Viscoelastic impact characterisation of solid sports balls used in the Irish sport of Hurling

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Abstract

In recent years, variability in behaviour of the sliotar, a small leather-bound ball used in the Irish sport of hurling, has become evident in championship matches. The inconsistency in performance was attributed to the range of constructions and material compositions of currently approved ball types. With a view to adopting a standard core, a new methodology has been commissioned to assess the dynamic impact behaviour of approved sliotar cores. In this paper, the relationship between the dynamic stiffness and the coefficient of restitution is presented with regard to material properties, ball construction and viscoelastic strain and strain-rate dependencies. The modern polymer ball types were shown to exhibit strain-rate sensitivity, while the performance of the traditional multi-compositional ball types exhibited lesser strain-rate dependence. The traditional balls types were shown to be up to 2.5 times stiffer than the modern ball types, with this finding having implications for ball energy dissipation.

1 Introduction

Hurling is one of the Irish national sports, involving a ball called a sliotar being struck by a wooden stick called a hurley. The controversial variation in performance of the sliotar in recent years has been attributed to the variation in construction of the core of the ball. Current regulations donot specify the core material or construction, but do necessitate that the ball lies within a specified range of mass, diameter and rebound height (when dropped from a height of 1.8 m) [1].

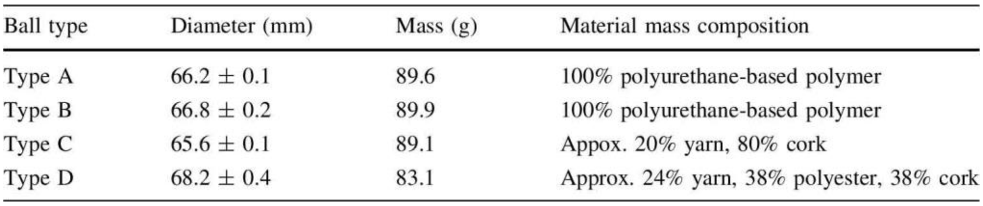
Traditionally, the sliotar core was constructed from a cork sphere wrapped in yarn, but in recent years popularity has grown for a single polymer sphere due to the lower cost and labour required for manufacture. The increased variation in core design, combined with a growing variation in the design of the polymer balls [observed at the Gaelic Athletic Association (GAA) testing facilities 1] has resulted in a change in per-formance of the sliotar. This has led the GAA, the gov-erning 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 currently approved sliotar cores had to be characterised in order to identify the desired impact characteristics.

To understand the effect of a ball's structural properties on performance, it was necessary to explore the contribution of its viscoelastic components to the perfor-mance characteristics. Such an understanding was required in order to manufacture ball types of specific playing performance. While the results of this study are applied directly to hurling balls, they also have clear applications in understanding the impact behaviour of similar solid spherical balls.

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 ribs (2.0-2.8 mm). It is similar in size to a baseball or cricket ball, with diameter of 69-72 mm (excluding the ribs) and a mass of 110-120 g. Four sliotar ball types are presented in this paper, representing the two principal core construction types: the traditional cork-and-yarn ball type and the modern polymer foam ball type. Details of these ball types are specified in Table 1.

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	100% polyurethane-based polymer
Type B	66.8 ± 0.2	89.9	100% polyurethane-based polymer
Type C	65.6 ± 0.1	89.1	Appox. 20% yarn, 80% cork
Type D	68.2 ± 0.4	83.1	Approx. 24% yarn, 38% polyester, 38% cork

The diameter is of the core (excluding the leather)

For the purposes of this work, the leather skin was removed to allow testing of the core. This was done for two reasons: first, the variation in the material of the core had been previously identified as the dominant source of variation in the ball performance [2]; and second, the simpler geometry of the core (i.e. absence of ribs) enabled a more comprehensive impact characterisation. The cross-sectional composition of the cores of the four ball types are displayed in Fig. 1.

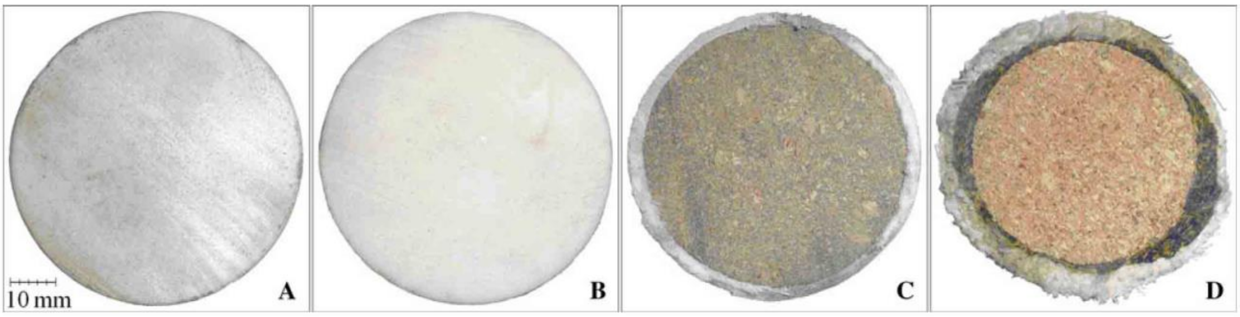


Fig. 1 Cross-sectional pictures of sliotar core ball types A (polymer), B (polymer), C (yarn and cork) and D (yarn, polyester and cork). Note: the non-spherical appearance of balls C and D are due to disfiguration from cutting

1.2 Impact characterisation

The impact behaviour of a sports ball can be described principally by the two viscoelastic components of stiffness and hysteresis energy dissipation. The stiffness component dictates how a ball deforms under impact, while hysteresis energy dissipation or damping describes the kinetic energy loss corresponding to that deformation. Energy dissipation is frequently measured by the coefficient of restitution (COR), as seen in official regulations for major sports [3, 4]. A rigid impact surface is used such that the measured characteristics are intrinsic to the ball itself. COR can be translated to kinetic energy loss according to: (1 — COR2). The measurement of ball stiffness has become more prevalent in recent years, as evident from the new regulatory standard introduced for baseballs and softballs [5]. The stiffness value dictates how energy is partitioned between the ball and the striking object (such as the bat/hurley). This is significant for translating between rigid-surface characteristics of regulatory testing and compliant-surface impacts typical of sporting conditions. For example, two balls with similar rigid-body COR but different stiffnesses will have different rebound speeds from a compliant surface impact. When the restitutive properties of the striking object exceed those of the ball, as occurs with the trampoline effect' in a baseball bat, the stiffer ball will rebound quicker than a more compliant ball [6, 7]. In addition, stiffness is perhaps the closest engineering measurement to correspond to ball hardness as perceived by a player.

1.2.1 Viscoelastic characteristic dependencies

Viscoelastic properties can depend upon deformation magnitude (strain dependence) and deformation rate (strain-rate dependence). The strain dependence of viscoelastic characteristics, apparent from dynamic stiffness fluctuations throughout the impact duration, has been reported frequently in the literature [8-12]. This variation in stiffness is due to the engagement of disparate material layers depending upon the extent of deformation. This results in a difference in performance for multi-compositional constructions, such as in tennis balls [8, 9], multi-piece golf balls [10, 11] and hockey balls [12]. In addition, polymeric foam materials can exhibit abrupt changes in their force-time histories corresponding to a transition from linear elastic cell bending to foam cells collapsing by elastic buckling, plastic yielding or brittle crushing [13-15].

Some ball constructions, particularly those involving polymeric materials, exhibit strain-rate dependencies. This sensitivity to strain-rate appears more pronounced at high strain rates in the region of 1,000 s-1, a region representative of impact conditions [16, 17]. The high strain-rate dependence of polymeric foams has been attributed to both the matrix material properties and the presence of air inside the foam [13]. When the foam deforms, the air is com-pressed or forced outside, depending on the foam cellular structure (closed or open cells, respectively). This airflow is strongly influenced by the deformation rate, hence resulting in strain-rate sensitivity. In a bid to study the strain-rate dependence of stiffness in isolation of its strain dependent properties, Fuss conducted quasi-static compression tests on cricket balls, with higher stiffnesses recorded for faster compression rates [18]. In a study of softballs, Smith attributed the strain-rate dependence of stiffness to three components of non-linearity: ball curvature flattening, as accounted approximately by classical Hertzian theory; geometrical effects of large deformation (strain dependence); and material rate-dependent properties [19]. These results suggested that the material strain rate-dependent properties, in that case the non-linear softening of polyurethane material, dominated the geometrical (strain dependent) nonlinearities. Using quasi-static compression and split Hopkinson pressure bar apparatus, Bryson found the stiffness modulus of softball material samples increased by an average of 33% over the strain-rate range of 0.3-2780 s-1 [20].

1.2.2 Viscoelastic characterisation methodologies

A number of methodologies have been employed in the literature to evaluate material viscoelastic properties, with each reporting varying degrees of success. Many of these methods have sought to represent dynamic impact conditions without the complexities and deficiencies of actual impact testing. Quasi-static compression has been the subject of many conflicting reports [8, 11, 18, 20, 21]. While being relatively easy to conduct, this method has questionable applicability to impact behaviour due to the difference in deformation (bilateral symmetrical compression in quasi-static compression compared to unilateral asymmetrical deformation in impact) and the substantially smaller deformation rates involved [19, 22, 23].

Stress relaxation is another frequently used quasi-static method [18, 24-26], where the force response of a strained sample is measured for an extended period of time. Ranga et al. [26] concluded that stress relaxation is not sufficient for predicted short-term material response, thus having limited applicability to dynamic impact conditions. Dynamic mechanical analysis (DMA) is a well-established method for determining material viscoelastic properties, involving the measurement of the material response to cyclic vibrations.

However, Smith et al. [27] reported issues in using DMA to characterise the softball polymer material, where the small strains induced during DMA lie within the linear range of the polymer material response and therefore do not account for the non-linear softening that occurred at large strains. The split Hopkinson pressure bar apparatus has been used in recent studies of softballs [20, 28, 29]; however, a number of issues were observed. The thin specimen used to attain uniform stress distribution—a requisite for the validity of this technique—limits the strain magnitudes and range of strain rates achievable by the apparatus. In addition, the split Hopkinson pressure bar does not describe the unloading response, thus not permitting material hysteresis to be quantified. Few studies appear to measure viscoelastic characteristics directly from impact data, perhaps due to the complexities involved with high speeds and tiny durations of typical ball impacts. The selection of deformation values poses an issue in the derivation of force-displacement graphs. Numerous methods for quantifying deformation are featured in the literature: diameter compression, the reduction of diameter of the ball normal to the impact plate; lateral expansion, the increase in ball diameter parallel to the impact plate; and centre of mass (COM) dis-placement, calculated from the double time integral of the force divided by ball mass. Many publications assume, either explicitly or implicitly, that diameter compression and COM displacement are equivalent [30-32], neglecting the effect (if any) of lateral expansion. The studies that have considered lateral expansion do not refer to COM displacement [33, 34]. The publications that have constructed force-displacement curves used COM displacement values, although these graphs were not used to evaluate stiffness [27, 32]. Equation 1, an expression for dynamic stiffness (k), has been widely used in recent years in softball studies [6, 19, 20]. This equation is derived from the energy balance at maximum deformation, under the assumption that the ball exhibits linear elasticity. The equation is a function of ball mass m, peak impact force Fp and incident speed u.

$$k = \frac{1}{m}\left(\frac{F_p}{u}\right)^2.$$

This equation has been used with reported success, providing a better association with ball performance than the quasi-static measure of stiffness [6]. This measure of dynamic stiffness has since been incorporated in official regulations for baseball and softball in the recently published ASTM F2845 standard [5]. However, it is not fully evident that a singular value of dynamic stiffness can be used to completely evaluate experimentally derived dynamic stiffness, particularly given the reported fluctuation of dynamic stiffness throughout impact [8-15].

1.3 Aims

The primary aim of this paper was to evaluate the viscoelastic impact characteristics of the solid cores of the sports balls used in hurling. The contribution of the different material compositions to the viscoelastic characteristics was investigated, enabling the ball's structural properties to be related to performance.

A secondary aim of this paper was to explore the merits of the methodology utilised for viscoelastic characterisation, with comparison to the methods employed in the literature. A number of obstacles were referred to above regarding the derivation of viscoelastic characteristics directly from impact data. This study addressed these issues, including the ambiguity surrounding the measurement of ball deformation, the evaluation of dynamic stiffness and the strain and strain-rate dependencies of ball dynamic stiffness.

2 Experimental work

An automated test system was developed to evaluate performance and viscoelastic impact characteristics. This system was to serve as the platform for official regulatory testing for the GAA. In this system, a custom-built pneumatic system projected the ball at speeds of 5-38 ms^{-1} (15-140 km/h), with precise aim and zero spin, to strike a rigidly mounted steel impact plate. Speed and deformation characteristics were acquired from high-speed footage at 4,000 frames-per-second with a shutter speed of 1/12,000 s (MC1302, Mikrotron GmbH, Germany). Force-time data and COM displacement were attained at 50 kHz from an axial compression load-cell (RLU02500, RDP Electronics Ltd, UK) integrated into the impact plate. The data acquisition was validated by the impulse (area under the force-time curve, $\int F$ dt) agreeing with the momentum differential (measured from high-speed footage, m {u — v}) within 3% for all impacts. The operation of this test system was described in greater detail in a previous publication [35]. Four samples of each ball type were subjected to impact testing at speeds between 5 and 25 ms^{-1} in 5 ms^{-1} increments. Testing was conducted at 22 ± 2°C at 55 ± 10% relative humidity, with the ball samples equilibrated at these ambient conditions for at least 2 weeks. This period of time allowed the balls to reach steady state ambient conditions in accordance to previous studies on polyurethane softballs [6].

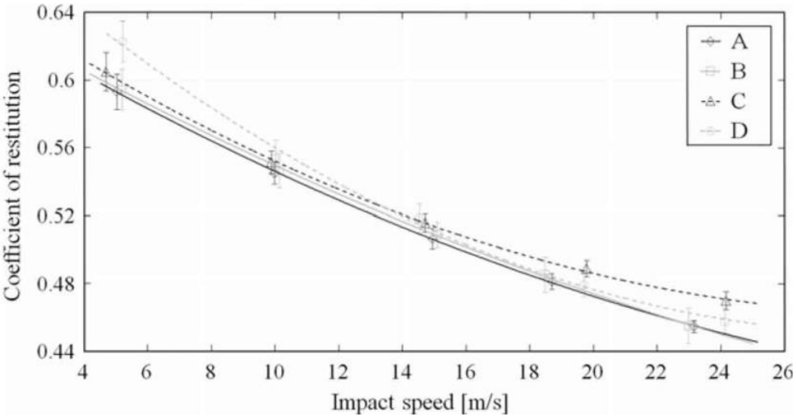
The intra-ball type variation in experimental data, which was attributable to variations in ball material and constructions arising from ball manufacture inconsistencies, was small compared to the inter-ball variation. In order to directly compare the stiffness and COR data without being misled by averaging across this intra-ball variation, the results of one representative sample of each ball type are presented in this paper. Ball speed, coefficient of restitution, diameter compression and lateral expansion were measured from high-speed footage via a custom-written image processing algorithm [36]. The viscoelastic data were derived from the combination of force and deformation data to form the force-displacement hysteresis curve, with the data combination validated when the area under the loading portion of the hysteresis curve equalled the initial kinetic energy of the ball. To account for the non-constant gradient of the force-displacement curve, two measures of stiffness were evaluated for each impact.

These measures of stiffness were computed by using two linear sections to define the compression phase of force-displacement curve. The linear sections were calculated by fitting linear trends to the experimental data using the Least Square method. The extremity points of the linear trends were initially determined visually, with refined adjustment to optimise the R-squared correlation values. The slopes of the two linear trends yielded two stiffness values, where the initial averaged slope was termed initial stiffness and the subsequent averaged slope was termed bulk stiffness.

3 Experimental results

The coefficients of restitution values for the four ball types are displayed in Fig. 2. All ball types were seen to exhibit relatively similar rigid-body impact energy dissipation, as indicated by the rigid-body COR values of all ball types lying within a 10% range. However, differences were evident in comparing the two principal construction types. The two modern polymer ball types (A and B) followed similar, almost linear trends with increasing impact speed.

Fig. 2 Variation in coefficient of restitution with impact speed for sliotar cores A, B, C, and D



The two traditional cork-based ball types (C and D) exhibited a greater non-linearity, as evident from the deviation of ball type D at lower speeds and of ball type C at higher speeds. Discrepancies between the values of diameter compression and COM displacement were observed for some ball types, particularly the polymer ball types A and B, becoming more pronounced at increased speeds. This is shown in Fig. 3, where the distance between the dotted outline and the ball edge indicates the difference between the diameter compression and COM displacement values.

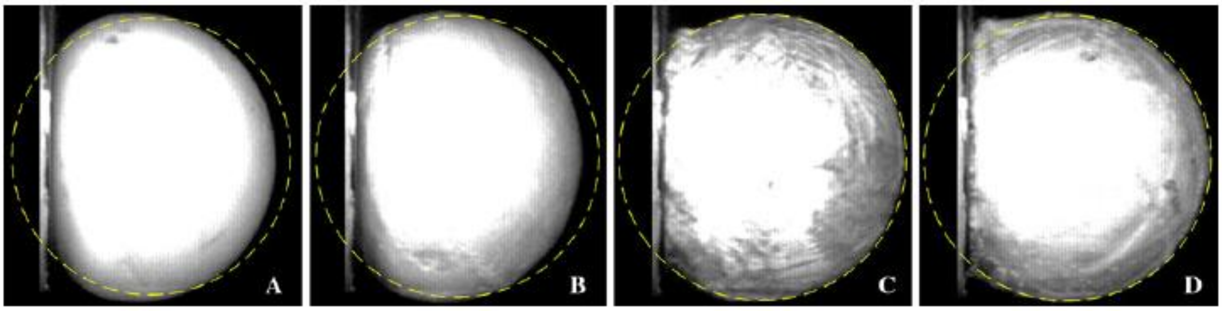


Fig. 3 Images captured at maximum deformation from impact tests performed at 25 ms^{-1} for ball types **a** A, **b** B, **c** C, and **d** D. The *dashed circle* shows ball original circumference, centred at maximum COM displacement

This disparity was linked to the extent of lateral expansion of the ball during impact, as seen in comparing ball types A/B and C/D in Fig. 3. Where lateral expansion occurred, as in ball types A and B, the diameter compression values exceeded the COM displacement due to the spreading of ball material parallel to the impact plate. The derivation of dynamic viscoelastic characteristics required the compilation of force-displacement curves from impact data; however, the disparity between the diameter compression and COM displacement posed an issue in the selection of appropriate X-axis values.

The validity of force—displacement curves was confirmed by comparing the area under the compression phase (top edge) of the curve, ff' dx, to the initial kinetic energy of the ball, m u2: these values should equate as the cumulative energy from initial contact at a speed u to static maximum compression corresponds to the complete expenditure of the ball's incident kinetic energy. Similarly, the proportion of area enclosed within the hysteresis loop should correspond to the kinetic energy loss, 1 — COR^2.

It was found that the use of diameter compression values resulted in an area under the loading portion of the curve in excess of each ball's initial kinetic energy, thus indicating that this measure of deformation was unsuitable for compiling force-displacement data curves. Use of the COM dis-placement values resulted in both the areas under the compression phase of the curve and within the hysteresis loop agreeing within 3% of the initial kinetic energy and kinetic energy loss, respectively. Examples of the validated force-displacement curves for the range of test speeds are shown in Fig. 4.

The non-linearity of the compression phase of the force—displacement curve indicated that the dynamic stiffness was not constant. This non-linearity was accounted for the two approximations of linear stiffness, namely initial stiffness and bulk stiffness. These approximations accounted for the observed change in gradient of the force—displacement curves that occurred between 20 and 30% of maximum deformation for all ball types.

The evaluation of the initial and bulk stiffness values is illustrated in Fig. 5. A good R-squared correlation of at least 0.98 was found between the experimental data and the linear trends of both initial stiff-ness and bulk stiffness. The correlation was seen to reduce to between 0.94 and 0.96 for ball type A at higher impact speeds (greater than 20 m/s), where fluctuations with a maximum deviation of 7% from the linear fit were attributed to the deformation response of this material type.

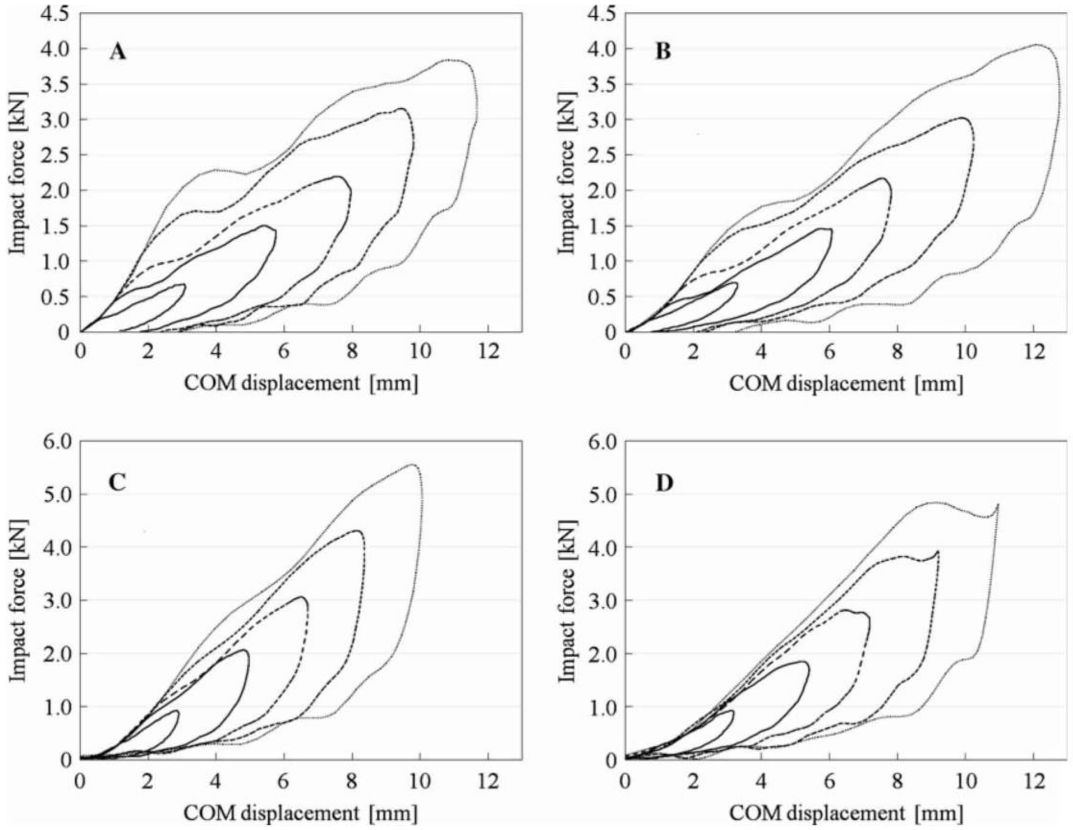


Fig. 4 Typical force-displacement data for impact speeds of 5, 10, 15, 20 and 25 ms^{-1} for ball types A, B, C and D

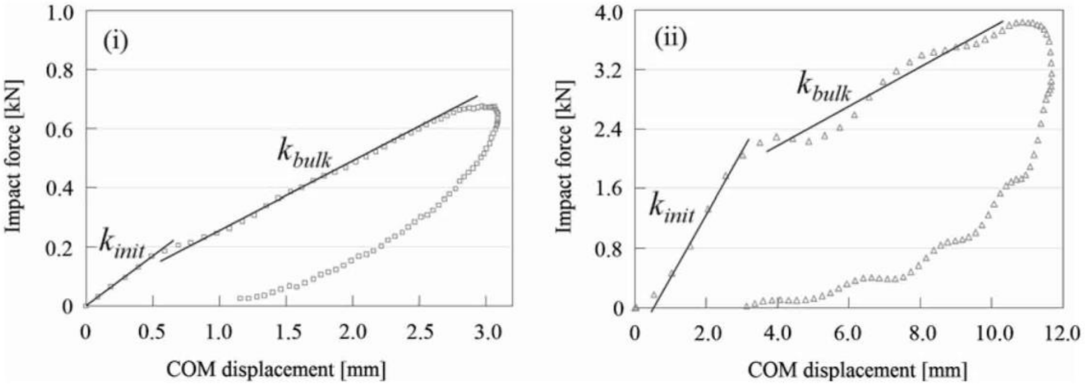


Fig. 5 Demonstration of initial stiffness and bulk stiffness for ball type A for impact speeds of (**i**) 5 ms^{-1} and (**ii**) 25 ms^{-1}

The initial and bulk stiffness values, along with values computed from Eq. 1, were plotted for all tested impact speeds in Fig. 6.

In general, the stiffness values for all ball types increased with increasing speed. For ball types A, B and to an extent C, the initial stiffness exceeded the bulk stiffness, with discrepancy diverging with increasing speeds. Conversely, for ball type D, the initial stiffness was less than the bulk stiffness for all impact speeds. The computed values of Eq. 1 were found not to be universally applicable to all tested ball types. For the polymer ball types (A and B), the equation results were within the region of the bulk stiffness values, although underestimating the magnitude by approximately 10%. For ball type C, the magnitude discrepancy between the equation result and bulk stiffness was less satisfactory at up to 15%.

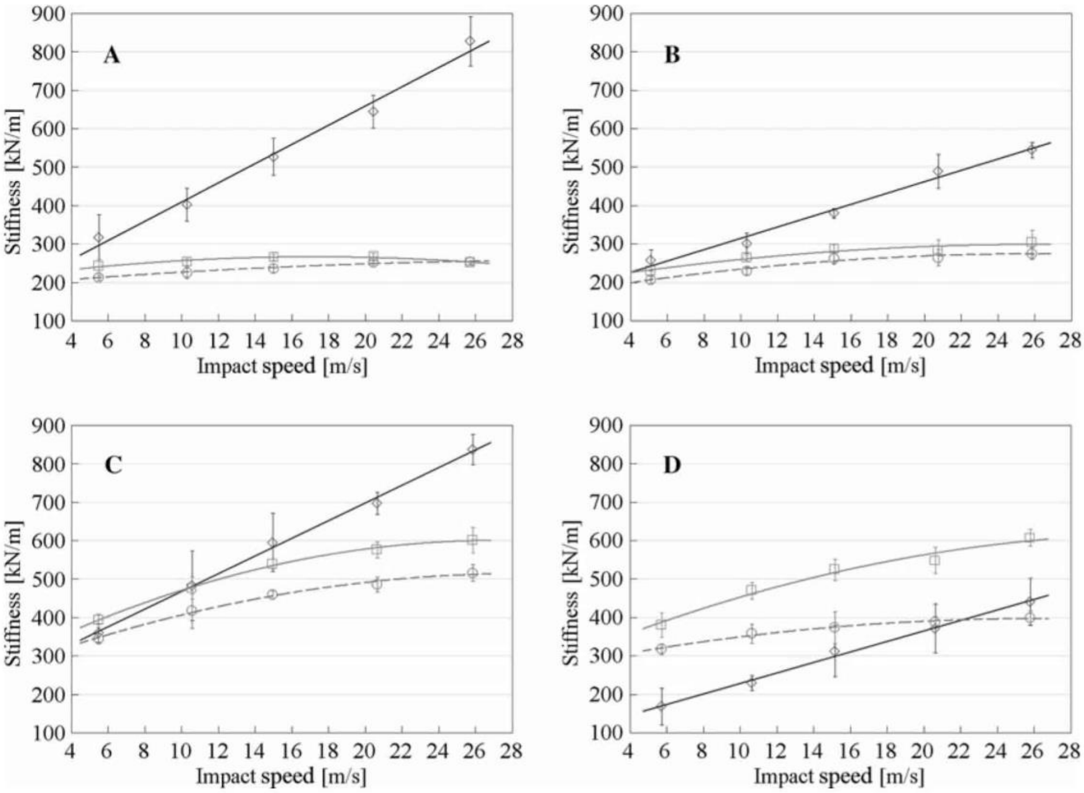


Fig. 6 Trends of dynamic stiffness according to Eq. 1 (*circles*), initial stiffness (*diamonds*) and bulk stiffness (*squares*) for ball types A, B, C and D

There was no reasonable association between the equation computation and either experimentally measured value of stiffness for ball type D, with significant diverging deviation of 20 to 35% observed between bulk stiffness and the equation result.

4 Discussion

In terms of performance, the similarity of the coefficient of restitution values for the four ball types as shown in Fig. 2 was not surprising, considering that these ball types had previously exhibited rebound properties within the approved range as determined from the 1.8 m drop test, albeit with their leather covering in place. The speed-relationship of the traditional ball types (C and D) was more non-linear, resulting in a divergence in performance from the modern types (A and B). The fact that this deviation in performance was not evident in the current low-speed regulation testing illustrates the need for high-speed testing for comprehensive characterisation.

As discussed in Sect. 2, the quantification of deformation has been the subject of many conflicting reports, particularly with regard to the measures of COM dis-placement and diameter compression. Over the course of testing the sliotar cores, a difference was observed between these two measurements for ball types that exhibited lateral expansion. Previous publications' statements of equivalence [30-32] between COM displacement and diameter compression methods were shown in the present study as being acceptable, not for the reasons given in the original papers but rather due to the absence of lateral expansion in the ball impacts examined. As the lateral expansion occurred parallel to the impact plate and hence was imperceptible to the axial load-cell, it augmented the diameter compression due to volumetric spreading of ball material without affecting the COM displacement as derived from the load-cell force data.

Diameter compression and lateral expansion were in fact useful measures for characterising impact behaviour [33, 34], yielding a true description of the change in shape of the ball. However, the deformation values of diameter compression and lateral expansion were dissociated from the measured impact force, thus being invalid for viscoelastic characterisation. With the force data validated from agreement of impulse and momentum differential in the present study, the derived COM displacement satisfied the criteria for valid force—displacement curves. To consider it from a different point of view as seen in Fig. 3, the COM displacement depicted the depth of the ball engaged with the impact plate, thus representing the dis-tance through which the force acted. This was verified by COM displacement values producing validated force-dis-placement curves in terms of energies and graph area calculations.

Examples of the validated force—displacement data for the four selected sliotar types were plotted in Fig. 4. The shape of the hysteresis curve differed for each ball type, though non-linearity was discernible in the leading edge of each curve. This implied a fluctuation of dynamic stiffness throughout the impact. Initial stages of deformation involved the flattening of the ball curvature up to 20-30% of maximum deformation for all ball types, with sub-sequent stiffness response dependent upon the ball material and construction. The initially steep gradient observed for the polymer ball types was a compound of the inherent cell wall bending material response and the flattening of the surface curvature. The stiffness decreased beyond this initial response, which likely corresponds to the collapsing of the foam cells [13-15]. In addition, the occurrence of lateral expansion served to reduce the stiffness due to the dissipation of impact force perpendicular to the load-cell. Additional fluctuations were apparent in ball type A, evident from the lesser agreement of the bulk stiffness at higher speeds [compare Fig. 5(i) and (ii)].

These fluctuations arose from this material type's response to deformation, though the precise nature of deformation was difficult to determine. External deformation, i.e. surface wave propagation from the contact point during compression, was not conclusively evident from high-speed footage due to pixel resolution and frame-rate constraints. Internal deformation, involving the compressive response of the polymeric internal structure, could not be characterised by conventional high-speed footage due to material opaque-ness. Comparison of the radial Shore hardness measure-ments [37] of the internal cross section of the dissected ball types A and B did not reveal any significant difference that would explain the observed difference in material response in high-speed impacts.

For the multi-compositional traditional ball types (C and D), the fluctuation in dynamic stiffness was due to the dissimilar material layers' contribution at increased levels of deformation. In ball type C, the early stages of deformation involved tightly wound yarn with subsequent deformation involving the cork material. In ball type D, increased deformation progressively engaged the yarn layer, polyester layer and eventually the internal cork core. Where the yarn and polyester layers were the dominant materials involved in the deformation (i.e. at lower impact speeds), a smaller stiffness was produced due to the strands slipping over each other. As the ball became compressed beyond the yarn/polyester layers, the cork material presented a higher stiffness to the deformation. At such deformations, the oscillation of the small cork core within the other material layers produced a double peak force, a finding consistent with previous observations of multi-compositional ball types [8, 10]. This was apparent from the fluctuation in experimental data at maximum deformation for the 20 and 25 ms-1 force-displacement curves as seen in Fig. 4d. The fluctuation of dynamic stiffness throughout impact was simplified by approximating linear trends in two regions. These regions were divided by the change in gradient of the force—displacement curve that occurred at 20-30% of maximum deformation for all ball types. This produced two measures of dynamic stiffness labelled 'initial stiffness' and 'bulk stiffness', as demonstrated in Fig. 5. The speed relationship of these stiffness values was plotted in Fig. 6. For the polymer ball types, the initial stiffness exceeded the bulk stiffness for all speeds due to the compliance arising from inelastic foam cell buckling and lateral expansion. For ball type C, the initial stiffness was less than the bulk stiffness at lower speeds due to the dominant contribution of the softer yarn layer. The inner cork core became increasingly engaged at greater deformations, resulting in the initial stiffness converging with and exceeding the bulk stiffness. For ball type D, the initial stiffness was less than the bulk stiffness for all tested speeds due to the compaction of the relatively thicker layer of soft yarn and polyester. The initial stiffness was found to increase at a significantly more rapid rate with respect to impact speed than the bulk stiffness.

For polymer balls, a significant divergence between initial and bulk stiffness was observed at higher speeds. As the initial stiffness occurred during the maxi-mum strain rates during impact, the deviation between initial and bulk stiffness was attributed to the increased contribution of polymer strain-rate dependencies at such speeds. The smaller deviation between initial stiffness and bulk stiffness for the traditional ball types suggested a lower strain-rate dependency in this material, in accordance to previous findings regarding cork in the literature [12]. Bulk stiffness was seen to increase at a slower rate for all ball types, in contrast to the more rapid increase in initial stiffness. For ball type A, the bulk stiffness trend appeared to decrease at the maximum tested speeds, with this observation attributed to the dominating effect of initial stiffness for this ball type. Compared to the traditional ball types, the bulk stiffness increased at a smaller rate for the polymer ball types, with approximate increases of 11 and 32% for ball types A and B respectively over the range of tested speeds.

In contrast, the rate of increase in bulk stiffness was significantly greater for the traditional ball types, with the magnitude increasing by approximately 47 and 65% for ball types C and D, respectively. This strain dependence of the traditional ball types (C and D), consistent with previous findings regarding multi-compositional balls [8-12], related to the disparity in linearity of the ball types' COR-speed relationship. The bulk stiffness strain sensitivity of these traditional ball types resulted in the greater non-linearity evident in Fig. 2, accounting for

the divergence in performance between the modern and traditional ball construction types. In addition to explaining the linearity of ball COR data, the stiffness values allow the translation of rigid-body impact characteristics to compliant body characteristics that would be more representative of the sport. Considering the bulk stiffness values, the traditional balls were significantly stiffer than the modern types. The polymer ball types occupied a stiffness range of 200-300 kN/m; by comparison, the traditional ball types C and D occupied stiffness ranges of 450-650 and 350-580 kN/m, respectively.

This difference in stiffness is relevant for sports-representative compliant-body impacts, such as involving the hurley. The greater stiffness of traditional ball types would result in a larger proportion of the impact energy stored as strain energy in the compliant body and a smaller proportion stored in the ball. For example, if the compliant body was more energy efficient than the ball, as occurs with the trampoline effect in baseball bats, the traditional ball would rebound quicker than indicated by the rigid-body COR due to the lesser amount of energy dissipated in the impact. Therefore, the difference in stiffness between the modern and traditional ball types would result in a greater difference in performance between the two principal construction types than indicated by the rigid-body COR values in Fig. 2.

In addition to the change in rebound speed from a compliant surface, the dissimilarity in stiffness between the two principal ball constructions would have implications for players' perceptions of feel and comfort. This may explain, in part, the growing preference of the polymer ball types in the sport. There was no consistently favourable comparison between dynamic stiffness derived from Eq. 1 and that experimentally measured for the ball types tested in this work. While an approximate agreement was observed between the equation results and bulk stiffness values for the polymer ball types, such agreement was more tenuous for ball type C, and no reasonable association was apparent for ball type D. The discrepancy in the results from Eq. 1 highlights the limitations of the underlying assumptions of this equation. The first assumption, that a ball exhibits linearly elastic behaviour, was violated by the observed increase of stiffness with respect to speed for all ball types. Moreover, the strain-sensitivity of the traditional ball types (A and B) implied significant non-linear elasticity, explaining the poorer comparisons with these balls' stiff-ness values. The second assumption of the equation con-cerned the time-coincidence of peak force and maximum deformation. As discussed previously, ball type D exhib-ited a double peak in the force-time profile—a character-istic of ball types with dissimilar material layers.

Therefore, the peak forces occurred a short time before or after maximum deformation. Aside from the accuracy of the equation results, Eq. 1 ' s purpose of defining a single stiffness value for an impact has questionable applicability given the non-linearity of stiffness observed in these ball impacts. The disparity between initial stiffness and bulk stiffness evident in Fig. 5 indicates that no single measure of stiffness describes the ball behaviour in isolation. Indeed, representation of the fluctuating force-displacement gradient as two linear sections was also a significant simplification, one which did not fully express the true stiffness response of the ball. However, research studies, particularly those that represent commercial or official regulatory interests, may require a simple expression of ball stiffness rather than convoluted functions of dis-placement or speed. Perhaps this was the motivation for the incorporation of Eq. 1 in the new ASTM regulatory standard, although the present study indicated limited applicability for this equation for some ball constructions.

5 Conclusions

The viscoelastic characteristics of the solid sports balls used in hurling were evaluated in an automated test system developed for this purpose. This test system was commissioned by the GAA to serve as the official regulatory plat-form for ball testing. The impact characteristics of four ball types were presented in this paper: two modern polymer types and two traditional multi-compositional constructions. The four ball types were found to have relatively similar rigid-body coefficient of restitution characteristics, but with greater speed-dependent non-linearity evident for the traditional ball types. This non-linearity was attributed to the significant strain-sensitivity of the stiffness response exhibited by the traditional ball types.

Consistent with findings in the literature, the stiffness response of the polymer ball types was strain-rate dependent. There was a significant difference in stiffness between the different ball constructions, with the traditional ball types tending to be 60-140% stiffer than the modern types. This would produce differences in performance between ball types beyond those indicated by rigid-body COR values. The translation from rigid-body impact to compliant surfaces representative of sporting conditions, where the ball is struck with a wooden hurley/stick, would require the definition of the restitutive properties of the hurley.

The aforementioned conclusions were derived from characterisation of impact data, facilitated by the developed test system. This test system overcame the limitations associated with other methods of viscoelastic characterisation by allowing the evaluation of both stiffness and energy dissipation at deformations and deformation rates representative of those occurring in the sport. This paper addressed the ambiguities presented in previous studies of impact testing, such as the quantification of ball deformation, the derivation of stiffness from impact data and the investigation of strain and strain-rate dependencies of ball stiffness.

The COM displacement and diameter compression were found to be non-equivalent in the presence of lateral expansion. Although each measure of ball deformation had its merit in ball characterisation, COM dis-placement was found to be appropriate for viscoelastic characterisation due to its correct association with the impact force data. The fluctuating nature of the dynamic stiffness was represented by two measures, the initial stiffness and bulk stiffness. Although these measures did not fully replicate the true dynamic stiffness response, they provided simple and useful representation of ball stiffness with good experimental repeatability.

In addition, this offered an improvement in comparison to the common method of using a single measure of stiffness. The deviation between initial and bulk stiffness values was an indication of the strain-rate sensitivity, while the rate of increase of bulk stiffness with respect to impact speed demonstrated the strain dependence of the viscoelastic response. The simplicity and convenience of use of the dynamic stiffness equation (Eq. 1) is undeniable, and its recent acceptance in softball regulatory testing is understandable given its approximate replication of polymer bulk stiffnesses. However, the unacceptable representation of the tradition ball types provided by this equation implied that it could not be implemented in sliotar guidelines.

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