Golf Ball Impact: Material Characterization and Transient Simulation

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Abstract

This paper presents an LS-DYNA® simulation of the impact event when a golf club hits a golf ball. This is a challenging subject for finite element simulations because it is characterized by high strain rate behavior: the impact occurs within milliseconds and the golf ball experiences very large deformation during this period because of the ball's polymeric shell and core. The simulation strategy emphasizes on accurate material characterization and realistic model construction. Specifically, the Parallel Network Model (PNM), an advanced nonlinear viscoelastic and strain rate dependent material model from Veryst Engineering's PolyUMod™ library is calibrated with high-rate testing data to accurately capture the highly nonlinear behavior of the golf ball core material during impact. At the same time, a detailed finite element model of the golf ball is constructed with multiple layers of structure. The complex dimple pattern on the ball cover as well as the grooves on the golf club are modeled, both potentially important factors in impact response. The simulation is validated by comparing the deformed shape at maximum impact to that in real experiments. The paper then discusses two important issues in material characterization: selection of the right material model and the availability of reliable high-rate testing data. The PNM material model is compared to a linear viscoelastic (LVE) model to demonstrate its superiority.

Keywords: Impact Simulation, Golf, Constitutive Model, High Strain Rate, User defined materials

Introduction

The competitive nature of the sports industry pushes the limit for better product designs. In the case of the golf industry, both ball and club manufacturers strive for new products that will give their players the edge in playing the game. The impact event when a golf club hits a golf ball is a big part of the game and plays a key role in the design of both golf clubs and golf balls. However, it has been a challenging subject for finite element simulations because of its high strain rate characteristics: the impact occurs within milliseconds and the golf ball experiences very large deformation during this period because of the polymer material from which the ball is constructed. Due to this fact, the constitutive model used in the finite element model has to be able to capture the behavior of the material within a very wide range of strain rates in order to produce trust-worthy results.

In this paper, LS-DYNA is utilized with the aim to produce a realistic simulation of this impact event. Emphasis is put on accurate material characterization and realistic model construction. Specifically, the Parallel Network Model (PNM), which is from Veryst Engineering’s PolyUMod™ library and an advanced nonlinear viscoelastic material model with strain rate dependence, is calibrated with high-rate testing data to accurately capture the highly nonlinear behavior of the golf ball material during impact. The following sections discuss the various aspects of the finite element model, including geometry, material model, impact simulation and results.

Overview of the golf ball finite element model

The golf ball modeled in this study has a geometry that is based on the USGA/R&A Calibration model golf ball by Bridgestone Sports. It is of a two-piece construction that has a nominal diameter of 42.72mm, a core diameter of 38.5 mm and a cover thickness of 2.1mm [1]. The dimple pattern is based on a geodesic icosahedral pattern [2]. A snapshot of the golf ball solid model in LS-PrePost is shown in Figure 1. It is worth noting that in many of the previous numerical studies of golf ball impact [3] [4], the dimples are omitted from the golf ball model. While this may not be an issue when the interested quantity is non-local in nature, such as the coefficient of restitution (COR), the role of the dimples cannot be ignored the more complex interaction between the ball and the grooved club faces and it could have a significant effect on behaviors like spin generation.

Figure 1. Golf ball solid model

Figure 2 shows the meshed golf ball model. A dense mesh is required on the face of the cover to model the dimple geometry. As a result, the cover is meshed with 159139 tetrahedral elements. The spherical core is meshed with 27269 6-node and 8-node hexahedral elements. The size of the model is well within the capability of modern high performance computing.

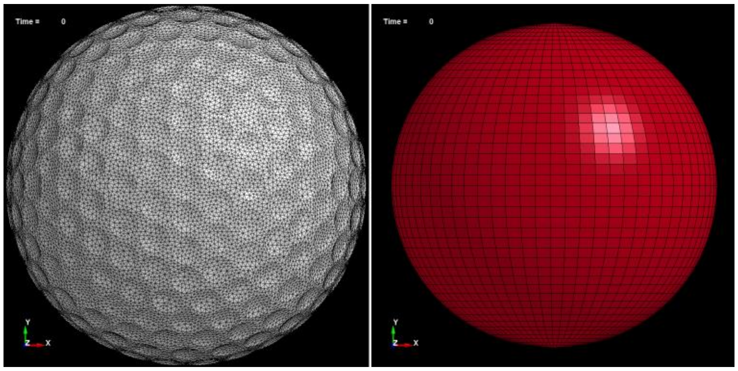

Figure 2. Finite element mesh on the golf ball

The golf club modeled in this study follows what is used in the USGA Report On the Study of Spin Generation [5] and is represented by a grooved steel plate. A example plate with V-shape grooves is shown in Figure 3.

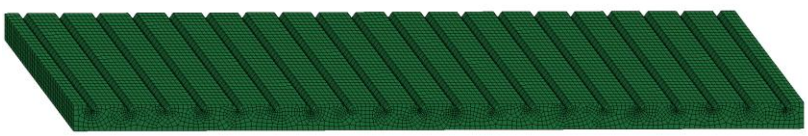

Figure 3. Steel plate representing the club face

Material Characterization

The response of the golf ball during impact is dominated by the more flexible core. As a result, material characterization efforts are mostly dedicated to the core material. For the cover, a straightforward hyperelastic model with generic properties from the literature [3] is used.
The peak strain rate that the core experiences during impact can be as high as a few thousands inverse second. Material testing at that strain rate requires special techniques like the Split-Hopkinson Pressure Bar [6]. The experimental facility at Veryst Engineering is capable of producing such type of data. For this study, in order to be consistent with the experimental study of USGA the data from Quintavalla and Johnson [7] is used to calibrate the core material model. The stress-strain curve from the uniaxial compression test is shown in Figure 4.

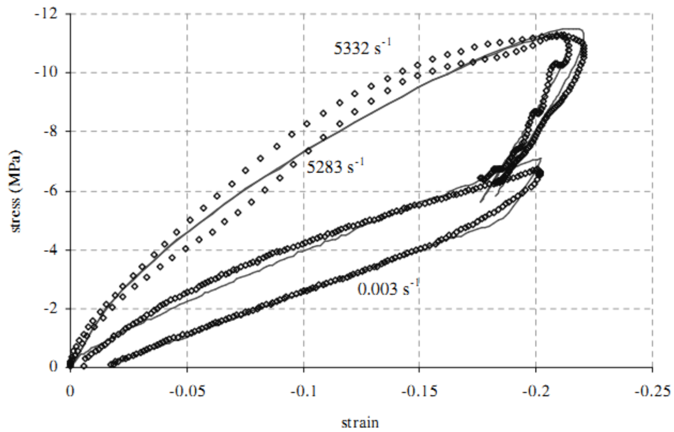

Figure 4. Material data for the golf ball core

It is clear from Figure 4 that the golf ball core material displays both strong rate-dependence and strong nonlinearity. To accurately capture such complex behaviors, the Parallel Network Model (PNM) [8] [9] is chosen. The PNM is developed by Veryst Engineering and is available as a user defined material for LS-DYNA. The calibrated PNM model for the core is shown in Figure 5 along with experimental data and good agreement is observed. The calibration process is expedited by the MCalibration™ software developed by Veryst Engineering, which optimizes the material parameters for best fit of the experimental data.

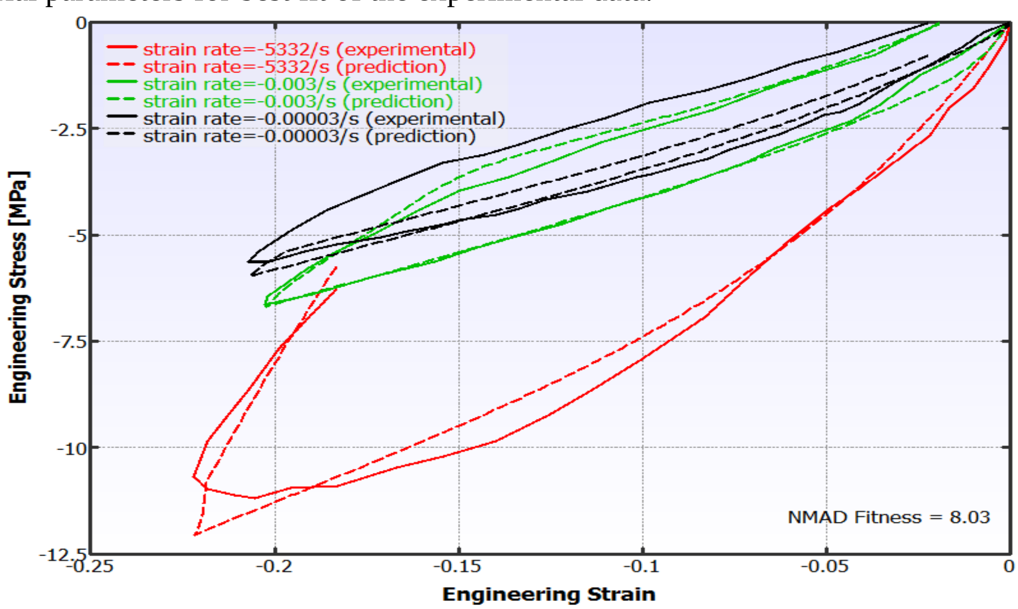

Figure 5. Material calibration for the golf ball core with the PNM model

Impact Simulation and Results

The finite model of the golf ball impacting the golf club plate is executed in LS-DYNA to simulate various impact conditions. The explicit algorithm is chosen to be the simulation scheme. No mass scaling is used for this inertia-dominating event. To compare to the experimental work done by USGA [10], the impact speed is chosen to be 150 mph and the impact angle is 83-degree. A duration of 1 mili-second is simulated and that takes about 1 hour on an 8-core Intel Core i7 workstation. Figure 6 shows the comparison of deformed ball shape between the simulation and the experiment at 3 different time instants: during the compressing phase, at maximum deformation and when the ball is rebounded off the plate. It can be seen that the simulation produces realistic results throughout the impact.

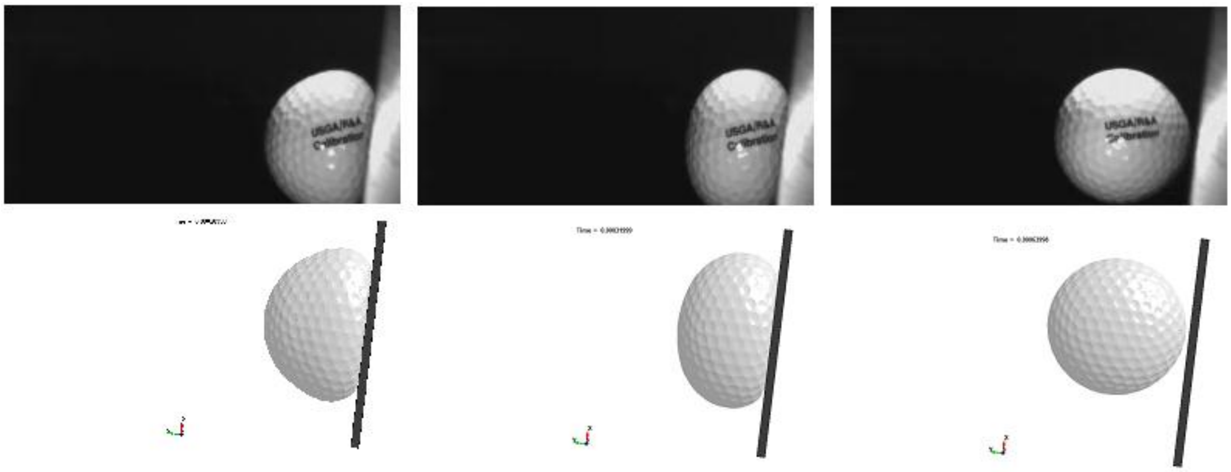

Figure 6. Comparison of the deformed golf ball shape between simulation and experiment at various time points. The impact speed is 150mph and the impact angle is 83-degree.

Figure 7 shows a snapshot of the deformed golf ball with compressive strain rate being the fringe plot variable. The maximum strain rate is about 6000 1/sec, which is consistent with the experimental assumption and verifies the high-rate nature of this impact event. It is also clear from Figure 7 that the strain rate is far from uniform inside the core. This shows the importance of being able to accurately account for a wide range of strain rates when calibrating the material model.

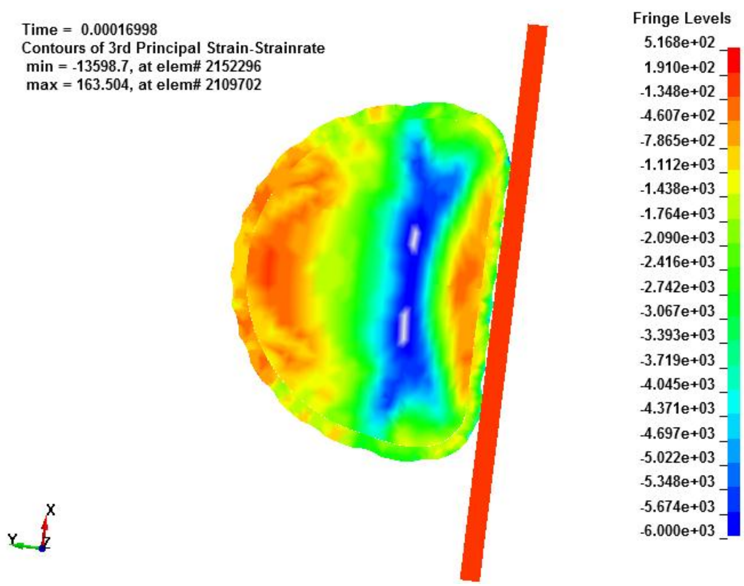

Figure 7. Minimal principal strain rate fringe plot during impact

Discussion on Material Characterization

It is of interest to study how the selection of different material models affects the simulation. To this end, the same material data is used to calibrate a linear viscoelastic (LVE) model. The result is shown in Figure 8 along with the previously calibrated PNM model. It can be seen that the LVE model has difficulty to adapt to the wide range of strain rates.

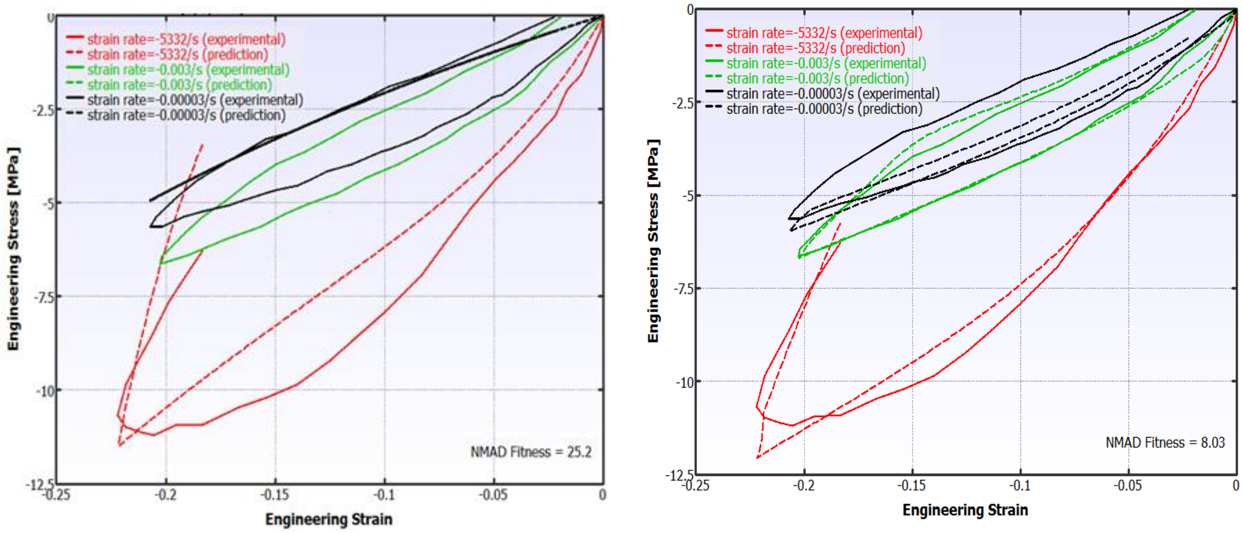

Figure 8. Material model comparison: LVE (left) and PNM (right)

To compare actual simulation results from the two material models, we look at the time-history of kinetic energy, which is shown in Figure 9. We can see that the LVE model predicts much smaller kinetic energy loss, which is not realistic. This is a consequence of the fact that the LVE model in this case under-predicts the hysteresis of the core material.

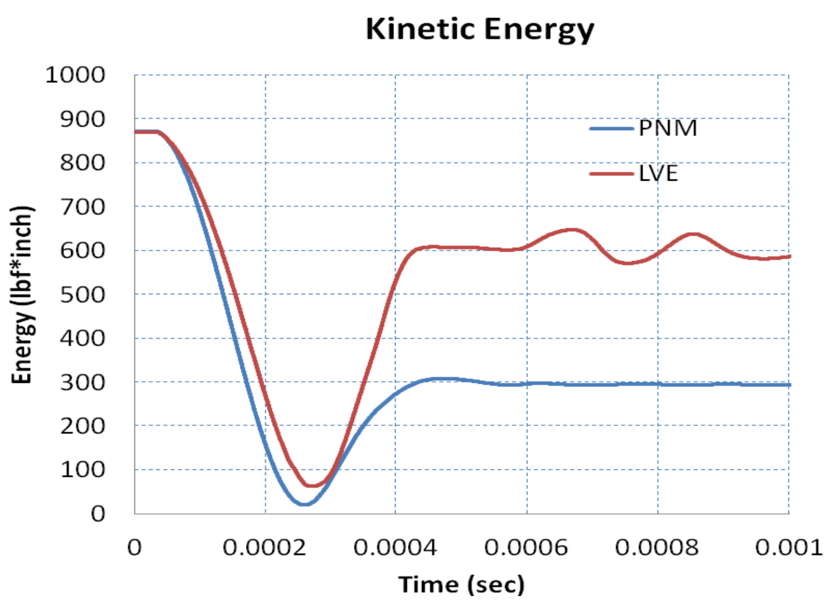

Figure 9. PNM vs. LVE: Kinetic Energy time history

It is also of interest to study the case where high-rate data is not available. For this purpose, a PNM model is calibrated with only low-rate data. The calibrated material model is shown in Figure 10. Also shown in Figure 10 in grey color is the **predicted** material behavior at high rate, as well as the real material behavior at that rate. We can see that although the calibrated model fits the low-rate data very well, it significantly under-estimates the material stiffness at high-rate. This case shows that the availability of the high-rate data is crucial for accurate material characterization. The consequence of lack of knowledge of high-rate behavior is reflected in the impact force time history plot, shown in Figure 11. The difference between the two cases does not appear to be very significant, but is well beyond the precision requirement of the golf industry.

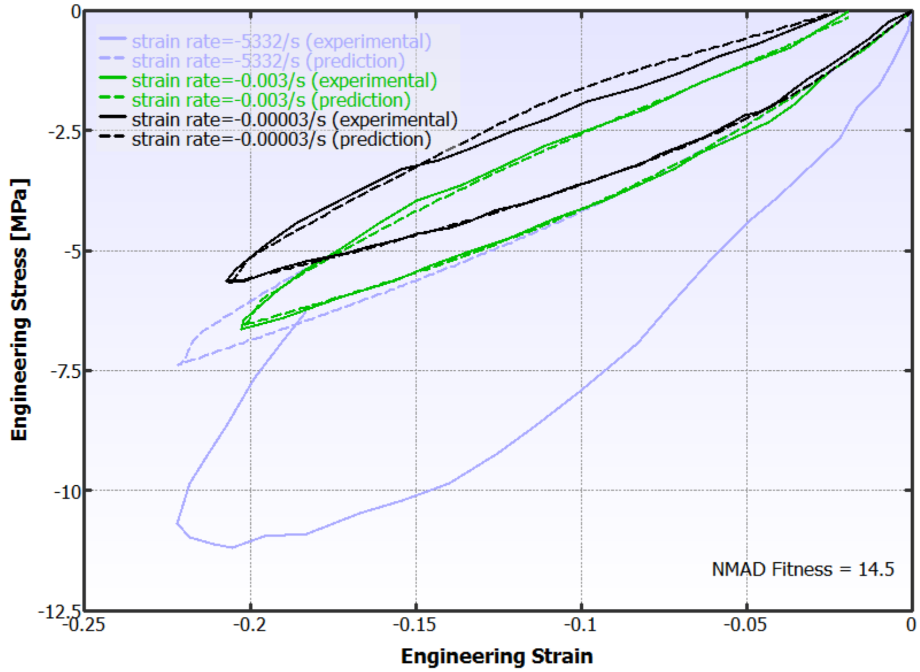

Figure 10. A PNM model calibrated without the high-rate data

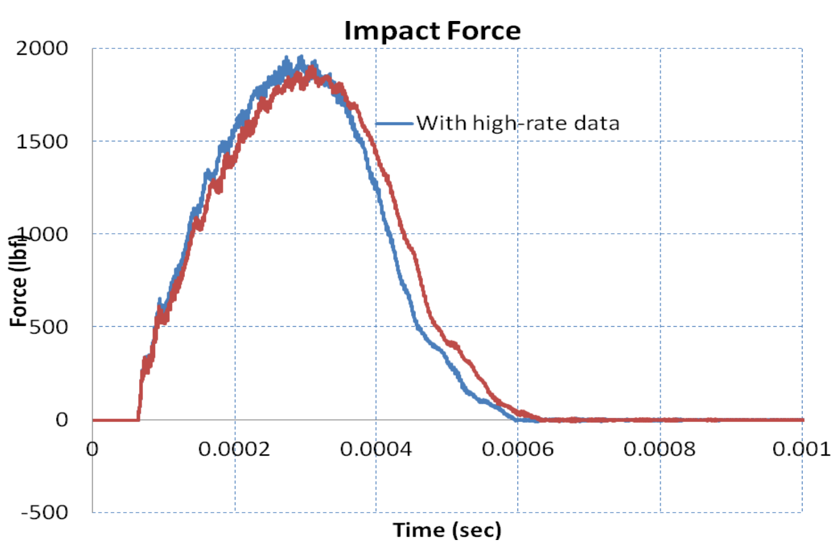

Figure 11. Impact force time history comparison

Conclusion

The key to the accuracy of the golf ball impact simulation hinges on accurate characterization of the core material. Simple material models like the LVE model works well for events characterized by small strain or by a narrow range of strain rates. Neither condition is true for the golf ball impact event and hence advanced material models like the PNM model has to be used produce realistic simulation of the impact event. Please note that if only a particular output (e.g. impact force) at a particular impact condition is of interest, it is possible to for a simple material model to work well for that particular case. However that is by no means a physical solution for the problem.

At the same time, results from this study also show that the knowledge of high strain rate behavior is also very important for correct material characterization and should be pursued. To obtain reliable data at high strain rates for soft polymer materials is a challenging task by its own and care should really be put into this process.

To sum it up, design cycles in the golf industry is short and the accuracy requirement for simulations is very high. The work done in this study, highlighted by advanced material modeling and parametric model creation, is capable of meeting the challenge and becomes a powerful design tool. Work is underway to simulate more complex ball-club interactions during impact, such as spin generation.

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