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Development of an FE model of a cricket ball

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Abstract

Studies of impact dynamics of cricket balls have the potential of significantly improving the development of cricket equipment and also contribute to improving the player's safety and performance. This work presents the development of a detailed multi-layer FE model for the structural analysis of cricket balls. The model was derived using experimental data obtained from tests developed for this purpose, including drop tests and high speed impact tests. The multi-layer, multi-material FE model was constructed using ABAQUS. Calibration of the model involves a multidisciplinary optimization technique. Comparison shows good agreement between experimental results and predictions from the refined model.

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*Keywords:*Cricket; impact; dynamics; optimization

1. Introduction

Impact between a sports ball and a planar barrier has been widely investigated by researchers using both theoretical modelling and experimental testing approaches [1 - 4]. The review of research to date shows that baseball, golf ball and tennis ball are the most common ball types investigated.

An approximate FE model was developed by Subic *et al.* [5] to simulate the effects of the interaction of the cricket ball with a rigid or deformable surface. Quasi-static axial compression tests were used to obtain the ball stiffness at several relatively low velocities. The behaviour of the ball at the actual striking velocity used in the standard tests (6.26 m/sec) of cricket gear was then predicted by non-linear extrapolation from the values measured at lower velocities. A simplified numerical model of the cricket ball was developed based on the concept of a soft surface encasing a rigid body. Even though this

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modelling approach significantly reduced the complexity of the finite element modelling, it still has some inherent limitations. For example, in a simple compression test the ball is subjected to pressures from both sides, which is different from real application. Also, this model has not been verified through high speed dynamic testing. As an extension to Subic's work, this paper repents an innovative method of constructing a detailed FE model of cricket ball.

Even though this modelling approach significantly reduced the complexity of the finite element modelling, it still has some inherent limitations. For instance, in a simple compression test the ball is subjected to pressures from both sides, which is different from real application. Also, this model has not been verified through high speed dynamic testing. As an extension to this work, Cheng *et al.* [6] developed another two numerical cricket ball models: a fast-solving mathematical model and a universal FE model. Both models have been verified experimentally and proved successful. For further study, this paper presents an innovative method of developing a detailed cricket ball FE model.

2. Experiment Testing of Ball Behaviour

Prior to model development, experiments were designed and carried out to investigate the impact behaviour of the cricket ball in order to establish a benchmark that can be used to validate the developed ball model. Generally, the apparatus used for the experiments consisted of a load cell mounted on a heavy brass rod and a speed gate (Figure 1). To obtain a suitable ball speed for testing, the ball can be dropped from a predetermined height [7] or it can be fired through a cannon gun or a pitching machine.

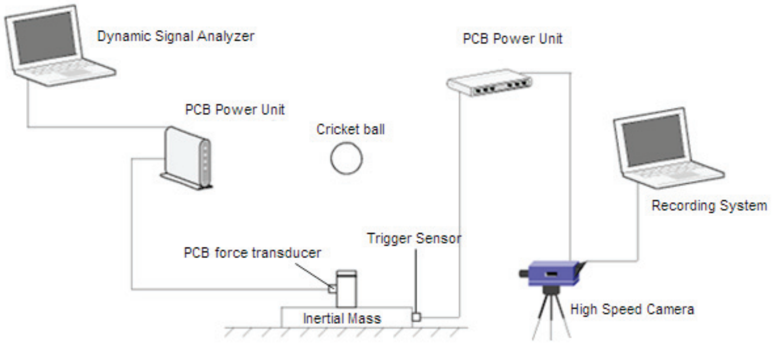

Fig.1. Experimental setup for cricket ball drop test.

Impact tests were carried out for cricket balls colliding with a rigid surface at high speeds that were normally above 10 m/s. A cricket ball pitching machine (JAG, Australia) was used in these tests to accelerate the ball to the required speed levels. An impact speed of up to 30 m/s could be achieved via acceleration. Both the pneumatic wheels of the machine were set to have the same rotating speed to avoid imparting side spin to the balls as they were fired. The entire experiment facility was set up with the help from Professor Lloyd Smith, Washington State University, USA.

As shown in Figure 2 all measuring instrumentation remained the same as in the drop tests. The impact force wave, impact speed and the rebound speed of the ball were also recorded in a similar manner. To obtain the immediate speed readings before and after impact with a better level of accuracy, the recorded images were analysed using the image analysis software, Image-Pro Plus (Media Cybernetics, USA).

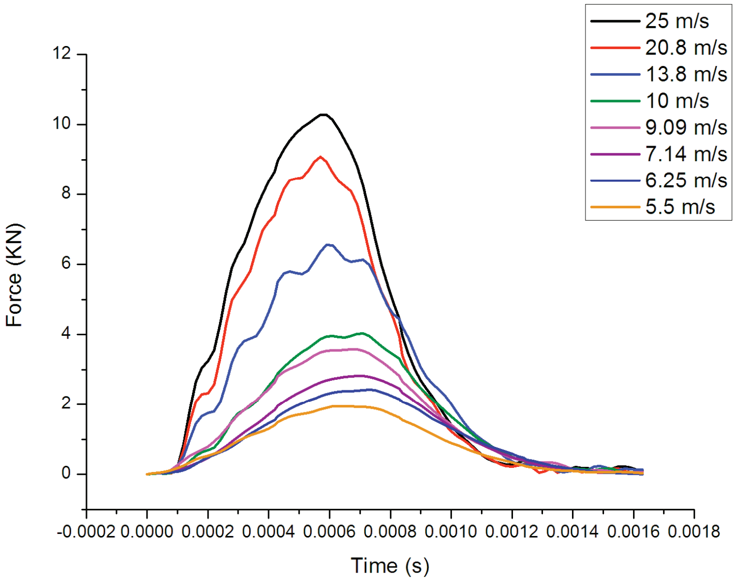

Fig. 2. Experimental impact load results for three-layer cricket ball with impact speed from 5.5 m/s to 25 m/s.

3. Development of FE Model

This paper presents the development of a validated, multi-layered and multi-material FE model of a cricket ball. The developed FE model includes detailed ball geometry and verified material parameters. It can also simulate a wide range of impact speeds. The development of the FE model includes the construction of geometry, the assignment of material properties, and the application of surface interactions between the different components of the ball. During the simulation, temperature effect was not considered.

A cricket ball consists typically of multiple layers. As shown in Figure 3, a central cork-rubber core, cork-and-twine packing, and a stitched leather cover usually constitute the three major layers of a cricket ball. The materials used in manufacturing cricket balls are highly rate-dependent and, accordingly, impact-speed dependent.

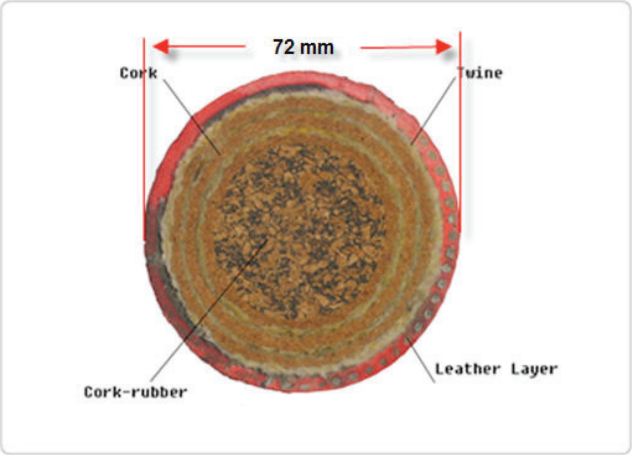

Fig.3. Cross-section of a Kookaburra three-layer cricket ball

The FE model presented here consists of three major components (Figure 4): A central solid sphere, a middle hollow sphere and an external hollow sphere. These components are respectively developed to emulate the cork-rubber inner core, cork-and-twine midsole layer, and the leather cover of the cricket ball.

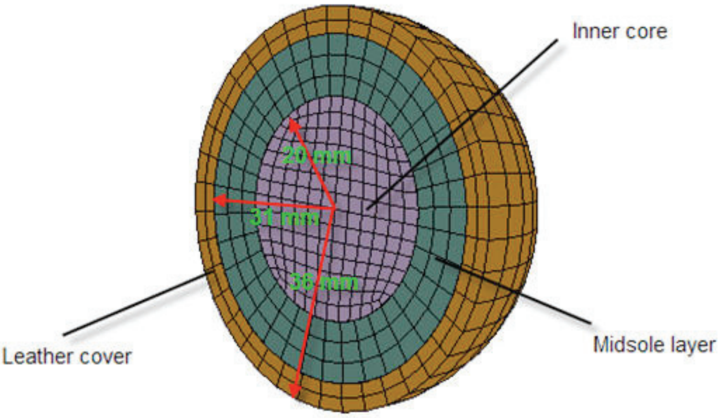

Fig.4. Cross-sectional view of an assembled FE model of a cricket ball

All components within the FE model are meshed with eight-node solid elements using ABAQUS CAE. Table 1 shows the number of nodes and elements for each component.

Table 1. Number of nodes and elements for FE ball model components

Component	No. of nodes	No. of elements
Inner core	2634	2209
Midsole layer	2088	1560
Leather cover	1806	1200

The inner core of a cricket ball is generally a rubber-like material although consisting of mixed rubber and cork. Rubber and rubber-like material properties are not represented by Hooke's law, but are characterized by a strain-energy function. In order to define material parameters, uniaxial compression tests were conducted using the INSTRON universal testing machine. These compression tests were performed in order to understand the basic material's behaviour. The raw material for testing was supplied by Kookaburra Co., Ltd.

The results from the uniaxial compression tests were used to develop the constitutive models. In this study, the material model was chosen as Mooney-Rivlin. The fitted material parameters are displayed in Table 2.

Table 2. Material parameters for the inner-core unit after fitting with the Mooney-Rivlin model

Material parameters	Value
D1	0.00000000
C10	3.09068828
C01	-1.49503368

A dynamic impact test involves large local deformation and rapid strain changes. Therefore, the ideal material test would be an instantaneous recording of stress/strain response during impact. Moreover, there is no energy loss being considered during this basic simulation, which also results in the calculated COR being higher than the experimentally measured value. Although the initial static response of the material was linear, introducing such a response in the model produced large discrepancy with the experimental results. This response was modified through the optimization process into non-linear behaviour, which produced agreement between numerical results and experimental measurements.

Due to physical limitations, it was impossible to measure the material properties at high impact velocities. An alternative robust approach as detailed below was applied in order to indirectly determine the material properties. The material parameters under dynamic conditions were determined by modifying the initial material properties, obtained from the quasi-static test, to satisfy the results of experimental impact test of the inner core at different impact speeds.

The entire process is based on a reverse engineering technique using modeFRONTIER 3.2 (ESTECO Inc., Italy), a computer program used for process integration and optimization (Figure 5) which integrated ABAQUS and MATLAB to include FE simulation, results extraction, evaluation, and optimization.

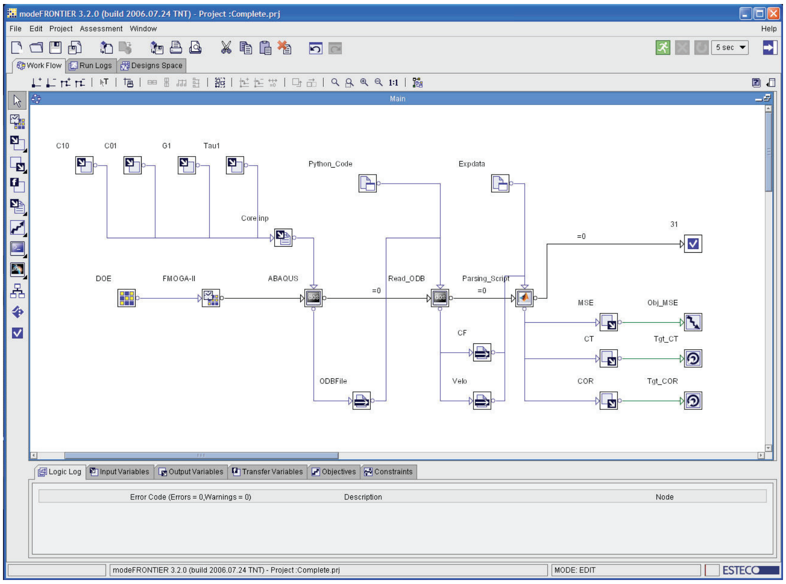

Fig. 5. Workflow developed within the modeFRONTIER to identify material parameters

At the start of each iteration, modeFRONTIER instructs ABAQUS to run an initial impact simulation using the material parameters obtained from static testing. Then, a Python script, which was specially developed for this purpose, was used to transfer the simulation results (impact load and rebound speed) from the ABAQUS output database (ODB file) to MATLAB for model accuracy evaluation. Finally, an optimization technique (a multi-objective genetic algorithm) was used in modeFRONTIER to adjust material parameters until a specified number of optimization runs has been generated. The optimization process flow is displayed in Figure 6.

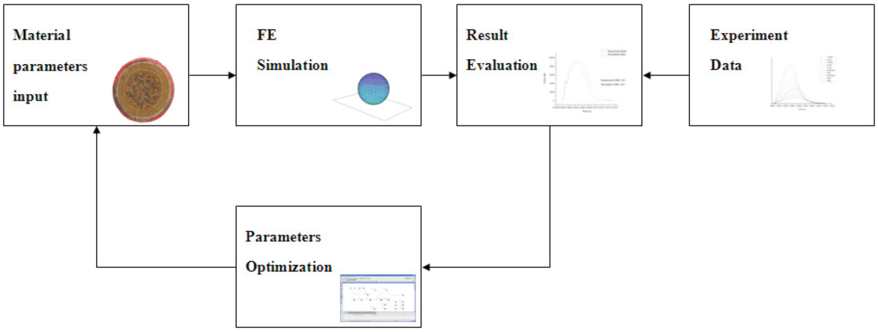

Fig. 6. Flowchart of material parameters optimization process

Generally, three indicators were used to describe the dynamic impact characteristics: Mean Square Error (MSE), which measures the difference between the simulation force curve and experimental force curve; the coefficient of restitution (COR); and contact time (CT). These indicators were treated as optimization targets.

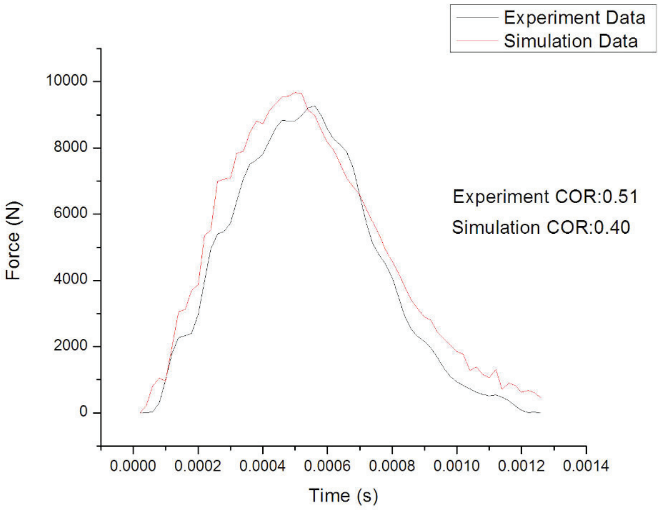

Fig. 7. Comparison of impact force results for the complete three-layer cricket ball under an impact speed of 20.8 m/s

Figure 7 shows the comparison of the simulation results and the experiment results using optimized material parameters for a complete three-layer cricket ball under an impact speed of 20.8 m/s. It can be seen that the impact load curve and the contact time are both in good alignment. However, the COR calculated from FEM simulation was 21% lower than that obtained experimentally.

4. Conclusion

Detailed structural models of the cricket ball are required to gain more insight into the impact dynamics of cricket balls. This study introduced the development of a detailed FE model for the structural analysis of cricket balls. The models were calibrated against experimental data obtained from tests developed for this purpose, including drop tests and high speed impact tests.

The experimental work presented in this study included measurements of impact behavior of two-layer, three-layer, and five-layer cricket balls using a dynamic signal analyzer and high speed video analysis software. This research successfully delivered a multi-layer and multi-material cricket ball model with high accuracy. The intended use for such a model is to provide accurate results that incorporate the geometry of the cricket ball and area deformation characteristics. This model can also be used as a valuable tool to enable manufacturers to discover and synthesize new materials and new designs for cricket balls. Furthermore, the application presented here can be extended to simulate any solid ball impact. To determine the material parameters within this model, this study developed a highly automated approach that significantly reduced the amount of handwork required. Comparison of the simulation results and the experimental results reveals that the force-time curve and the contact time are both in good alignment. However, the COR that was predicted by the model and the COR obtained from the experiment do not match closely. This is probably because the initial values of the material parameters were of poor quality. Manual fine-tuning or adopting better numerical optimization methods are possible ways of improving this model.

Acknowledgements

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