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Research Paper

Impact Dynamics of Nonlinear Materials: FE Analysis

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Abstract. The paper presents an experimentally validated 3D finite element modelling impacts of viscoelastic and natural materials. It considers, in particular, the material set of ash wood and rubber in the context of the impact between the bat (the "hurley" made of ash wood) and the ball (the "sliotar" made of polyurethane-cork composite) in the Irish game of hurling. The hurley is highly anisotropic in its mechanical properties and this impact system therefore presents a unique modelling challenge. The FE models do not rely on either the assumption of linear materials models or on calibrated materials models. The FE models are able to take all three geometric, status and material nonlinearities into account yielding a close correlation with real-world impact scenario. The reported FE results were validated against experimental measurements showing an excellent correlation of more than 91% in term of maximum ball deformation.

Keywords: Viscoelastic materials, ash wood, finite element, materials nonlinearities, modeling and simulation.

1. Introduction

High-force impacts between natural materials, e.g., wood, and nonlinear elastic materials, e.g., cork-rubber materials, are very common in real-world applications, in particular, bat-and-ball sports. Such impacts cause high forces in the equipment structure, and in turn result stresses in the equipment structure itself. Knowing the resultant stresses is very essential in engineering bat and ball structures and materials. In literature, Finite element (FE) has been extensively utilized to offer a thorough analysis of such impacts, however, F analyses of such impact is very complicated [1] as it requires (1) advanced materials models to account materials nonlinearity, (2) considering the large amount of deformation of impactors, and (3) considering nonlinear boundary condition, or what so called, contact problem. Due to the multiple non-linearities involved, mechanical modeling of such interactions is very challenging and requires complex analysis and parameter measurements. A successful FE approach to model and simulate such impacts is presented in this paper which takes the Irish game of hurling as a specific case study. The game is played with a ball called a "sliotar" made of a viscoelastic cork/rubber core and a wooden bat called a "hurley" made of ash timber [2, 3]. Since a strong impact with the hurley can propel the sliotar at initial speeds of over 150 km/hr to a distance of over 100 m, hurling features amongst the highest bat-ball impact forces of any sport and amongst the highest impact forces for this type of material set in any real-life impact scenario. The nearest comparison, in terms of impact forces, is in baseball.

In the literature, FE analysis has been used widely to model and simulate the impact systems that occur in bat-and-ball sports. The approaches used are mainly based on linear isotropic material model approximation and/or on calibrated materials models to match a measured impact data set. Using the linear material model approximation approach, much work has been done on modeling the impact system in baseball, e.g., [4-8]. In [4], the dynamic interaction of a baseball and a wooden bat was numerically modeled and simulated, to confirm the dependency of the developed stress in the bat structure on the impact location and bat stiffness. A similar FE model was proposed in [6] to maximize baseball bat performance. The material model was, however, based on a linear elastic model of the ball and a linear orthotropic material model of the bat [4, 6, 8]. Nicholls et al. [5] developed an explicit FE model to simulate the time-dependent response of two brands of baseball based on a linear viscoelastic materials model approximation. Two baseball bat designs (hollow-metal-based and wood-based) were considered in [7] to investigate the influence of the bat design on the ball exit velocity (BEV); the study was FE-based with ANSYS/LS-DYNA as the FE solver and using linear elastic materials mechanical properties to study the influence of the bat design on the ball exit velocity (BEV). The maximum BEV was found to be 61.5 m/sec and 50.9 m/sec for metal and wooden bats, respectively. Furthermore, a recent study of baseball bats was presented by Smith et al. [9], the study examined the Maple and Ash wood materials, as baseball bats, using FE analysis based on linear materials model.

The impact system in golf, based on linear elastic materials models, has been investigated [10-13]. For instance, Cheong et al. [10] numerically evaluated the "gold shaft" (made of fiber-reinforced plastics), based on a linear transversely isotropic material model. In [13], a series of linear FE models of a golf ball was developed to study the effect of ball material and level of impact force on the ball response. Recently, a short abstract was presented in [14] as the only research work in the literature could be found about developing a FE model concerning the game of hurling: the abstract described basic FE models of a typical impact event in the game. The description, however, was limited to a linear elastic model of the materials with no experimental validation. A similar approach was proposed by Shen and Hopkins [15], a linear materials model was employed to study a rubber ball impact on a timber floor, aiming to predict the response of the timber floor when experience an impact from rubber ball at low speed, i.e., less than 5 m/sec. Although the use of a linear isotropic material model can help in developing a fast and low cost simulation, the accuracy of the simulation results cannot be depended on if a high impact-speed, i.e., a high strain-rate, is considered simultaneously with the nonlinear natural materials involved.

Many researchers have simulated high-speed impacts using calibrated material models, i.e., by tuning the mechanical properties of materials to experimental results in order to improve the simulation accuracy at high strain-rates. Mustone and Sherwood [16] developed and calibrated FE models to describe impacts in baseball, using an experimental data set to calibrate the materials models to get a high level of correlation of up to 99%. Singh [17] developed a calibrated FE model to simulate the bat-ball impact in cricket, different parameters were taken into account such as the ball mechanical properties, impact speed, and the properties of the bat willow wood. After materials properties calibration, the model was correlated with experimental data and found to be correlated to better than 5%. In [18], a research work was conducted to investigate rubber balls impacts dynamics. The work consisted of FE analysis based on fitted model of materials, where compression tests, for specific type of rubber materials, were conducted and the results employed to develop an Ogden's hyperelastic model. Thanakhuna and Puttapitukpornb [19] developed different fitted models of hyperplastic materials models available in ANSYS APDL, and employed these models in developing FE models. A good correlation was found in comparison to experimental data; however, the models were limited to Polydimethylsiloxane material only. Gutaj [20] also studied cricket bat dynamics using ANSYS as a FE solver: the Young's modulus of the bat material was tuned to match the natural frequency to a measured one. The model was found to be in a good agreement at low frequencies modes but some deviation was found at higher modes. Work on calibrated FE models for the tennis ball impact can be found in [21, 22]. In [22], an explicit calibrated FE model was developed to simulate tennis ball impact on a freely suspended racket and a wide range of ball speeds was considered at different impact angles.

However, in general, calibrated FE model have the drawbacks that (1) the developed model is only valid for the specific conditions of the impact scenario, i.e., according to the experimental data that used to calibrate the model and (2) the FE model is usually limited to only the specific design and material set of the impactors.

It can be concluded that current modeling approaches to the type of high strain-rate impacts do not take into account geometric/contact nonlinearities, and the actual models of the natural and viscoelastic materials involved in impacts. This paper, on the other hand, demonstrates a FE model of such impacts which does not rely on either of these approaches and which, furthermore, is capable of transient simulation. The model, ab initio, uses the actual anisotropic and nonlinear materials properties of wood and cork-rubber materials, superior to the common approaches in the literature such as: linear isotropic material models or materials models calibrated from experiments. Moreover, many published research work accounted small amount of strain during impact scenarios, while the proposed model accounts the high resultant strain which causes geometric nonlinearity. Finally, the proposed model considers changing status nonlinearity; or what so called contact nonlinearity, during the contact time. Combining all of these nonlinearities involved, FE analysis of such impact scenario is very challenging task, and requires complex analysis and parameter measurements. The main advantages in the description of the actual nonlinear behaviors of impactors can be summarized as: (1) it is capable to accommodate wide range of impact speed, (2) it predicts the impact dynamics more accurately, (3) it takes into account any possible interaction between impact parameters that might be caused by materials nonlinearities, and (4) the nonlinear models tend to be more robust compared with linear and calibrated models.

In terms of bat-and-ball sports, the model can provide a thorough understanding of such impact systems and can describe quantitatively the effect of the game equipment on the time-dependent variables of the impact. A unique case study, the Irish game of hurling, has been taken to verify this impact modeling approach and advances the modeling of this particular impact system beyond anything reported to date. The model has been simulated to speeds of up to 30 m/sec, where the relative speed in real impact scenarios is up to 30-35 m/second [23-25].

2. Methods

2.1 System variables

To study the input variables influence on the impact interaction, the design of experiments (DoE) approach was used. The input variables are the ball and bat brands, and the impact speed. For the ball brand, two brands A and B were assigned to level 1 and 2, respectively. The diameter of both brands was 70 mm and masses of 114 and 117 grams for brand A and B, respectively. The bat brand, two different brand A and B were considered and assigned to two different levels, with 813 mm (32 in) length each. All the ball and bat brands were approved by the Gaelic Athlete Association (GAA), the governing body of the sport [26]. The detailed materials models are presented in the next subsection. These variables were studied over a wide range of impact speeds, which was treated as a third input variable with two different levels. A 20 m/sec impact speed was assigned to the first level and 30 m/sec to the second level. Table 1 shows the coded matrix of the input variables levels. The ambient conditions, e.g., temperature and humidity, were kept constant as 20 C and 60% through the experimental runs, and so they were not considered in the proposed analysis.

Table 1. Coded matrix design.

No.	Ball brand	Bat brand	Impact speed
1.	1	1	1
2.	2	1	1
3.	1	2	1
4.	2	2	2

Four output variables were investigated as a part of the proposed model. The parameters the most significant for the bat-ball impact in hurling and other bat-and-ball sports were considered to be:

(1) The resultant impact force and duration, as it would be used for equipment design purpose, particularly when a new material is introduced.

(2) The stress distribution, this parameter is needed for equipment design purposes.

(3) The rebound speed, one of the most important standards of bat-and-ball sports is the coefficient of restitution (CoR) of the ball - it measures the dissipated energy during the impact. By measuring the rebound speed, the CoR is determined from: CoR = (Rebound Speed)/ (Inbound Speed).

(4) The contact area diameter and the maximum ball deformation (which is defined as the amount of ball squashed during the impact measured in mm), since the ball suffers frequent impacts during the game, observing the type and magnitude of deformation will provide useful information to study ball durability.

2.2 Materials model

An approach based on a linear elastic model was developed in previous work [14]. However, in this paper, a nonlinear materials model is developed. An Instron mechanical tester was used to construct the stress-strain diagrams at different strain-rates for the ball and bat materials.

2.2.1 The ball material model

The ball of the Irish game of hurling has a homogenous core made of polyurethane/cork core encased in a leather outer skin and is 70 mm in diameter and weighs 110-120 g [2]. Modeling of the ball core material is, however, a very complex task because of the highly nonlinear stress-strain behavior at high strain rates. In addition, the authors' research has identified significant variation in material properties for different ball brands, which requires testing of many samples.

Five samples of each brand were machined into a cube shape with 10±0.5 mm edge length. A high strain rate was then applied using the Instron to compress the samples to up to 50% strain and the corresponding load was recorded for each load sub-step. The stress-strain data, shown in Fig. 1, were then employed directly to develop a "response function (RF)" implemented in ANSYS software [27]. The advantage of RF allows fitting the experimental stress-strain data directly without a need for any nonlinear hyperelastic models. Moreover, it can handle highly nonlinear stress-strain data accurately in comparison to standard hyperelastic materials models [27]. Clearly, brand 2, which was assigned for the second level, is harder than brand 1, while both have the same Poisson's ratio 0.42. For the dynamic damping, an earlier work by the authors has characterized the dynamic damping of the ball materials using high-speed camera technology [28].

2.2.2 The bat material model

The bat in the Irish game of hurling is made of European ash; i.e. Fraxinus excelsior, [2]. The ash is a strong, springy and highly regarded because of its shock resistant qualities [2, 29, 30] and it is used in many bat-and-ball sports. Modeling of ash wood material is, however, an exceptionally challenging task in mechanical engineering because of the highly anisotropic mechanical properties which requires the development of three models in three different directions [29, 31]. A further challenge arises from its natural origin with many inhomogeneity's meaning testing of many samples in each direction [23]. Beside these challenges, the stress-strain behavior in each direction is a nonlinear one [31, 32].

To overcome these challenges, ash timber wood samples were prepared and tested using an Instron mechanical tester. Nine samples of each bat brand were tested on three different axes to overcome the inhomogeneity of the wood. The samples had a cube shape with 10±0.5 mm edge length. The nonlinear stress-strain behavior was fitted into a bilinear model for all axes as Fig. 2. Shows; i.e., representing the nonlinear stress-strain graph by multi linear segments. Representing the ash wood by a bilinear model has been used by many researchers in the literature [33-36]. Although a transversely isotropic model was used by Fahey et al. [2] to represent the hurley, the validity of the transversely isotropic model for ash wood bat is questionable, this is combined with a high strain-rates. Therefore, the approach in this paper uses an orthotropic model to enhance the FE model accuracy. Figure 2a shows the origin of the principle directions of the bat material [2] while Fig. 2b-2d show the stress-strain graph of the tangential, longitudinal and radial directions, respectively. Compression tests were conducted up to 2.5% of strain in all axes, however, only elastic range we utilized in FE simulations and proposed research work. The Poisson's ratios were considered as 0.059 for tangential and radial directions, and 0.34 for the longitudinal direction [3].

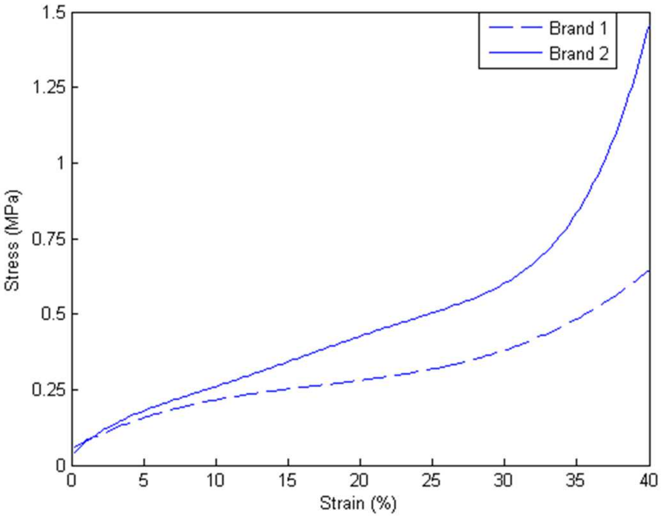
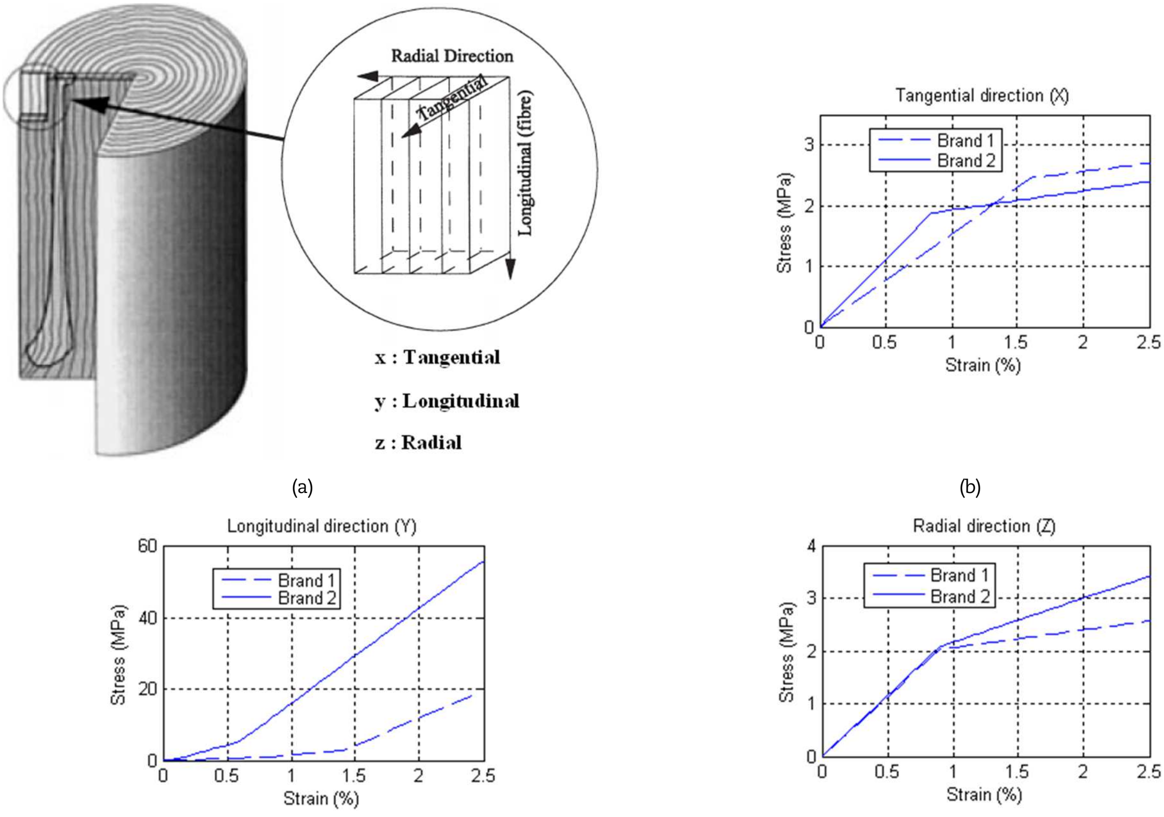


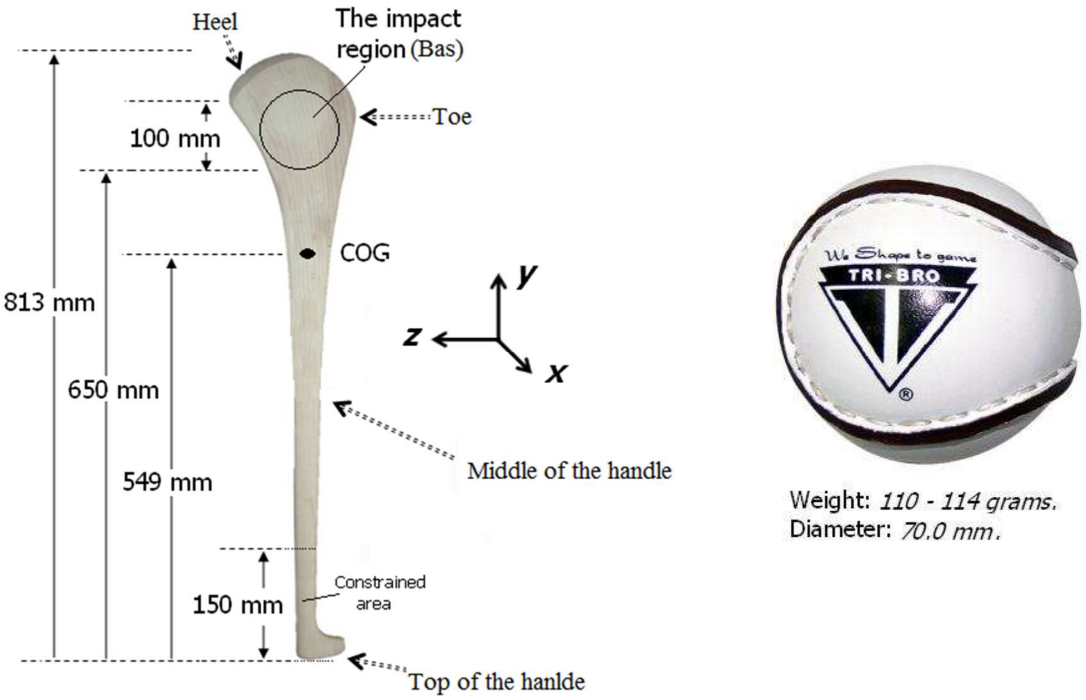
Fig. 1. Stress-strain curve of the balls materials.



(a) (b)

(c) (d)

Fig. 2. (a) The origin of the principle directions of the bat, (b) tangential, (c) longitudinal and (d) radial stress-strain models of the bat materials.



(a) (b)

Fig. 3. The bat geometry and dimensions (a), and the ball (b).

3. Finite Element Model

In this study, the ANSYS was employed as a FE solver to simulate the 3-D FE model. The simulation parameters were the Lagrange multiplier method as a contact algorithm, Mortar as a method of discretization [37], and a large transient displacement. Detailed descriptions of the model developed are described in the following subsections.

3.1 Model description

Figure 3 shows the ball and bat geometries and dimensions. Figure 3a shows the overall hurley dimensions in the yz-plane, including the center of gravity (COG) measured from the handle top; it also shows the impact region on the main striking face of the hurley. The investigated impact was a right-angle impact. Although, oblique impact can occur in the real-world game, the proposed study studied the impact system model under the most severe load conditions only, i.e., normal impact. Furthermore, Fig. 3a shows that the grip of the hurley was fully fixed as this part usually is held rigidly by the hurler. In reality, the hurler's hands provide some flexibility but the developed model ignored the hand flexibility for two reasons: (1) to study the impact system under the most severe load conditions and (2) to reduce the computation time and ensure rapid solution convergence.

The difficulty of developing the 3-D CAD model of such a structure is evident because of the dissimilarity and irregularity of the hurley structure. An approach which has been used in the literature to model such a complex structure is structure decomposition or the multi-block approach [38-40]. Similarly, building the hurley CAD model in this work was carried out by decomposing the hurley structure into tiny blocks, building each individually and joining them together to form the entire hurley model. Building an approximated model avoids the complexity of developing such an irregular model, but the authors have tried to describe the bat as closely as possible to the real bat.

The SOLID185 element was used to mesh the bat and ball structures. This element is defined by eight nodes with three degrees of freedoms at each node (translations in the nodal x, y, and z directions) and it incorporates large deflection and strain capabilities. On the other hand, the mesh size was chosen by the ANSYS itself by configuring what so called "smart meshing" in the option of the mesh sizing. Figure 4 shows the bat and the ball structures after meshing, generating 92,032 elements with an average mesh size of 0.29 mm. The adequacy of the proposed mesh size, and results sensitivity to the mesh size [41], was assessed by repeating the analysis with 25% finer and 25% coarser meshes, in each case, the maximum von Mises stress was found to be the same.

3.2 Nonlinearities due to geometry

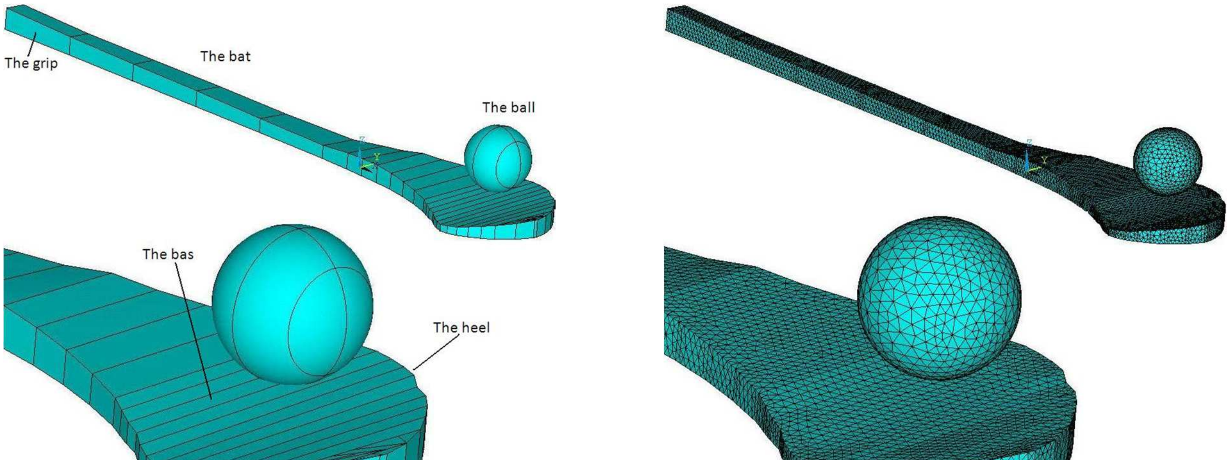
Earlier work by the authors has shown that the ball may deform by up to 7 mm (10% of original diameter) and that a deflection of up to 60 mm of the hurley tip may occur in a typical real-world impact [14, 28]. Such large amount of deformation/strain will cause a consequent geometric nonlinearity. The geometric nonlinearity involves changes in the element's shape and orientation which leads to changes in the structure stiffness [42-44].

To address the issue of geometric nonlinearities, two further steps were taken: the first was to set the model code to handle the large strains and deflections by activating a nonlinear geometry (NLGEOM) command implemented on ANSYS [45-47]. By issuing the "NLGEOM,ON" command, the large strain/deflection effects will be activated. The large strain procedure places no theoretical limit on the strain experienced by an element [27]; however, proceeding with such commands requires a judicious choice of the duration of time substeps which was the second task. The time substep duration has to be short enough to ensure solution convergence without compromising on processing time. By trial and error, 50 µs was found to be the optimum substep duration. The adequacy of the substep duration was evaluated by repeating the analysis with 10 µs and 100 µs substep durations.

3.3 Nonlinearities due to changing status

During impact events between flexible bodies, the statuses of the impactors changes as the forces transmitted across the surface and the area of contact change. From this point of view, the contact problem is titled as a nonlinear problem [45, 48, 49] or it is sometimes even classed with nonlinear boundary conditions [50, 51].

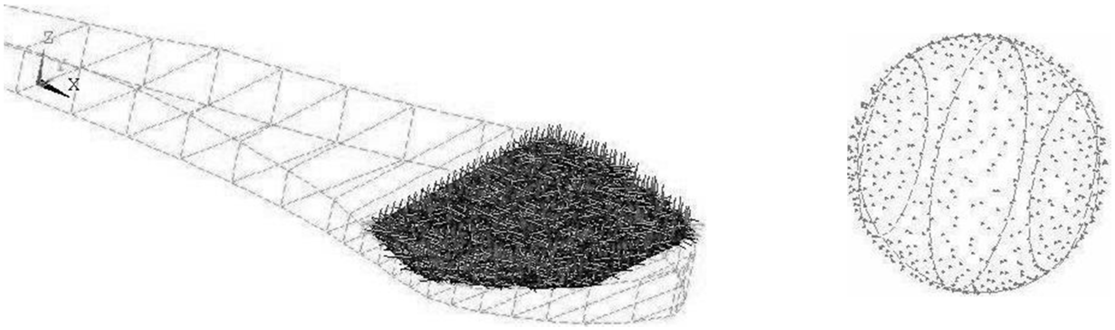
ANSYS, as FE solver, provides elements for analysis of 3-D contact events [27]. Figure 5a shows the target area after meshing, i.e., the bat surface area that would be in contact with the ball during the contact; this area was meshed using a three-dimensional target element called TARGE170. This element is used to represent various 3-D target surfaces and it can accommodate any translation, force and moment on its segments. For the contact area, a 3-D contact element CONTA175 is used to mesh the ball surface area; and it is defined by one node and can be used for many purposes such as structure, e.g., translations, and thermal analyses, e.g., temperature. These elements allow to simulate the proposed problem explicitly. The all-to-all algorithm and the Lagrange multiplier method were employed as contact detection and optimizations methods, respectively. Full details of these methods are discussed in [37]. Figure 5b shows the target area and contact surface after meshing.



(a)

(b)

Fig. 4. The bat and ball (a) before and (b) after meshing.



(a) (b)

Fig. 5. The meshed target area and contact surface of the bat (a) and the ball contact area (b).

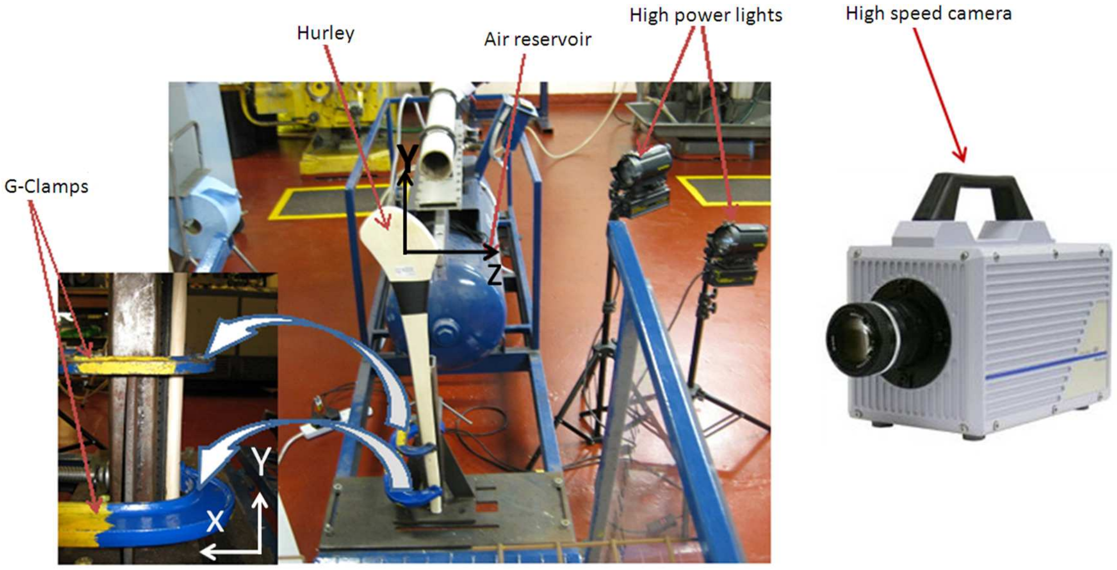


Fig. 6. The experimental set-up of the air cannon unit with a flexible fixture and high-power lights.

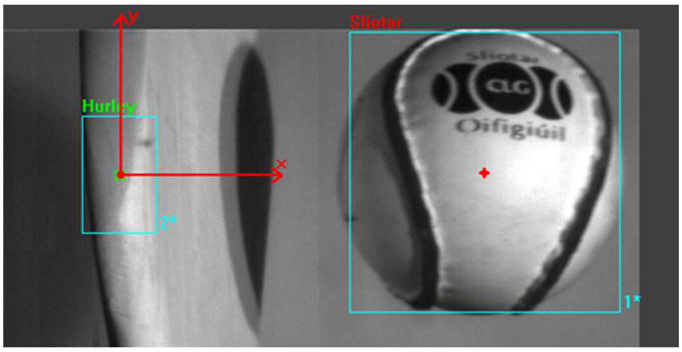


Fig. 7. The reference frame and tracked area.

4. Experimental Set-up

In this research work, an experimental work was conducted to validate the proposed FE simulations. The work started by developing an integrated test rig in the department of mechanical engineering at Munster Technological University, Ireland. This test rig was primarily constructed for studying the sport of hurling. It consists of the following parts:

1. A high-speed camera (Photron, APX) connected to a PC. The camera was directly facing the ball trajectory.
2. Air cannon unit (ACU) with a 100-liter compressed air reservoir.
3. Two pneumatic valves for launching purpose.
4. Two photocells to measure the ball inbound speed.

To hold the bat in a manner similar to holding the players clamps were used, at 50 mm and 150 mm from the bat base, to constrain the first 150 mm of the bat. The clamp tightening torque was constant as 25±2 Nm for all experimental runs. Figure 6 shows the test rig. More details about the experimental set-up reported by previous research work [24, 25].

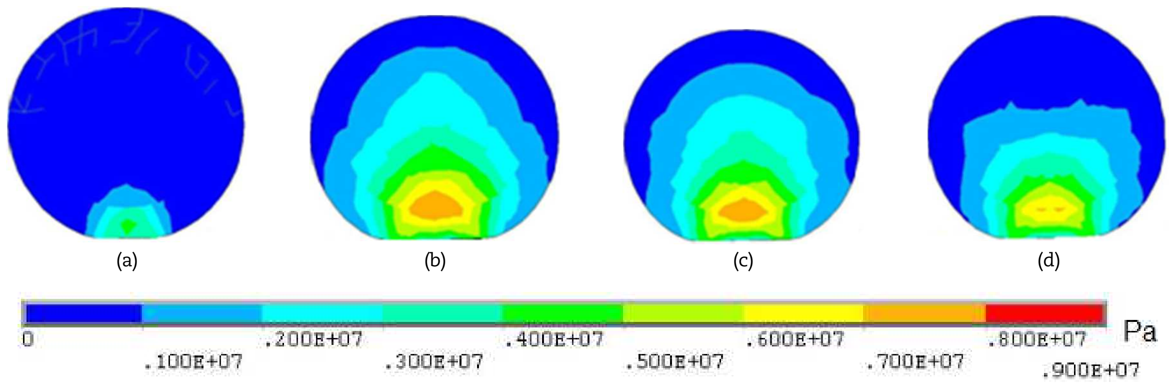


Fig. 8. The von Mises stress distribution of the middle cross section of the ball: (a) 0.1 msec after the impact, (b) 0.5 msec after the impact, (c) 1.5 msec after the impact, and (d) 2.0 msec after the impact.

Each run was begun by selecting the desired ball and Hurley brands, the ACU pressure was set to an appropriate value to get the desired ball speed. A photocell sensor was used to measure the inbound speed just before the impact, this because a small difference in ACU pressure could cause a noticeable speed change. Tracking motion-analysis software (ProAnalyst, Itronx Imaging Technologies, CA) was used to analyze the captured videos. For all videos, a square area, with edge length equal to the ball diameter, was tracked to determine the xy position of the ball's center of mass. Another square area was considered to track the xy position of the hurley head. The reference frame was set at the hurley top as shown in Figure 7. The xy-position of the ball was documented for each frame and, by dividing the traveled distance by the time of one frame, it was possible to obtain the ball speed. The impact force was determined by calculating the change of linear momentum of the ball.

5. Results and Discussion

The ball middle cross section status during the impact of Run number 1 is shown in Fig. 8. The figure shows the von Mises stresses through the ball structure at different time shots during the impact together with the ball deformation. Because of the symmetry of the ball core, the maximum stress is always at the middle cross section of the ball whatever the impact point at the surface and, hence, analyzing this stress will provide sufficient information for the entire ball stresses. Figures 8a and 8b represent the loading period during the impact while Fig. 8c represents the ending of the loading period and the start of the unloading period; it also shows the maximum stresses built up during the impact event. The unloading period stresses can be seen in Fig. 8c and 8d.

Figure 9 shows the developed stresses at the ball center during the impact. The effect of using different ball and hurley brands on the developed stresses is shown in Fig. 9a and Fig. 9b, respectively. It can be observed that the stress increased up to a maximum value, decreased and then increased again just before leaving contact. The physics behind this can be interpreted as follows: the ball deceleration to zero velocity causes the first peak of the stress and, soon after; the bat tries to reassume its normal position and hits the ball in the rebound direction, causing the second stress peak. In other words, the ball firstly hits the bat, and compression/restitution phases take place. During the restitution, the bat deflects and leaves the ball. Finally, the bat goes back to hits the ball again causing the second stress peak. On the other hand, Fig. 9a and 9b show the effect of using different ball and bat brands, respectively, on the resultant stress. Ball brand 1 resulted 3.8 MPa while ball brand 2 resulted 5.1 MPa, and bat brand 1 resulted 3.9 MPa while brand 2 resulted only 3.1 MPa.

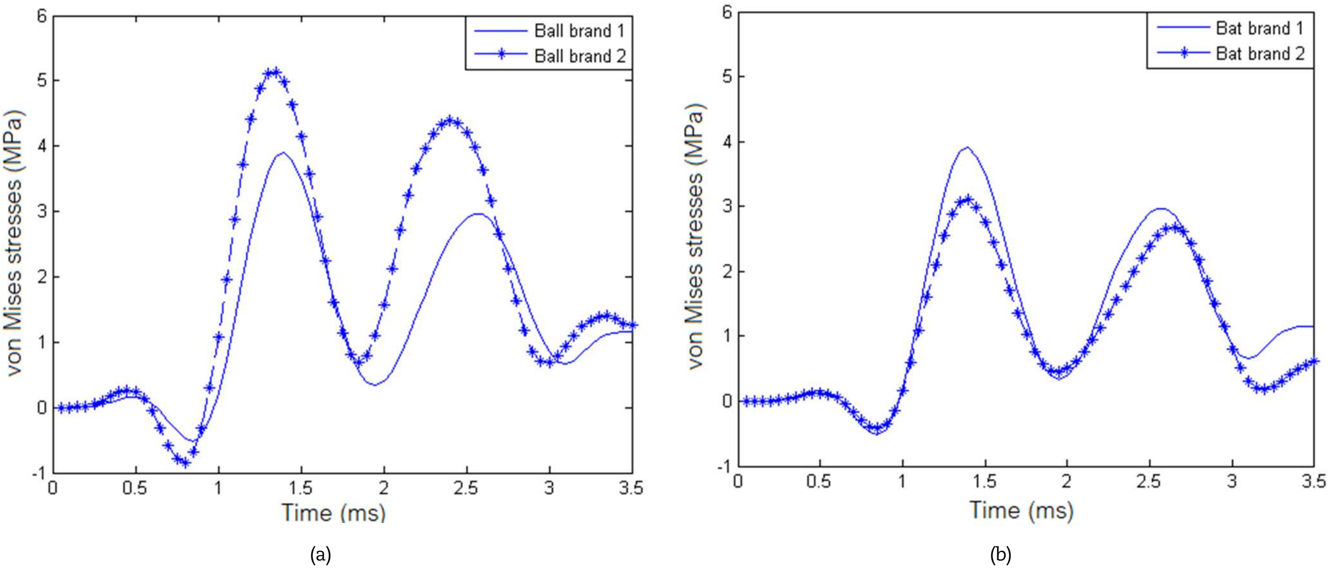


Fig. 9. The resultant von Mises stresses at ball center as function of time: (a) two different brands of ball (constant impact speed and bat brand), and (b) two different brands of bat (constant impact speed and ball brand).

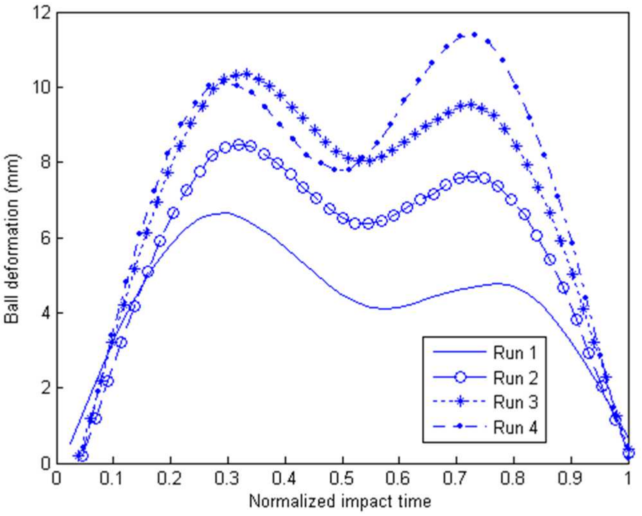


Fig. 10. The resultant deformation of the ball versus the normalized impact time during the impact scenarios.

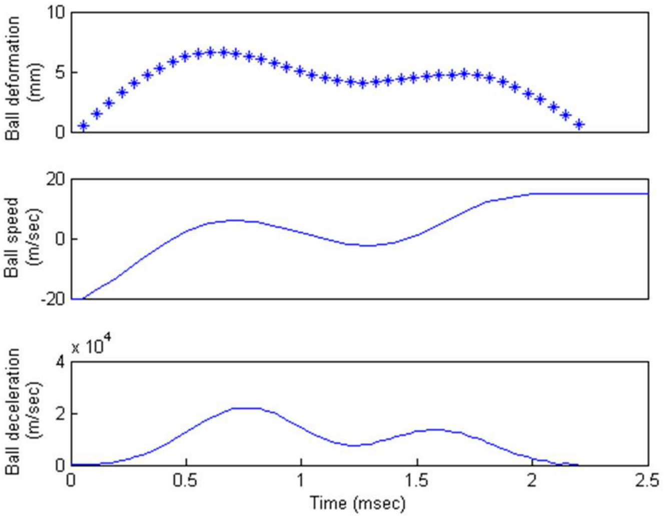


Fig. 11. The resultant deformation, speed, and deceleration of the ball during the impact.

The ball deformation during impact in all runs is shown in Fig. 10. By comparing the deformations in Run numbers 1 and 2, the effect of using different ball brands on the observed deformation can be obtained; i.e., in Run 2 the ball was deformed 25% more than Run 1. As has been discussed earlier in section 2, different stress-strain behavior exists in all the different ball brands even though all of them meet GAA standards. The hurley effect on the ball deformation is obtained from Run numbers 2 and 3, where the ball was deformed by more than 20% in Run 3 in comparison to Run 2. The difference can again be interpreted as arising from the different mechanical properties of the hurleys, i.e., hitting a ball against a rigid bat (run 3) will cause more deformation and vice versa.

Figure 11 shows the ball kinematics results during the impact. The results are expressed in term of deformation, speed and absolute value of deceleration; i.e., the magnitude of the ball deceleration computed during inbound and rebound phases, of the first run. The ball deforms up to 6.4 mm within the first 1 msec of the contact duration, the loading period, to reach a speed of 4 m/sec in the rebound direction with deceleration of 22,034 m/sec^2. The figure shows that the ball decelerates afterwards in a different manner from the inbound one where the ball seems to be rest (having zero velocity) on the hurley for a very short time before its subsequent unloading period.

The impact force during the contact time is detailed in Fig. 12. The figure shows the impact force versus the normalized impact time, which is defined as the impact time divided by the total contact time of each impact scenario, this to facilitate presenting impact forces of impact scenarios against similar scale of normalized contact time. Investigating the first and third runs, same ball brand and impact speed and different bat brand, the figure suggest that almost the same impact force even though different bat brands were used. A similar conclusion can be found when the second and third runs are investigated, almost the same impact force was reported at different ball brands while other parameters, bat brand and impact speed, held constant. The figure suggests another peak of the resultant impact force, changing the bat brand (runs 1 and 3) or changing the ball brand (runs 1 and 2) may increase/decrease the impact force by up to 15% at constant impact speed.

Figure 13 shows the FE and experimental results of maximum ball deformation. Because of the maximum ball deformation was the only factor can be measured directly using the high-speed camera, it was selected to validate the FE results against the experimental data. The FE predicted the maximum ball deformation accurately, in run 4, for instance, the FE predicted the maximum deformation to be 11.4 mm, and the measured value was 11.7 mm with an error of 2.6% only. Some deviation was reported in other runs, FE in run 1 for example predicted the maximum deformation to be 6.6 mm, while the measured value was 5.9 mm. In general, the figure shows an excellent correlation between FE and experimental results with an overall correlation of more than 91%.

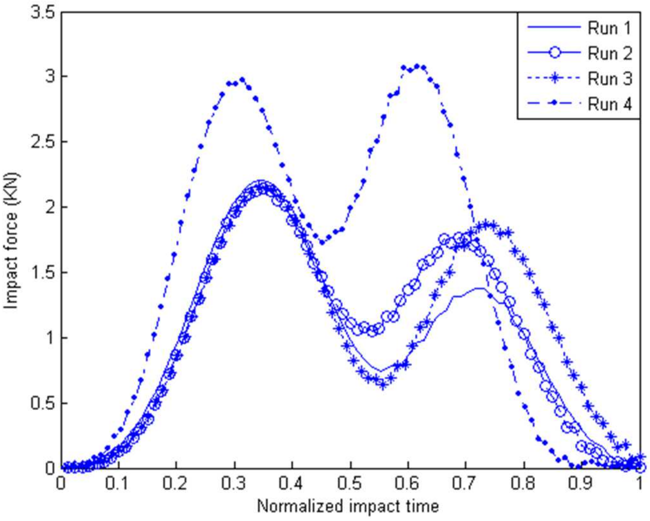


Fig. 12. The resultant impact force versus the normalized contact time during the impact.

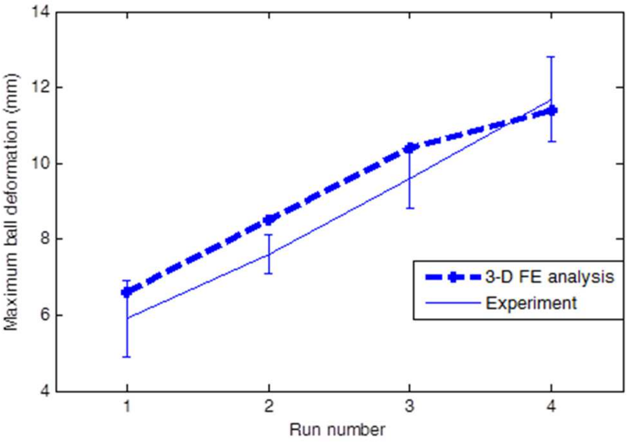


Fig. 13. The predicted maximum ball deformation by different approaches.

5. Conclusion

Numerical modeling and simulation of an impact system occurring between nonlinear elastic and natural material objects have been completed successfully. While most of the published work in this field is based on either linear isotropic or calibrated material models, the paper demonstrates a FE model of such impacts which does not rely on either of these approaches and uses real orthotropic material, ash wood, model and which, furthermore, is capable of transient simulation. A unique case study, the Irish game of hurling, has been taken to verify this impact modeling approach and advances the modeling of this particular impact system beyond anything reported to date. The work developed and simulated a series of 3-D numerical models. The work started by investigating the von Mises stresses, at ball middle cross section, interestingly, two peaks of stress were reported during impact scenarios, one during the compression and another one during the restitution phases. The ball hits the bat first causing the first peak of stress, and then the bat tries to reassume its normal position and hits the ball in the rebound direction causing the second peak of stress. Regarding the maximum developed von Mises stress in the ball, at constant impact speed and bat brand, the developed stress in ball brand 1 was found to be 3.8 MPa only in comparison to 5.1 MPa developed in brand 2. Bat brand also found to be affecting the generated stress in the ball, 3.9 MPa of stress was developed using bat brand 1 while bat brand 2 developed only 3.1 MPa of stress in the ball. In term of ball deformation, at constant speed of impact, the results showed the ball's deformation was increase by 25% when different ball brand is used, knowing that all comply with the same standard. Similarly, different bat brand results increasing the ball deformation by more than 20%. The presented results were validated in term of maximum ball deformation, i.e., an excellent correlation was found where the FE predicted the maximum deformation with accuracy of more than 91% in average, proofing the powerful FE as an approach to study nonlinear materials impacts scenarios. An interesting further outcome of the research presented in this paper, with implications for the game of hurling itself, is that the impact force increases/decreases by up to 15% was observed when using different ball and bat brands, even though all of the brands conform to game standards.

Author Contributions

A. Alsakarneh writing, conducted the experiments, and FE analysis using ANSYS; T. Tabaza writing, reviewing the conducted experiments and analyzed the empirical results; G. Kelly reviewing the FE analysis and other technical aspects of the paper; J. Barrett project management, funding, and reviewing the final draft. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

No datasets were generated or analyzed during the current study.

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