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Experimental Benchmarking Golf Ball Mechanical Properties

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ABSTRACT: In order to do effective simulation for design purposes it is necessary to obtain good material properties for modeling. When benchmarking competitive products, the engineer does not normally have access to basic experimental materials information generally held as confidential by the manufacturing company. This creates the need for somewhat challenging experimental work to obtain good parameters for simulation models. Such is the case for characterizing properties for golf ball cores and covers for the purpose of impact simulation. The majority of the balls used today are two-piece construction having an ionomer cover over a polybutadiene core. It is possible to cut off the cover and remold tensile and DMA specimens using a DSM Research 15cc Micro Extruder/Injection Molder. Tensile and DMA testing yield the mechanical properties required. Cores present a slightly more difficult task because they cannot be re-molded. For the cores, mechanical properties were obtained using DMA tests. Core specimen preparation is discussed in some detail since specimens must be extracted from a limited 42 mm (1.64 in) diameter sphere. Impact simulation results indicate that the measured properties accurately predict the coefficient of restitution in a range of impact speeds of 35 to 55 m/s when compared to published experimental values.

INTRODUCTION

In striving for larger driver heads with large coefficients of restitutions (COR) the simulation and modeling of impact have become critically important. Not only does simulation help with deciding club face structural fidelity and weld line forces, but it can also be used to evaluate initial launch conditions. The modeling of this impact involves somewhat complex constitutive relationships involving large deflections and rate-dependent behavior.

Modern golf balls have changed from wound balata construction to 2-, 3- and 4-piece solid construction [1]. Materials used in ball covers are generally ionomers and the cores are highly crosslined polybutadiene [2, 3]. Experimental characterization of the golf ball structure has been done by impelling the ball against a rigid force plate [4, 5]. Considerable work has been done using 1-D nonlinear viscoelastic models of the ball structure to model the oblique impact [5, 6] in addition to finite element simulation.

This paper reports the experimental results obtained by benchmarking several commercially available golf balls to determine material properties for use in impact simulation. Thermoplastic covers were cut off and re-molded into standard dynamic modulus analysis (DMA) and mini-tensile specimens using a DSM micro extruder/injection molding machine following published Surlyn recommended molding procedures. Flexure specimens were cut out of the ball cores for DMA testing. Initial stress-strain response was measured at room temperature to get quasi-static response. Flexure relaxation testing was done at various temperatures and time-temperature superposition was used to generate a master curve referred to room temperature. The experimental results were used in a 3-D hyperelastic, rate-dependent material model and compared to previously published 1-D viscoelastic model and experimental data.

Results for two balls are reported in this paper: a calibration and premium ball. The calibration ball is the ball that is used by the United States Golf Association (USGA) for coefficient of restitution testing in the previous year. Generally speaking, this ball is considered a ball for use by moderately skilled golfers who are seeking extra distance on shots. This ball has a polybutadiene rubber core and a ionomer cover. The premium ball is a ball used by expert to moderate golfers whom are seeking control over distance. This particular ball has a polybutadiene rubber core covered by an ionomer casing which is just below a thin polyurethane cover. Throughout the paper, the two balls will be referred to as the calibration and premium balls.

COVER AND CORE SPECIMEN PREPARATION

The ball outer covers were removed by making circumferential cuts through the outermost layer using a band saw. A flat head screw driver was inserted into the intersection of the two cuts and twisted to start the removal of the cover. In this case the outer urethane cover was first removed and the process repeated to remove the Surlyn casing. During all of the ball deconstruction it was observed that the material's temperature never rose to noteworthy levels. Once the covers were removed, the thermoplastic materials (calibration cover and premium casing) were cut into small pieces (< 1 cm) using diagonal pliers. Small pieces were needed for subsequent molding into flexure and tension test specimens. Molding was done with a mini-injection molding machine (DSM Research 15cc Micro Extruder/Injection Molder) using process parameters based on DuPont's molding recommendations [7]. This process allows for the making of tensile bars from a limited amount of material. A molding pressure of 1.034 MPa was used (nitrogen assisted) as well as a holding cylinder temperature of 240 $^{\circ}C$ and a mold temperature of 41 $^{\circ}C$. Cover material and subsequent test specimens are shown in Figure 1a.

The calibration and the premium cores were turned down to 31.75 mm cylinders using a high speed lathe. Next, the end of the ball was face cut flat by chucking the cylinder in a three jaw, self centering chuck. From this cylindrical shape ASTM D575 specimens could be made for

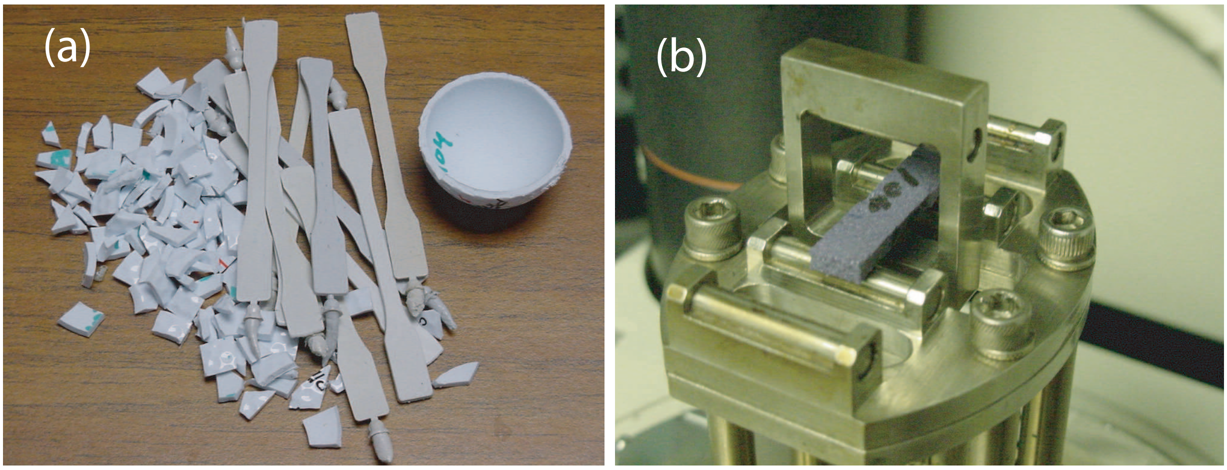

Figure 1: (a) Calibration ball cover, cover material, and tensile test specimens, (b) core flexure specimen in 3-point bend DMA fixture

compression testing. In addition, the cylindrical shape was used as the starting point for cutting/machining small flexure specimens (25 x 6.25 x 2.65 mm) that would be used for dynamic modulus analysis (DMA) (Fig. 1b). Again, throughout the process it was observed that the cores remained very near room temperature.

COVER/CASING TESTING

It is well known that the cover of the calibration ball is Surlyn. To make certain the premium ball casing material was Surlyn, thus defining the molding parameters, spectral data was collected on the two materials using FTIR. Thin films were pressed using a Carver single daylight press preheated to 170 $^{\circ}C$. Thin aluminum sheets were coated with a sintered release agent (MONO-COAT 1472W sintered at 335 $^{\circ}C$) to protect the platens. The FTIR graphs produced similar enough results to declare the casing material an ionomer (Fig. 2). The peaks in the graphs found at 1700 are due to the carboxylate and ion influence. Also seen in this region are C-O, C-C, and C-H stretch along with symmetric and anti-symmetric modes.

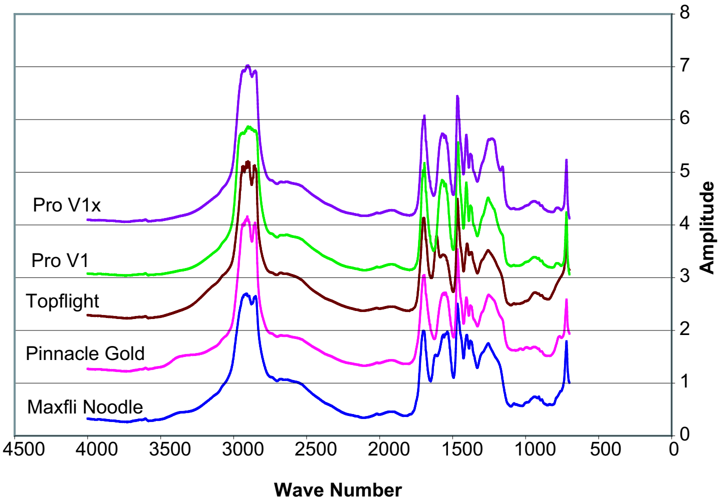

Figure 2: FTIR data for various ball covers. Amplitudes are shifted for ease of viewing.

Specimen dimensions for cover flexure testing were 61.25 x 12.5 x 3.175 mm. Room temperature, static modulus properties were measured using a DMA (TA Instruments Model 2980) in strain sweep mode. The span for the 3-point bend test was 50 mm and a maximum strain of 0.02% was used with a frequency of 1 Hz. For these tests, the elastic (storage) modulus was measured as 390 and 360 MPa for the calibration cover and premium casing, respectively. Tensile specimens (shown in Fig. 1a) tested in a universal electromechanical test machine (UTS SFM-20, 100-lb load cell, laser extensometer EXT-62-LHM0) resulted in lower elastic modulus values of 329 (7% COV) and 276 (5% COV) MPa for calibration cover and premium casing, respectively. Poisson's ratio was measured in the tensile test as well and found to be 0.410 (15% COV) and for 0.433 (9% COV) for calibration cover and premium casing, respectively. Poisson's ratio was calculated from strain acquired from clip-on extensometers (Epsilon Technology Corp., models 3542-0100-010-HT2 (longitudinal) and 3575-020-HT2(transverse)). The reason the DMA modulus values were higher than the uniaxial was the strain rate was higher (0.02 s^{-1} versus 0.008 s^{-1}). Uniaxial testing allowed for measuring the ultimate strength and post-yield tangent modulus. Both materials have failure strains well above 50%. Table 1 summarizes quasi-static material properties for calibration cover and premium casing.

Table 1 Cover and casing properties

Material	Modulus (MPa)	Modulus COV, %	Poisson's Ratio	Poisson's Ratio COV, %	Strength (MPa)	Strength COV, %	Tangent Modulus (MPa)	Tangent Mod. COV, %
Calibration Cover	329	7	0.433	15	21.9	7	14.09	18
Premium Casing	276	5	0.410	9	12.81	13	—	—

CORE TESTING FOR A RATE DEPENDENT, HYPERELASTIC MODEL

To characterize the core as a rate-dependent, hyperelastic material two types of tests were completed: modulus and stress relaxation. Both of these tests were easily done using a DMA test machine. The modulus was determined from conducting a strain sweep at a fixed frequency. In this test method, the specimen was flexed at 1 Hz in a prescribed increasing sequence of five strains. Force, and thus stress, were also recorded at each strain level. Modulus was found from a linear fit of the stress-strain pairs.

Even though the DMA testing was done at small strain, it well represents the response of the polybutadiene core. Modestly nonlinear elastic response is well modeled as a Mooney-Rivlin material having two constants A and B from which stress is found by

$$\sigma = 2\left(\lambda^2 + \lambda^{-1}\right)\left(A + B\lambda^{-1}\right) \tag{1}$$

where λ is the stretch ratio. Testing (Instron 810 universal electromechanical test machine) has shown that golf ball core response may be modeled as a neo-Hookean rather than a Mooney-Rivlin material as can be seen in Fig. 3. Here, stress-strain data from an ASTM D575 specimen loaded in compression shows minimal nonlinear response up to 30% strain. Thus, a single parameter was all that was needed to represent the core response for strains up to 30%. Setting Mooney-Rivlin constant $B = 0$ reduces the model to a neo-Hookean model.

Measuring Poisson's ratio of the cores was more difficult than that of the covers because the specimen's small size. Many rubbers are considered incompressible which implies $\nu = 0.5$. Poisson's ratio can be computed from the modulus of elasticity and modulus of rigidity through

$$\nu = \frac{E}{2G} - 1 \tag{2}$$

With the small rectangular specimens, the modulus of elasticity was measured via a flexure test using the DMA machine (Fig. 1b). Shear modulus was measured using a torsion DMA (Rheometrics RMS 800) as shown in Fig. 4. For the two tests the strain rates had to be matched. From these measurements the Poisson's ratio for the cores (calibration and premium) were found to be nominally 0.5 (the theoretical limit). Figure 5 show the measured Poisson's ratio. For all numerical simulations a value of $\nu = 0.499$ was used.

Knowing the neo-Hookean rubber core is essentially incompressible, the storage modulus is related to the hyperelastic constant A through

$$G = \frac{E}{2\left(1+\nu\right)} = 2\left(A + B\right) \Rightarrow E = 6A \tag{3}$$

where A and B are Mooney-Rivlin constants and $\nu = 0.5$ is Poisson's ratio for an incompressible material.

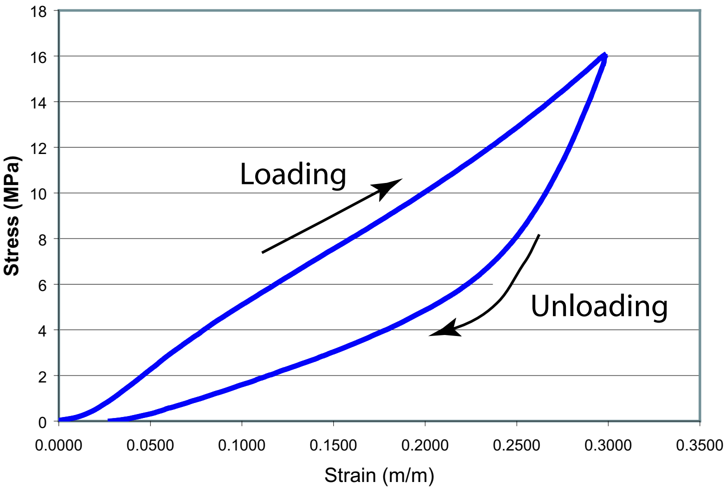

Figure 3: Stress-strain loading and unloading curve for a calibration core ASTM D575 compression test. Specimen was a 28.6 mm diameter right cylinder that was 12.5 mm in height.)

The second test needed to add time-dependent response to the material model is a relaxation test. Once again, this test was done in 3-point flexure in a DMA test machine. Since the golf ball impact occurs in a short period of time, a sequence of relaxation tests were conducted at different temperatures in order to construct a master relaxation curve [8] spanning several decades of time. The master curve was then fit to a Prony series of the form

Figure 4: Torsion testing of core.

$$g\left(t\right)=\sum_{i=1}^{6}G_{i}e^{-\beta_{i}t} \tag{4}$$

where $g\left(t\right)$ is the relaxation function of the material in excess to the hyperelastic static response. In general, the stress rate effect is accounted for by adding to the hyperelastic response stress defined by the convolution integral

$$\sigma_{ij}=\int_{0}^{t}g_{ijk\ell}\left(t-\tau\right)\frac{\partial\varepsilon_{k\ell}}{\partial\tau}d\tau \tag{5}$$

The Prony series of Eq. 4 was used since simple rate effects were deemed sufficient for modeling the golf ball core [9].

A series of flexure relaxation tests were completed at temperatures ranging from -90 $^{\circ}C$ to room temperature. Relaxation modulus data were shifted onto a master curve referenced at room temperature for determining the Prony series coefficients. The master curves for two core materials were shown in Fig. 6. The master curve data are fit to the Prony series model using Matlab. For all of the data, a matrix **A** was formed having the columns $e^{-\beta_{i}\mathbf{t}}$ where **t** is a vector of times. The linear coefficients, G_i, were solved for and the difference between this approximation and data was minimized to solve for β_i. This unconstrained minimization was done using a Nelder-Mead simplex method [10]. The relaxation fit for the calibration core are given in Table 2. Parameters in this Table are sufficient for modeling visco-hyperelastic behavior in LS-DYNA (*MAT_HYPERELASTIC_RUBBER), a commercially available finite element code.

Table 2 Calibration core neo-Hookean material properties ($B\equiv0$)

Parameter		$i=1$	$i=2$	$i=3$	$i=4$
A, (MPa)	10.00				
G_i, (MPa)		3.075	2.834	11.56	20.56
β_i		70	250	8 130	324 470

IMPACT RESULTS

Having done the experiments to characterize the core and cover material for the calibration ball, impact simulation was carried out to validate the model. In addition to the viscoelastic, hyperelastic material model simulation, a 1-D nonlinear viscoelastic model was also considered [5]. In this work, the impact of an unnamed ball[1] with a rigid plate was modeled as follows:

$$m_{ball}\ddot{x}=-kx\left|x\right|^{a}-c\dot{x}\left|x\right|^{b} \tag{6}$$

It is a simple task to set up the initial value problem and integrate to get a model of the impact. Having solved for the velocity and position, one can readily calculate the coefficient of restitution (COR) and contact time.

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[1] Because of the importance the calibration ball played in USGA testing it was assumed Cochran [5] was reporting on this ball.

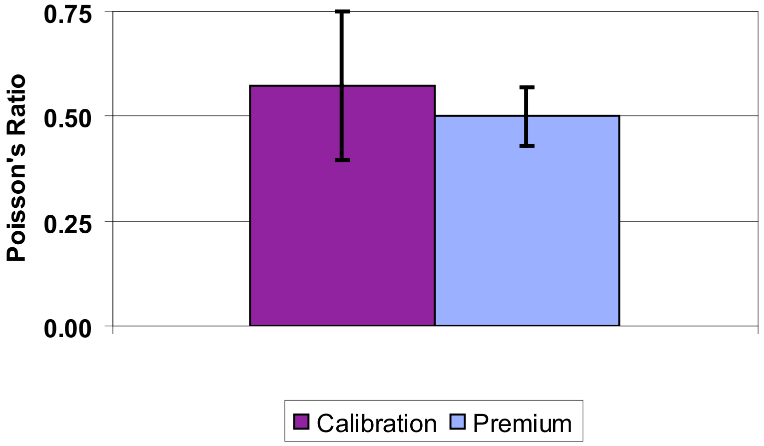

Figure 5: Poisson's ratio for calibration and premium cores.

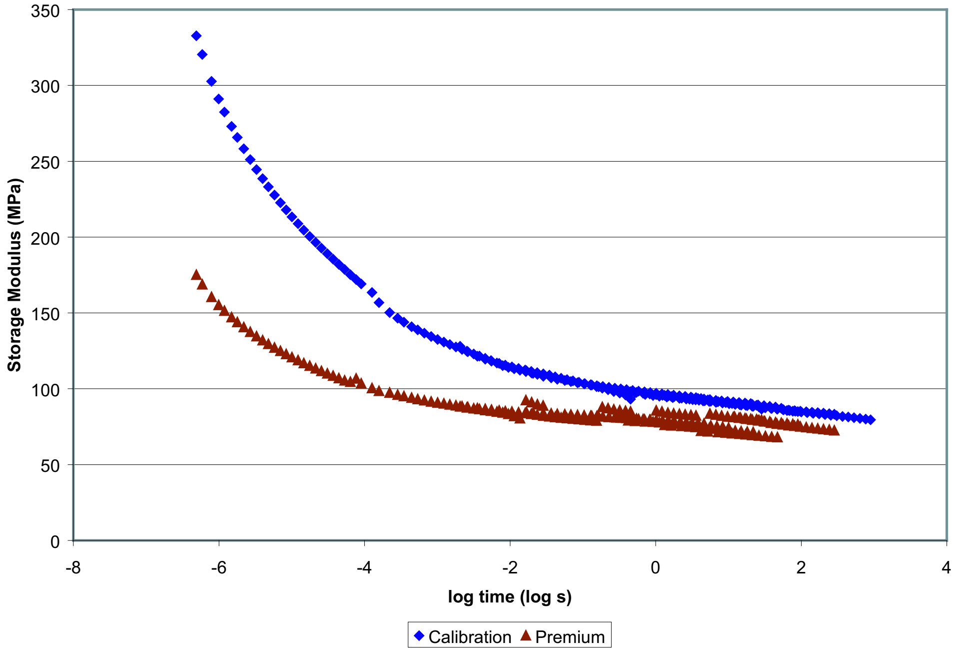

Figure 6: Relaxation master curves reduced to room temperature for two core materials.

For finite element modeling with the viscoelastic, hyperelastic core material a calibration spherical ball model was made using solid elements. Elements in the outer 2.29 mm of the sphere were given cover properties (elastic-plastic). The remainder of the elements were given core material properties (visco-hyperelastic). This ball was given an initial velocity and impacted with a single, fixed rigid element. Default contact parameters were used. Once again, the coefficient of restitution and time of contact were determined. All finite element simulations were conducted using LS-DYNA.

Figure 7 shows a plot of the coefficient of restitution for a wide range of initial velocities. Plotted in this figure are data from Cochran's model as well as experimental results [5]. Both the 1-D model and visco-hyperelastic models well represent the experiments between 35 and 55 m/s. For impact speeds below 30 m/s the current visco-hyperelastic model underestimates COR. Impact time is another important parameter in validating simulation material properties. Figure 8 shows the 3-D visco-hyperelastic model presented in this paper predicts impact times that are less than the experimental data.

CONCLUSIONS

A method for determining the rate-dependent mechanical response of golf ball thermoplastic covers and polybutadiene cores was reported. The properties for the USGA calibration ball were measured. These properties were used in finite element simulation to model the ball's impact with a rigid plate. Simulation coefficient of restitution results show that the visco-hyperelastic model closely matches prior experimental data in the range of velocities between 35 and 55 m/s. Determining core properties from DMA flexure tests is better than ASTM D575 compression tests because "barrelling" in the latter yields erroneously low stiffness values.

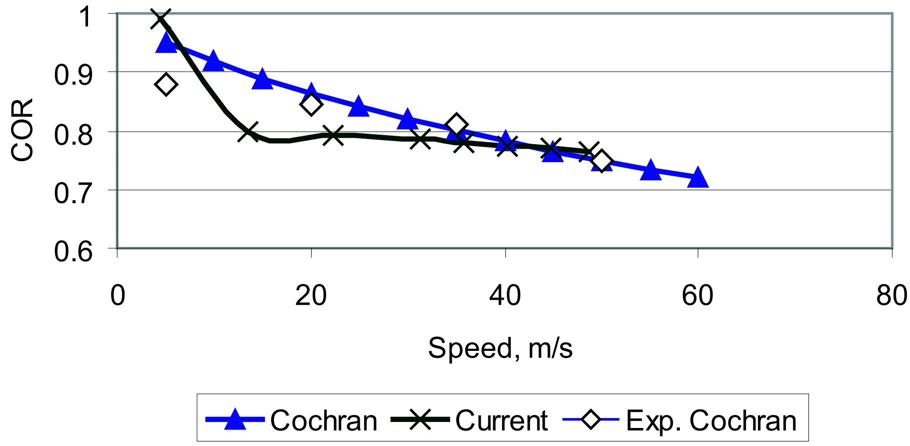

Figure 7: Coefficient of restitution for 1-D model (Cochran), visco-hyperelastic model (Current), and experimental (Exp. Cochran) results for calibration ball .

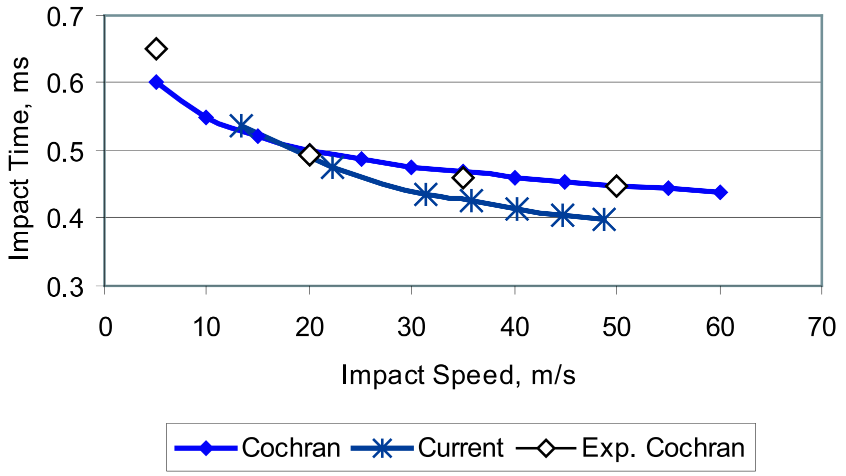

Figure 8: Impact time for 1-D model (Cochran), visco-hyperelastic model (Current), and experimental (Exp. Cochran) results for calibration ball.

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REFERENCES

[1] Nesbitt, R.D., M.J. Sullivan, and T. Melvin, "History and Construction of Non-Wound Golf Balls," *Science and Golf III: Proceedings of the 1998 World Scientific Congress of Golf*, M.R. Farrally and A.J. Cochran, Editors, Human Kinetics, Champaign, IL, USA, pp. 407-414, 1999

[2] Statz, R.J., "'Surlyn' ionomers for golf ball covers," *Science and Golf: Proceedings of the First World Scientific Congress of Golf*, ed. A.J. Cochran, E. & F.N. Spon, London, UK, pp. 205-212, 1990

[3] Statz, R.J. and J.F. Hagman, "Methods for Developing New Polymers for Golf Ball Covers," *Science and Golf III: Proceedings of the 1998 World Scientific Congress of Golf*, M.R. Farrally and A.J. Cochran, Editors, Human Kinetics, Champaign, IL, USA, pp. 481-485, 1999

[4] Tavares, G., M. Sullivan, and D. Nesbitt, "Use of Finite Element Analysis in Design of Multilayer Golf Balls," *Science and Golf III: Proceedings of the 1998 World Scientific Congress of Golf*, M.R. Farrally and A.J. Cochran, Editors, Human Kinetics, Champaign, IL, USA, pp. 473-480, 1999

[5] Cochran, Alastair J., "Development and use of one-dimensional models of a golf ball," *Journal of Sports Sciences*, Taylor & Francis, Ltd. London, UK, 2002

[6] Johnson, S.H. and J.E. Hubbell, "Golf Ball Rebound Enhancement," *Science and Golf III: Proceedings of the 1998 World Scientific Congress of Golf*, M.R. Farrally and A.J. Cochran, Editors, Human Kinetics, Champaign, IL, USA, pp. 493-499, 1999

[7] Dupont, web site http://www.dupont.com/industrial-polymers/surlyn/H-37063-2/H-37063-2.html, 2004

[8] Ferry, John D., *Viscoelastic Properties of Polymers*, Wiley & Sons, Inc., New York, NY, pp.203 ff, 1961

[9] LS-DYNA Keyword Users Manual, Version 950, Livermore Software Technology Corporation, Livermore, CA, p. 20-227, 1999

[10] Nelder, J.A. and R. Mead "A Simplex Method for Function Minimization," *Computer J.*, Vol. 7, pp. 08-313, 1965