. Starting with the material coefficients applied by Smith and Singh (2008) the density and modulus values were systematically adjusted so the inertial and structural properties of the models corresponded to those of the actual bats (Table 3). The inertial properties of the bat models were within 1% of those of the actual bats. Modal analysis simulations were used to determine the structural stiffness of the bat models. The 1st modes for both bat models matched those of the actual bats. The Flare model under predicted the 2nd mode by 12 Hz and the Icon model over predicted the 2nd mode by 25 Hz. Ball/bat impacts were simulated at 30 m/s from 0.10 to 0.45 m from the toe at 0.05 m increments, resulting in 8 simulations per bat.

Table 3 Material coefficients applied to the finite element models of the bats. L = Longitudinal, T = Transverse and R = Radial.

	Density (kg/m^3)	Young's modulus (GPa)			Shear modulus (GPa)			Poisson's ratio		
		E_L	E_T	E_R	G_{LT}	G_{TR}	G_{RL}	v_{TL}	v_{RL}	v_{RT}
Willow - Icon	435	6.650	0.442	3.530	0.665	0.067	0.665	0.015	0.160	0.600
Cane - Icon	520	5.000			-			0.300		
Willow - Flare	490	6.650	0.442	3.530	0.665	0.067	0.665	0.015	0.160	0.600
Cane - Flare	595	5.000			-			0.300		

2.2. Rigid body model

A rigid body model (James et al. 2012) was applied to both bats to predict the rebound velocity of the ball,

$$v'_b = \frac{v_b\left(\frac{m_b}{M}+\frac{m_b z^2}{I}-e\right)}{\left(1+\frac{m_b}{M}+\frac{m_b z^2}{I}\right)} \quad (2)$$

where v_b is the inbound velocity of the ball, m_b is the mass of the ball, M is the mass of the bat, z is the impact distance from the centre of mass (COM), I is the MOI of the bat and e is the COR. A fixed value for COR accounts for energy losses in the ball. The value for e was obtained from the experimental data for the ball/plate impacts, at 10 m/s. Ball elasticity for an impact on a rigid plate was assumed to be equivalent to ball elasticity for an impact on a fully constrained cricket bat. A value of 30 m/s was used for the inbound ball velocity in the model.

3. Results

Figure 2 shows results for the ball/plate impact. The experimental data shows COR decreased as inbound velocity increased. Applying the material coefficients from Smith and Singh (2008) resulted in the FE model over predicting COR, while increasing G_0 and β resulted in good agreement with the experimental data.
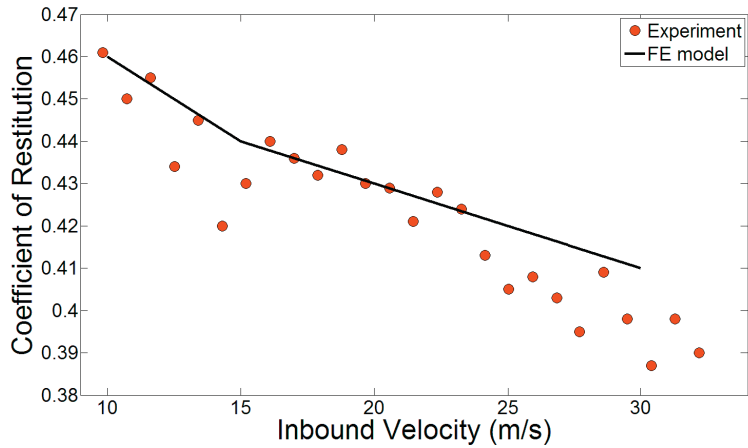
Figure 2 Results for the ball/plate impact. The model results correspond to Plate-tuned 2 in Table 2.

Figure 3 shows the results for the ball/bat impacts. The experimental data shows ACOR was dependent on the impact location on the blade. A region of high ACOR exists around the Nodal Sweet Spot for both bats. Higher values of ACOR can also be observed for the Flare, in comparison to the Icon. Initially, the materials coefficients determined from the bat/plate simulations (Plate-tuned 2) were applied to the ball/bat impact models. The plate-tuned ball model, however, resulted in the FE models for the ball/bat impact under predicting ACOR in comparison to the experimental data. Decreasing G_0, as done by Smith and Singh (2008), resulted in good agreement between the FE models and experimental data. The rigid body model failed to predict ACOR along the length of the blade. The model was in good agreement with the experimental data for impacts up to ~0.25 m from the toe, while ACOR was over predicted for impacts further along the blade.
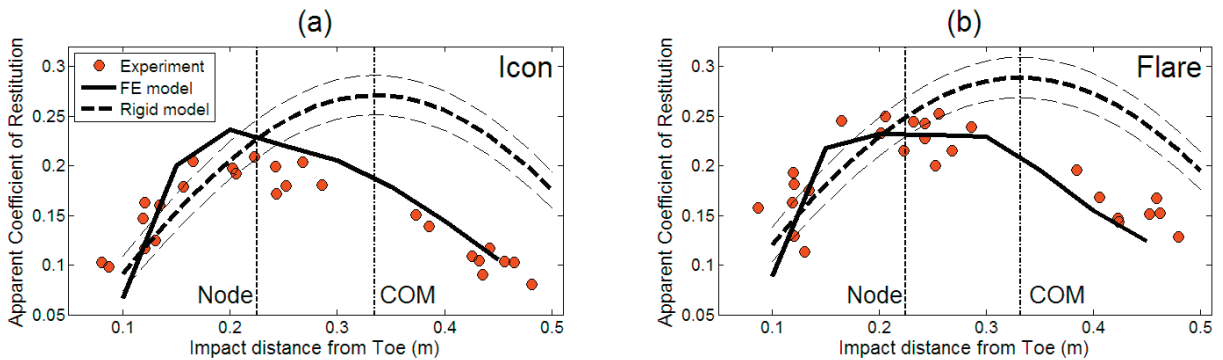

Figure 3 Results for the ball/bat impact a) Icon and b) Flare. Material coefficients for the ball in the FE model were Bat-tuned in Table 2. e for the rigid body model was 0.46 ± 5%. Node corresponds to the Nodal Sweet Spot.

4. Discussion

Finite element models were able to accurately predict ACOR along the length of two cricket bat designs. The experimental data showed both bats to have the highest ACOR in a region approximately 0.15 to 0.30 m from the toe, a region which contains the Nodal Sweet Spot. Performance deteriorated as the impact moved closer to the ends of the blade, in agreement with Bower (2012). As maximum ACOR was not at the point with the highest effective mass (COM) energy dissipation to bat vibration played an important role. The point which results in the lowest energy losses to bat vibrations is likely to lie between the nodes of the 1st and 2nd modes (Brooks et al.,

2006; Eftaxiopoulou et al., 2012). The rigid body model over predicted ACOR for impacts greater than ~0.25 m from the toe, as it cannot account for energy dissipation in the bat. As players typically strike the ball in a region less that 0.25 m from the toe, the rigid body model has potential to be applied to predict ball rebound velocity for actual cricket strokes. Further work could involve validation of both modelling techniques for a range of bat designs.

The results presented in this study are limited to an impact speed of 30 m/s. Further work could involve validation of both modelling techniques for a range of impact speeds. Both the rigid body and FE models showed relatively high sensitivity to the elasticity of the ball. Further work could focus on a more appropriate method for characterising ball elasticity specifically for ball/bat impact models.

5. Conclusion

Ball rebound from a freely suspended cricket bat was shown to be dependent on impact location on the long axis. The application of rigid body modelling techniques resulted in an over prediction of ACOR for impacts greater than approximately 0.3 m from the toe of the bat. Finite element modelling techniques were able to accurately predict ACOR along the length of the blade. The FE modelling techniques presented here could be applied to the design and development of cricket bats.

References

Allen, T., Bowley, A., Wood, P., Henrikson, E., Morales, E., James, D., 2012. Effect of temperature on golf ball dynamics. In: Edited by Drane, P., Sherwood, J. (Ed.). The Engineering of Sport 9 - Proceedings of 9th ISEA conference, Procedia Engineering 34, pp 634-639.

Allen, T., Haake SJ and Goodwill S., 2010. Comparison of a finite element model of a tennis racket to experimental data. Sports Engng. 12:87-98.

Bower, R., 2012. The sweet spot of a cricket bat for low speed impacts. Sports Eng. 15:53–60.

Brooks, R., Mather, J.S.B., Knowles. S., 2006. The influence of impact vibration modes and frequencies on cricket bat performance. *Proc. IMechE, J. Materials: Design and Application*; 220:237-248.

Carré, M.J., James, D.M., Haake, S.J., 2004. Impact of non-homogeneous sphere on a rigid surface. Proc. IMechE, Part C: J. Mechanical Engineering Science 218:273-281.

Centre for Sports Engineering Research. Check2D - camera calibration tool for 2D kinematic analysis. Available at: http://www.check2d.co.uk/default.html. Accessed 1 Mars 2012.

Cross, R, in press. Impact of sports balls with striking implements. Sports Engng.

Eftaxiopoulou, T., Narayanan, A., Dear, J., Bull, A., 2012 A performance comparison between cricket bat designs. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 226:16-23.

James, D., Curtis, D., Allen, T., Rippin, T. 2012 The validity of a rigid body model of a cricket ball-bat impact. In: Edited by Drane, P., Sherwood, J. (Ed.). The Engineering of Sport 9 - Proceedings of 9th ISEA conference, Procedia Engineering 34, pp 682-687.

Kretschmann, D. E., 2010. "*Mechanical properties of wood*". In Wood Handbook: Wood as an Engineering Material, 5.1–5.46. Madison, WI: General Technical Report FPL-GTR-190, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Chap. 5.

LSTC. 2012. LS-DYNA Keyword User's Manual. Livermore Software Technology Corporation.

Marylebone Cricket Club. The laws of cricket. Available at: http://www.lords.org/laws-and-spirit/laws-of-cricket/. Accessed 1 Mars 2012.

Smith, L., Duris, J., 2009 Progress and challenges in numerically modelling solid sports balls with application to softballs. J Sports Sci. 27:353-60.

Smith, L., Singh, H., 2008. An examination of cricket bat performance. In: Estivalet, M., Brisson, P. (Ed.). The Engineering of Sport 7 - Proceedings of 7th ISEA conference, Springer, Biarritz, pp 475–482.

Subic, A. J., Cooke A. J., 2003. Materials in Cricket, in *"Materials in Sports Equipment"*. In: Jenkins M. (Ed.). Woodhead Publishing Limited, Cambridge, pp. 407.

Walker, P., 1991. Chambers Science and Technology Dictionary. W & R Chambers Limited, pp 1008.

Wiart, N., Kelley, J., Allen, T., 2011. Effect of temperature on the dynamic properties of soccer balls. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology 225:189-198.