Characterization of the materials in golf ball construction for use in finite element analysis

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Abstract

The overall aim of the present work is to develop suitable material tests and use the acquired data to produce a fully validated finite element (FE) model that is capable of predicting hysteresis during cyclic loading as well as coefficient of restitution (COR) on high speed impacts. This paper reports the detailed experimental study that has been carried out in order to establish accurate and reliable material properties of a two-piece golf ball. The data has been used with FE package ABAQUS to produce a model of the ball which takes into account material heterogeneity.

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1. Introduction

The complex nature of the impact between a golf ball and club and in particular how the influence of golf ball material characteristics affect the mechanics of the impact, are not yet fully understood. The overall aim of this study is to use validated finite element studies to investigate the role of golf ball material properties on the mechanics of golf ball impact. The current work utilizes standard mechanical testing techniques to obtain accurate and reliable material data from the various layers of a commercially available golf ball and uses the collected data to calibrate non-linear viscoelastic material models within the FE analysis package ABAQUS. Currently there is a lack of literature that describes modeling processes from start to finish in a clear, concise manner with full details on material testing and FE modeling. The objective of the work is to address this issue and provide details on the optimum testing/modeling techniques and material models.

2. Golf Ball Construction

Multi-piece solid construction golf balls consist of two, three or four components. In the main, they comprise a cross-linked polybutadiene (PBD) based core whose precise behavior can be modified by the mixture of additives and fillers added [1]. Furthermore, the manufacturing process utilized in the construction of the core results in it being non-homogeneous with changes in the material properties of the core being observed with changes in distance from the centre of the core. The variations of these properties lead to variations in the impact performance of the ball [2]. The outer layer(s) are generally comprised of ionomers and/or polyurethanes depending on the desired performance characteristics of the specific ball. Consequently, the ball should be considered as a multi-material system.

Published literature [3] reports that the mechanical behavior of the golf ball cannot be accurately modeled using simple linear elastic models and that more sophisticated modeling utilizing more accurate material properties are required. The published literature [3] suggests that the core should be modeled as having both viscoelastic and hyperelastic material properties and the cover as having hyperelastic material properties. Figure 1 shows the components of a two piece golf ball.

![Figure 1: Reported components of a two piece ball [3].](image)

3. Material Testing

To achieve accurate results from FE simulations it is vital to have dependable and accurate material data; therefore a detailed experimental investigation was carried out on the core of a two-piece golf ball. In order to establish whether the core was heterogeneous, test samples (12mm in diameter and 5mm in height) were produced from a variety of locations across the diameter of the core. The locations of the core samples are shown in Figure 2. Each sample was tested in uniaxial compression at 3 different uniform compression rates based on initial strain rates of: 0.08s\(^{-1}\), 0.008s\(^{-1}\) and 0.0008s\(^{-1}\), with the tests each following the same procedure. The sample was placed between
the compression platens with PTFE tape on both the top and bottom faces of the sample to allow Poisson’s effect. The samples were pre-loaded to 100N to ensure full contact with the compression plates. It is well reported in the literature that the structural properties of elastomers change significantly during the first several times that the material experiences straining [4]; this is often referred to as Mullin’s effect [5]. Each sample was loaded cyclically 6 times to stabilize the stress-strain function. Further details on the testing procedure and results can be found in previously published work by the author – [6].

4. Finite Element Analysis

Using the material data gathered various material models were investigated. Previous work has focused on using standard stress strain data to calibrate the hyperelastic response of the material and relaxation data to calibrate the Prony series parameters used to describe the viscoelastic behavior of the material.

The Prony series [7] used by ABAQUS can be classified as a linear viscoelastic (LVE) material model and is suitable for describing the behaviour of LVE materials. As part of the experimental investigation, relaxation tests were carried out on the cylindrical core samples. Initially the sample is conditioned through cyclic loading to reduce any stress softening and a pre-load of 100N is applied to ensure full sample contact with the compression plates. A strain of 10% is applied and maintained for 300 seconds, during this period the reaction force of the sample on the compression plate is measured with respect to time. The sample is then left to recover for a further 300 seconds and a final strain of 20% is applied with the resultant force being monitored over the 300 seconds that the strain is maintained (Fig. 4).
If the sample displayed linear viscoelasticity, doubling the applied strain would cause the resultant stress to double [8]. A method to determine the extent of LVE is to normalize the data from various loadings and establish the extent to which the curves overlap. If the curves overlay another the material is deemed to be LVE [9]. As the data does not meet either criterion for LVE (Fig. 4 and 5) it can be concluded that it is non-linear viscoelastic (NLVE) and consequently requires a non-linear model to describe the behavior. LVE is generally used for small strain predictions and the strain-rate should be in a relatively narrow range [8]. Since the model will have to handle large strains and cover strain-rates from compression test to high speed impact it was decided that LVE was not suitable for this particular application.

NLVE models replace the linear spring and dashpot in “Network B” (Fig. 3) of the material model with non-linear springs and dashpots. The Bergstrom-Boyce (BB) model incorporates non-linear strain dependence and non-linear viscoelastic flow [8]. Unlike the Prony series, which requires relaxation test data, the parameters required by the BB model can be calculated from cyclic stress strain data directly thus negating the need to perform lengthy stress relaxation tests. The only requirement is that the load/unload data is gathered at various strain rates. Integration of the BB model into ABAQUS requires the use of a user material which is described by a number of material parameters. The calibration and optimization software PolyUMod [10] was used to compute accurate material parameters that can predict the material behavior at various strain rates. PolyUMod directly reads stress-strain data and optimizes the, initially guessed, material parameters to reduce the fitness error. Once the error is reduced to a suitable level the final parameters are included in an ABAQUS user material. In the BB model, the applied deformation gradient is acting on 2 parallel networks A and B (Fig. 3). Network A only concerns elastic response and is represented by the eight-chain model (Arruda-Boyce model). Network B is further decomposed into elastic and viscoelastic components. The stress on network B is also given by the eight-chain model but with a different effective shear modulus. It was found that altering the hyperelastic material model of the springs in each network (Fig. 3) improved the overall material model fitness. Using the Yeoh Hyper model [10] to represent network A (Fig. 3) and the Neo-Hookean model [10] to represent the spring in network B (Fig. 3) yielded very good results for the cylindrical core samples. The Parallel Network Model (PNM) allows the user to select different models for each component in the overall material; as a result it is very versatile and can produce accurate results.

Before attempting to predict the response of the full core under compression validation steps were carried out, involving modeling the behavior of the cylindrical core samples each at various strain rates. Figure 6 shows an elemental plot of a characteristic sample compression test. The boundary conditions applied in the FE simulation directly represent the physical system. The bottom face of the core sample is constrained to allow movement in the x and y direction but no movement in the z-direction. The centre node on the bottom face is fixed in all displacement and rotation modes. An analytically rigid plate is translated in the z-direction with displacement control to compress the ball to a given strain. As the ball is not fully constrained in the x and y directions the sample is free to undergo significant Poisson’s effect. The interaction between the compression plate and the ball is given a frictionless interaction in the tangential direction and the default “hard” contact in the normal direction. The geometry of the model and material parameters were adjusted to match each specific sample from the core. The optimized material parameters from PolyUMod which were integrated into an ABAQUS user material and the compression tests were simulated at the aforementioned 3 strain rates.

5. Results and Discussion

Figures 7, 8 and 9 show FE results from compression test simulations of a cylindrical core sample from the centre of the ball at 3 strain rates, each an order of magnitude smaller than the previous. The PNM was calibrated using cyclic stress-strain data from the 3 strain rates stated in section 3. It can be seen that at each strain rate the model accurately predicts the loading path and peak stress value, however the predicted unloading curve is somewhat different to the experimental. The 0.008s⁻¹ simulation yields the most accurate result with a normalized mean absolute difference (NMAD) of 1.965. As 0.08s⁻¹ (NMAD = 7.241) and 0.0008s⁻¹ (NMAD = 6.785) are the outer strain rates of the experimental data this difference in accuracy to the 0.008s⁻¹ data is to be expected as the model is described in ABAQUS with one set of material parameters.
The above procedure was repeated for the inner and outer samples with equal success. The next logical step would be to use the data in an FE model of the golf ball core. Symmetry boundary conditions were employed in the model allowing the complete core to be modeled as an eighth of sphere. The model was partitioned to allow different material parameters to be assigned to different sections of the model. Figure 10 shows the partitioned ball model. The optimized centre, inner and outer material parameters were assigned to the corresponding sections of the ball. It was not possible to obtain material data from the section labeled “waste material” due to sample geometry [6] therefore a compromise had to be made when assigning material parameters. It was decided to divide the “waste section” into 2 sub-sections and extend the inner and outer material properties into the two sub sections.

6. Future Work

Initial results from the full core compression simulations are encouraging. Future work will focus on ways to reduce error in the compression test simulations and investigate higher strain rate cases. The “waste section” in the model is an obvious source of error in the hysteresis predictions, a method of obtaining accurate material parameters for the waste section would possibly yield more accurate results and will be investigated. Due to the processes used in golf ball manufacture, there will always be discrepancies in the final material properties of “identical” balls. The material parameters used in the FE simulation are derived from a sectioned core. The results of the simulation are
being compared to experimental data from a different core. If these two cores do not have exactly the same properties there are likely to be discrepancies in the hysteresis comparison.

7. Conclusions

A methodology for creating FE models from raw material data has been proposed. The model captures material heterogeneity and does not require impact data to produce. The model was calibrated with stress-strain data from three strain rates, 0.08s⁻¹, 0.008s⁻¹ and 0.0008s⁻¹, it was discovered that this data resulted in a model that was most accurate at 0.008s⁻¹. This suggests that if the model is to be used to predict impact behavior of the ball it might be necessary to calibrate the model with data from strain rates much higher and lower than the golf ball experiences during impact.

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