Procedia Engineering 2 (2010) 2991–2997

8th Conference of the International Sports Engineering Association (ISEA)

The dynamic viscoelastic characterisation of the impact behaviour of the GAA sliotar

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Received 31 January 2010; revised 7 March 2010; accepted 21 March 2010

Abstract

In recent years variability in behaviour of the sliotar, a small leather-bound ball used in the Irish sport of hurling, became evident in championship matches. The current standard has not provided adequate repeatability of ball performance. A new method for assessing the dynamic impact behaviour of approved sliotar cores has been characterised. This test system was developed to measure the performance characteristics, such as coefficient of restitution, deformation and contact time, and the viscoelastic properties of dynamic stiffness and hysteresis energy dissipation. In this paper, the relationship between the viscoelastic properties and the coefficient of restitution is presented.

Keywords: Impact characterisation; viscoelasticity; ball sports; sliotar; hurling

1. Introduction

The controversial variation in performance of the sliotar in recent years has been attributed to the variation in construction on the core of the ball. Current regulations do not specify the core material or construction, but do necessitate that the ball has a rebound height within a specified range from a 1.8 m bounce test. Traditionally, the sliotar core was constructed from a cork sphere wrapped in yarn, but in recent years popularity has grown for a single polymer sphere due to the lower cost and labour required for manufacture. However, this departure from the original construction type has resulted in a change in performance of the sliotar. This performance variation was exacerbated by the poor quality control associated with some outsourced manufacturers. Some manufacturers have altered the material or process without the consent of the contracting Irish sliotar suppliers. This has led the Gaelic Athletic Association (GAA), the governing body for the sport, to examine the possibility of adopting a single standardised core for use in championship matches. Given the divided preferences amongst players regarding different sliotar types, the GAA decided that it may be more appropriate to manufacture new prototype cores that exhibited predetermined repeatable performance characteristics. Before prototyping could commence, the performance of the 15 currently approved sliotars cores had to be characterised in order to identify the desired impact characteristics. To understand the effect of the ball's structural properties on the performance, it was

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necessary to explore the contribution of the ball's viscoelastic components to the performance characteristics. Such an understanding was required in order to manufacture ball types of specific playing performance.

1.1. The sliotar

The sliotar consists of a leather skin and solid core. The two-piece white leather skin is stitched at raised seams to form distinctive black ribs. It is similar in size to a baseball or cricket ball, with diameter of 72 to 79 mm (including the ribs) and a mass of 110 to 120 g. For the purposes of this work, the leather skin was removed to allow testing of the core. This was done for two reasons: firstly, the variation in the material of the core had been previously identified as the dominant source of variation in the ball performance; and secondly, the simpler geometry of the core (i.e. absence of ribs) enabled a more comprehensive impact characterisation. The material of the core, which is not specified under GAA regulations, can be categorised into two types of compositions: the more traditional cork wrapped in a yarn winding; and the more modern polymer foam core. Four sliotar cores types of different compositions, as shown in Figure 1, were selected for presentation in this paper.

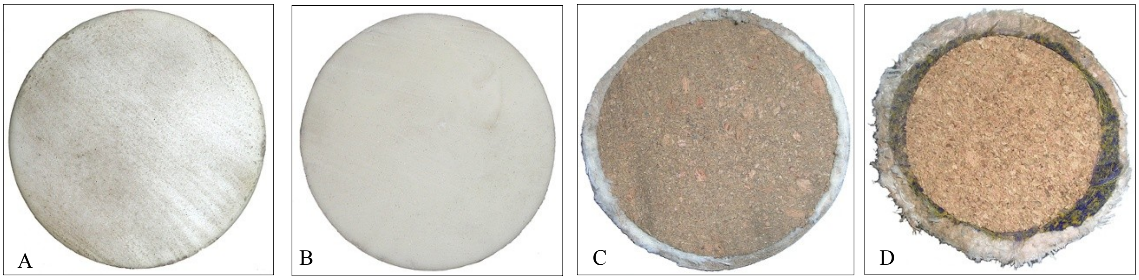

Fig. 1. Cross sectional pictures of sliotar core ball types A, B, C and D.

Table 1. Properties of sliotar core ball types

Ball type	Diameter [mm]	Mass [g]	Material mass composition
Type A	66.2 ± 0.1	89.6 ± 0.4	100 % polyurethane-based polymer
Type B	66.8 ± 0.2	89.9 ± 3.1	100 % polyurethane-based polymer
Type C	65.6 ± 0.1	89.1 ± 0.9	19 % yarn, 81 % cork
Type D	68.2 ± 0.4	83.1 ± 1.3	24% yarn, 38% polyester, 38 % cork

1.2. Impact characterisation

In an impact, a significant fraction of the ball's initial kinetic energy is dissipated during the impact process as a result of internal friction in the ball, or after the impact process through internal modes of oscillation due to the remaining wave effects and the recovery of the ball to its original shape [1]. The coefficient of restitution (COR), the ratio of velocities after and before impact, is a frequently used measure to quantify energy loss in sports balls, as evident from the official standards for baseball and cricket balls [2, 3]. Typically, the impact plate is a significantly harder material than the ball such that it contributes a negligible amount to the energy loss of the impact, thus ensuring a measurement that is intrinsic to the ball itself. The percentage of kinetic energy loss, often labelled the dynamic energy loss, can be calculated from the expression ($1 - COR^2$). However, the coefficient of restitution measurement excludes details of the rate of energy loss during and after the impact, the effect of deformation on energy loss, and residual oscillation and shape recovery after impact. In order to comprehensively characterise a ball impact, it is necessary to consider the viscoelastic mechanism of energy dissipation. A viscoelastic material exhibits the properties of both an elastic solid and a viscous liquid. The elastic property of stiffness defines how the object deforms and recovers when subjected to an applied force, while the viscous property, called viscosity or damping, defines how much energy is dissipated in deformation. The viscoelastic behaviour can affect the playing performance of the ball in a number of ways. A high rate of energy loss results in high peak forces, translating to increased shock perceived by a player, which has implications for player ball control and safety. A low rate of energy loss implies longer contact times, which would alter aim and control. Larger ball deformation would also affect the aim and control due to an increased surface area contact between the ball and striking object.

Viscoelastic characteristics are evaluated from relating the transient forces to the distance over which forces acts during the impact process. A hysteresis curve can be constructed by plotting the impact force against this distance. From this, the dynamic stiffness can be obtained from the slope of the curve while the work done can be calculated from the area under the curve. The area enclosed within the hysteresis loop corresponds to the energy loss, or damping, of the impact. While the impact force can be readily measured by incorporating a force transducer into the impact plate, there are two methods employed in the literature for measuring the distance over which the force acts. The first method involves the measurement of the compression of the ball's diameter using a device such as a high-speed camera [4, 5]. The second method involves the manipulation of the force data to estimate the displacement of the ball's centre of mass (COM). This is achieved by dividing the force data by the ball mass to get the acceleration, and integrating this twice with respect to time to determine the displacement of the COM. The COM displacement method appears to be more frequently used due to experimental ease, with several papers assuming explicitly or implicitly that both measures are analogous [6––8]. This assumption was strengthened by the fact that the percentage of area enclosed in their hysteresis loops agreed with their dynamic energy loss values [1, 6–8].

The performance and viscoelastic characterisation of four of the currently approved sliotars cores are described in the following sections. The primary aim of this paper is to investigate the relationship between the coefficient of restitution and the viscoelastic properties of stiffness and damping. A secondary aim of the paper is to review the assumption that COM displacement is analogous to ball deformation in evaluating viscoelastic characteristics.

2. Experimental work

An automated test system was designed and developed to evaluate dynamic impact characteristics. This system consisted of a pneumatic actuator which was used to project the ball vertically upwards at velocities of 5 to 38 m/s (15 to 140 km/h) with precise aim and no ball spin. The ball then struck a rigid steel impact plate which was directly bolted into an axial compression load-cell which acquired the impact force at 20 kHz. The motion and deformation characteristics of the ball were recorded by a Mikrotron MC1302 high speed camera running at 4000 frames per second (fps). Due to the short exposure times associated with high speed footage, the impact area was illuminated by 400W of halogen light with a cooling fan installed beside the impact plate to maintain a stable temperature environment at 25 °C. After impact, the ball was captured within an enclosure that lead into a feeder channel that could accommodate up to 14 balls for repeated automated batch testing. A mechanism at the base of the feeder channel allowed a single ball at a time into the firing chamber. Position sensors aligned along the channel informed the control program of the number of balls in the system and indicated when the ball returned so that the next ball could be made ready for testing. The entire system was controlled by a graphical user interface, involving the synchronised use of nine LabVIEW sub-system programs. In the interval of time between impact and the ball re-entering the feeder channel, the data acquired at impact was analysed, displayed for the user, and saved in spreadsheet format for post-analysis.

Three samples of each ball type were subjected to impact testing at velocities between 5 and 25 m/s in 5 m/s increments. The high-speed footage of the impact was saved to AVI format for post-progressing. The image processing algorithm performed several functions, including sharpening, thresholding and filtering to isolate the ball from the background. The centre co-ordinates were tracked from frame to frame to measure the velocities and hence, coefficient of restitution. The deformation profile was obtained by measuring the compression of the ball diameter normal to impact surface. The force reading of the load-cell was validated by comparing the measured impulse to the theoretical impulse. The theoretical impulse was the change of the ball's momentum, which was calculated from the ball mass multiplied by the difference between the approach and rebound velocities. The first time integral of the force giving the area under the force-time graph was used to experimentally measure the impulse. The viscoelastic data was derived from the combination of force and deformation data to form a hysteresis curve, with the data combination validated when the area under the loading portion of the hysteresis curve equalled the ball's initial kinetic energy. The stiffness was evaluated from the slope of a linear trend line fitted to the loading portion of the hysteresis curve, while the damping was calculated from the area enclosed within the loop formed by the loading and unloading portions of the hysteresis curve. The calibration of the system involved five projections of four ball types at set orientations at 10 and 20 m/s. The system was found to have excellent repeatability (± 0.14 m/s, ± 0.62 mm and ± 0.7 N for velocity, deformation and force measurements respectively).

3. Experimental results

The coefficients of restitution values for the four ball types are displayed in Figure 2. All ball types exhibited similar liveliness. Given their respective comparable constructions, the two modern ball types (A and B) followed similar trends with increasing impact velocity, as did the two traditional ball types (C and D). Hysteresis curves were constructed using both methods described in the section 1.2. Figure 3 shows examples of these hysteresis curves for impact velocities of 5 m/s, 15 m/s and 25 m/s.

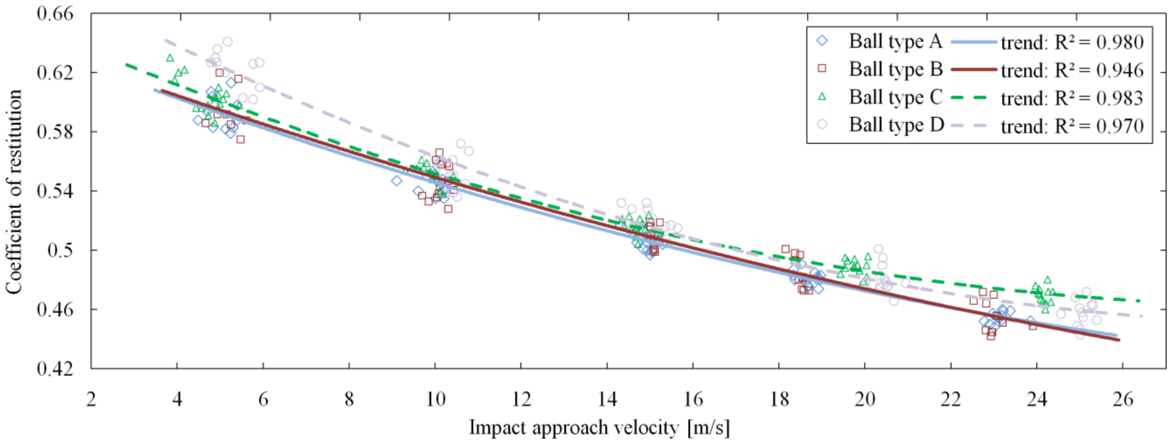

Fig. 2. Coefficient of restitution for impact velocities of 5 to 25 m/s.

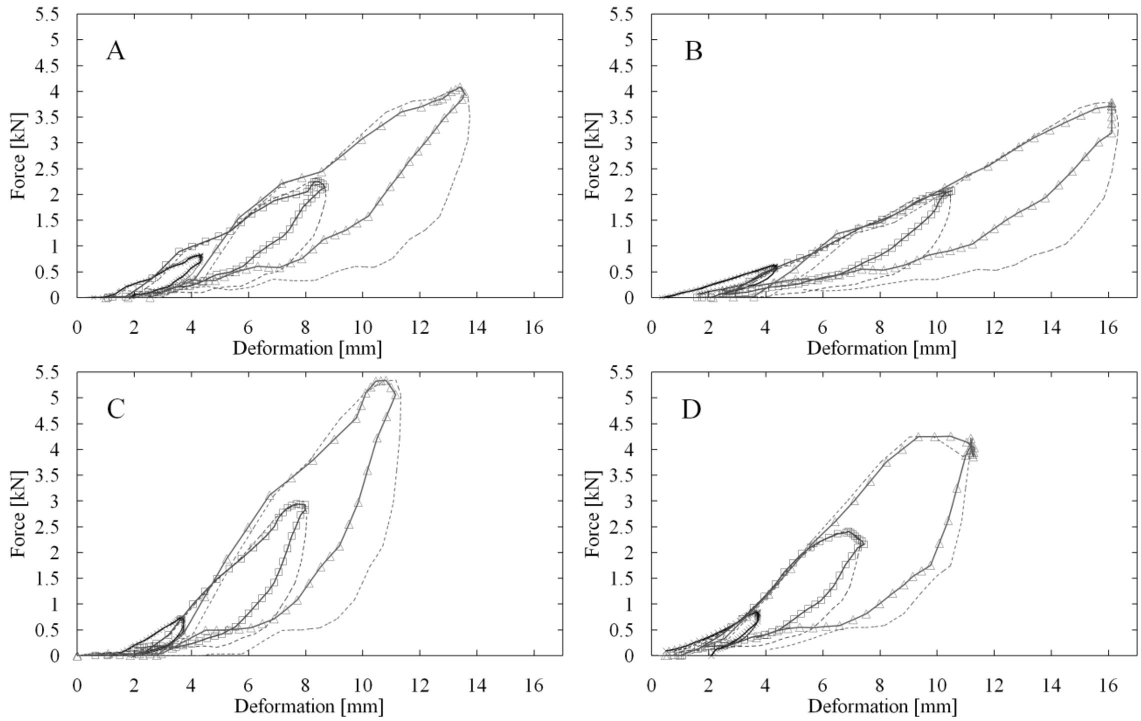

Fig. 3. Hysteresis loops for impact velocities of 5 m/s (—×—), 15 m/s (—□—) and 25 m/s (—△—) for ball types A, B, C, and D. Solid lines indicate measurements from diameter reduction method and dotted lines indicate measurements from the COM displacement method.

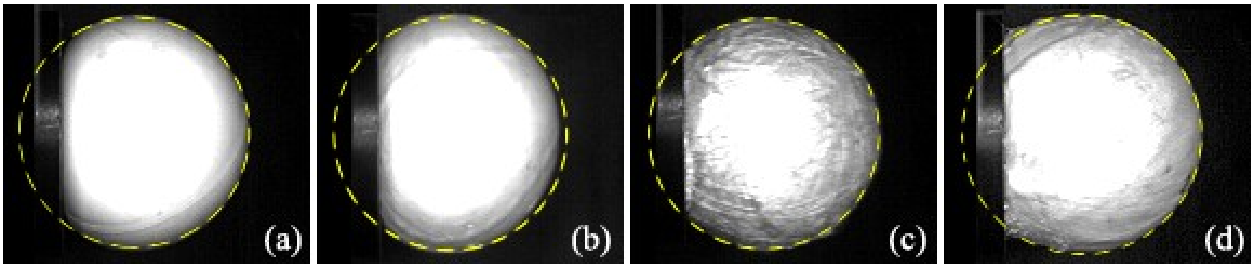

Fig. 4. Pictures captured at maximum recorded deformation from impact tests performed at 25 m/s for ball types (a) A; (b) B; (c) C; and (d) D. The dashed circle shows the circumference of the ball without any deformation.

4. Discussion

In terms of performance, the similarity of the coefficient of restitution values for the 4 ball types as shown in Figure 2 was not surprising, considering that these ball types were selected due to their similar rebound properties as determined from the 1.8-m drop test. The greater non-linearity of the traditional ball types resulted in a divergence in performance from the modern types at higher velocities. The fact that this deviation in performance was not evident in the current low-velocity regulation testing illustrates the need for high-velocity testing for comprehensive characterisation. There was excellent consistency of samples within each ball type for three of the ball types, with a higher degree of variation evident in ball type B. These differences could be attributed to the variations in sample masses, as shown in Table 1. In contrast to the excellent consistency in ball types C and D, which had a multi-compositional construction and naturally derived materials, the variation in polyurethane ball type B should be avoidable given that the material and production process could be controlled to a high degree.

The viscoelastic characteristics were derived from the hysteresis curves, examples of which are shown in Figure 3. The dynamic stiffness of the compression was calculated from the slope of the leading edge of the curve, where good agreement (within 10%) was evident for both the diameter reduction and the COM displacement methods. As expected, the dynamic stiffness increased with increased deformation. As with the coefficient of restitution data, this rate of increase is almost linear for modern ball types A and B, and more non-linear for the traditional ball types C and D. This non-linearity was attributed to the multi-compositional construction of the traditional ball types due to different materials becoming involved in the compression at increased levels of deformation and to the interaction between the different materials during this deformation. In ball type C, the first 3 mm of deformation involved tightly wound yarn with subsequent deformation involved the cork material, while in ball type D the first 4 mm involved yarn, the next 3 mm involves a layer of polyester and subsequent deformation impeded on a small cork core. Considering the yarn or polyester layer as a single material, it has a lower stiffness than the cork due to the ability for the strands to slip over each other. This explains the initial shallow slope at the start of each hysteresis loop from ball types C and D. As the ball became compressed beyond the yarn layer, the cork material presented a higher stiffness to the deformation. This accounts for the cluster of data points for ball type D at maximum deflection for the 25 m/s hysteresis curve where the small cork core became engaged with the deformation, as seen in Figure 3. In addition to each material's individual contribution, the interaction of each constituent layer resulted in a variation in stiffness. The high speed footage showed that the yarn deformed in waves beyond the area of local deformation in ball type C. This motion most likely caused a fluctuation in dynamic stiffness. For ball type D, the yarn and polyester layers were seen to bunch up and expand beyond the ball's original diameter in a more stable manner than ball type C, see Figure 3 (d) compared to Figure 3 (c). The corresponding extra degree of surface rippling can be seen in Figure 4(c) compared to Figure 4 (d). The high speed footage, as shown in Figure 4, reveals the deformation characteristics of the ball types. For ball types A, C and D, the deformation was predominantly local with little or no expansion parallel to the impact plate. In contrast, a larger proportion of the mass of ball type B was involved in the deformation, with the shape becoming elliptical and expanding slightly parallel to the impact plate.

A discrepancy between the two methods for measuring the distance over which the force acts is apparent when considering the damping. This difference is evident from the size of the hysteresis loops, as seen in Figure 3. The COM displacement method produces a hysteresis loop with a larger enclosed area than the diameter reduction method, particularly for ball types A and B, with the difference becoming more pronounced at increased velocities. This finding refutes previously published papers that claimed implicitly or explicitly that both methods are analogous [6–8]. The present paper appears to be the first to present data that contradicts this assumption. The difference between the two methods is manifested in the restitution phase of the impact (between maximum compression and the ball leaving contact with the plate), where COM displacement values lag behind the diameter reduction values. A larger difference is observed where the ball leaves contact with the plate with a larger residual deformation, which was the case with ball types A and B. This residual deformation was not permanent, as verified by measuring the ball diameter a few seconds after impact.

The difference in methods for quantifying the distance over which impact force acts may indicate a new measure for characterising the impact of a sports ball. Damping values calculated from the COM displacement method corresponds excellently to the dynamic energy loss ($1 - COR^2$) for all ball types and impact velocities. The lower damping values evaluated from the diameter reduction method is subject to further investigation, but testing to date suggests that the magnitude of this difference appears to be related to the rate of shape recovery of the ball. This in turn can possibly be related to the stress relaxation properties of the ball material. A larger difference between the methods seems to occur with ball types that exhibit a slower rate of shape recovery, as observed in the residual deformation in ball types A and B. Conversely, ball type D tended to reform to its original shape by the end of the restitution phase, with both methods yielding similar damping values for this ball type.

5. Conclusion

In order to produce a ball with desirable playing performance, it was necessary to characterise the performance of the currently approved sliotars cores. An automated test system was developed to characterise the impact against a rigid steel plate. Using data acquired using a load-cell incorporated into the impact plate and a high-speed camera running at 4000 fps, this system enabled the measurement of performance characteristics including coefficient of restitution, impact force, deformation and contact time, as well as the viscoelastic characteristics of dynamic stiffness and hysteresis energy dissipation (damping).

The characteristics of four sliotar cores were presented in this paper, two modern polymer ball types and two traditional cork-and-yarn ball types. Their viscoelastic properties were shown to be significantly different despite having similar rebound liveliness. This deviation in viscoelastic characteristics was attributed to the different materials and constructions, with constituent material interactions during impact resulting in a greater non-linearity in the performance of the traditional ball types with increasing impact velocities. This explained, at least in part, the deviation in performance experienced by players which had not been evident in the current low-velocity regulatory testing.

Two methods commonly accepted for quantifying energy loss were investigated, where the first method used the direct measurement of the diameter reduction during impact and the second method used the displacement of the ball's centre of mass (COM) as calculated from the double time integration of the force data. Comparison of both methods showed similar dynamic stiffness measurements but a significant difference in damping measurements, thus refuting the frequent assumption that these methods were analogous [6–8]. Work is ongoing to investigate if the difference between the methods is relevant to the characterisation of a sports ball impact.

Acknowledgements

The authors would like to thank the Gaelic Athletic Association for their financial support for this research.

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