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Characterizing the Interactions between Softballs and Softball Bats for Design of Batted-Ball Performance

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Abstract

Batted-ball speed (BBS) is a function of the interaction between the respective bat and ball constructions. The overall objective of the research is to study and identify bat characteristics that influence performance as quantified by BBS for a given ball construction while complying with the standards sanctioned by the respective softball associations. This objective is being achieved through a combined experimental and finite element modeling approach, and this paper will present some of those results at the current status of the overall research program. In the current work, four softballs are initially modeled in LS-DYNA as a viscoelastic material using the expression for the shear modulus G as a function of time: $G(t) = G_\infty + (G_0+G_\infty)e^{-\beta t}$, where G_∞ and G_0 represent the long-term and instantaneous shear moduli respectively, β is the decay constant and t is time. The ball model is tuned using experimental COR, dynamic stiffness and quasi-static compression test data. This viscoelastic model is found to be inadequate for capturing G(t) as it varies over the speed range of interest. The Prony series $G(t) = G_0\,[1-\sum g_i\ (1-e^{-t/\tau i})]$ is pursued as an alternative method to model the ball. Various DMA test methodologies are used in an effort to characterize the viscoelastic material behavior of the foam core of the softball.

Keywords: Softball; viscoelasticity; dynamic mechanical analysis; finite elements

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1. Introduction

The advancement in bat design has been significant in the past decade. These advances have raised concerns that increasing batted-ball speeds have shifted the balance between offense and defense and comprised the integrity of the game. To restore the balance, the NCAA and other baseball and softball

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governing bodies have implemented strict regulations to limit bat performance as quantified by BBS. As a result of these regulations, essentially all bats now perform at the respective BBS limit per the test method used to certify their compliance with the governing body's limit. Thus, there is essentially no advantage for a player to choose one bat over another if BBS is the deciding factor. However, in softball, there may be a reason for a player to select more than one bat depending on the softball construction being used in the game.

In softball, there is a variety of ball constructions such that there are different categories of softballs as denoted by the combination of COR (coefficient of restitution) and compression (a measure of ball hardness) classifications. It is now well known that BBS for a given bat is a consequence of the combination of ball COR and compression and the associated bat barrel construction. As a result, not all softballs will generate the same BBS for any one bat. Therefore, by understanding the mechanical behavior of any softball construction, which in turn can lead to having a good model of the softball for use in finite element analyses of bat-ball collisions, a bat design engineer would potentially have a design tool that could assist in optimizing the bat construction for a specific ball COR and compression combination. Thus, the designer could give players a choice of bat options. To achieve such a model requires experimental characterization to quantify the viscoelastic properties of the foam core of the ball. The paper will summarize some of the results of the current research as to the portion dedicated to developing a robust softball model that can give insight to the interactions between different softball configurations and softball bats.

2. Ball Characterization

Four softballs were studied, each with different COR and compression specifications. Quasi-static compression tests were done as prescribed in ASTM F 1888-09 [1], and 60-mi/hr (96-km/hr) COR testing was completed according to ASTM F 1887-09 [2]. Table 1 summarizes the manufacturer's specifications for COR and compression and the experimentally measured values of these quantities for three samples of each combination. The experimental results are used as target values for a finite element model of a softball in LS-DYNA. It can be concluded from this table that while there is some correlation between the manufacturer classification for COR and the experimental values, there are some significant differences between manufacturer classifications for compression and the experimental values. This disparity is not an objective of this research. However, it is important to note that such a disparity does exist.

Table 1. Experimental COR and quasi-static compression results compared with manufacturer's specifications

Ball Construction	COR/Compression (lb)	Experimental COR	Standard Deviation	Experimental Compression (lb)	Standard Deviation (lb)
1	0.47/375 [1668 N]	0.47	5.22E-3	325 [1446 N]	14.5 [64.5 N]
2	0.44/375 [1668 N]	0.45	5.66E-3	318 [1415 N]	11.6 [51.6 N]
3	0.52/300 [1134 N]	0.55	6.41E-3	256 [1139 N]	7.04 [31.3 N]
4	0.40/325 [1446 N]	0.48	3.46E-3	503 [2237 N]	26.2 [116. N]

Dynamic stiffness testing was done at 95 mi/hr (153 km/hr) according to ASTM F2845-11 to determine the peak load upon impact of the ball with a steel plate [3]. The results and standard deviation for each ball are shown in Table 2.

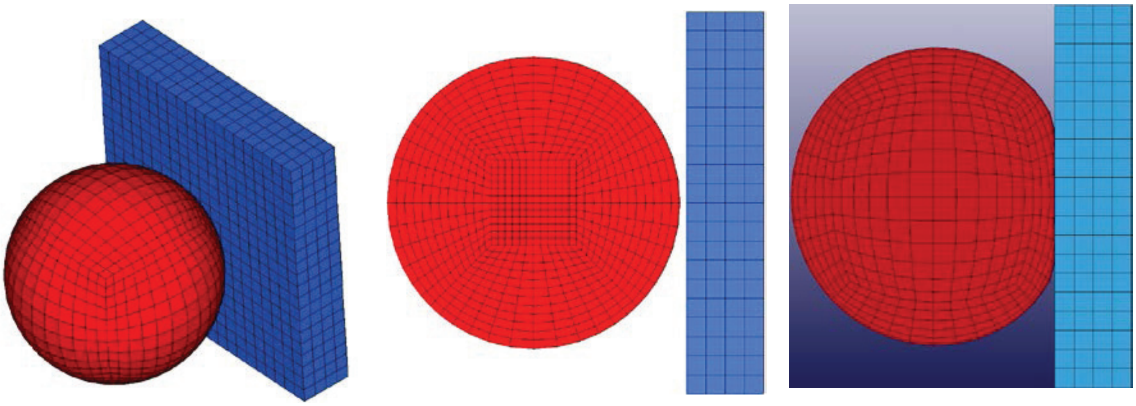
Table 2. Results from dynamic stiffness testing for peak load at impact of a rigid steel plate

Ball Construction	Peak Load at Impact (lb)	Standard Deviation
1	5300 [23576 N]	129.0 [574 N]
2	5830 [25933 N]	93.3 [415 N]
3	4670 [20733 N]	92.3 [410 N]
4	6710 [29848 N]	166.0 [738 N]

3. Finite Element Modeling Approaches

Softballs were modeled in LS-DYNA as a viscoelastic material using the expression for the shear modulus G as a function of time: $G(t) = G_\infty + (G_0+G_\infty)e^{-\beta t}$, where G_∞ and G_0 represent the long-term and instantaneous shear moduli, respectively, and β is the decay constant and t is time.

Parametric studies similar to Smith and Duris [4] were done to explore estimated values for G_∞ and G_0 in an effort to get correlation between experimental and ball finite element results. Fig. 1 shows various views of the finite element mesh used for the COR simulation. This methodology was successful in matching the finite element results for the 60-mph COR and quasi-static compression simulations with the experimental results for each of the four ball constructions. However, the models were unable to replicate the peak loads at 95 mi/hr (153 km/hr). Thus, it was concluded that a more robust model was needed and could potentially be achieved by adding more terms to the material model so as to expand the ability of the ball model to capture the viscoelastic behavior of the ball at speeds other than 60 mph (96 km/hr). Therefore, the shear modulus function was changed to use the Prony series for the shear modulus as given by $G(t) = G_0\ [1-\sum g_i\ (1-e^{-t/\tau i})]$ where g_i and τ_i are the effective instantaneous shear modulus and decay constant in the i^{th} range of material behavior, where i is an order of magnitude of speed. This multi-term formulation is available in LS-DYNA but is limited to 12 terms, which may or may not be sufficient. ABAQUS/Explicit allows for more than 12 terms. Thus, the finite element modeling effort is now being explored in parallel with LS-DYNA and ABAQUS to see if one program works better than the other. Dynamic Mechanical Analysis (DMA) was chosen as the experimental method to get test data over a range of speeds, and these data can be reduced to yield the values of g_i and τ_i.



(a) (b) (c)

Fig. 1 Finite element model of COR test (a) Isometric view (b) Cutaway view (c) deformed ball against wall in LS-DYNA

4. Dynamic Mechanical Analysis

DMA is a test method that induces small strains on a sample in a cyclic manner to observe the mechanical behavior of a material as a function of frequency and temperature [5]. A TA Instruments Q800 Dynamic Mechanical Analyzer was used for this characterization. The instrument applies a sinusoidal force and measures the in-phase storage modulus (E’), and out-of-phase loss modulus (E″). The storage modulus is associated with the stress of the material, while the loss modulus is associated with the strain. The ratio of the two, E″/E′ is called tan δ and is the measure of the viscoelasticity of the material 0. These parameters help determine the glass transition temperature (T_g) of the material.

The T_g of a material is the transition from a glassy state (high modulus) to a rubbery state (low modulus). The storage modulus can change by a decade or more when viewed as a function of temperature. The regions of viscoelastic behavior for a general polymer are shown in Fig. 2, and a representative curve from a softball sample is shown in Fig. 3. Upon comparing Figs. 2 and 3, it can be observed that the transition from the glassy to the rubbery region is much more gradual for the softball foam than for the hypothetical material presented in Fig. 2.

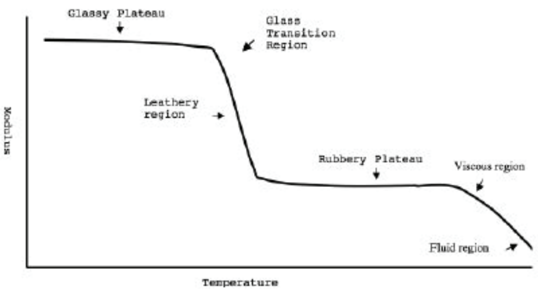


Fig. 2 Regions of viscoelastic behavior for a general polymer [5]

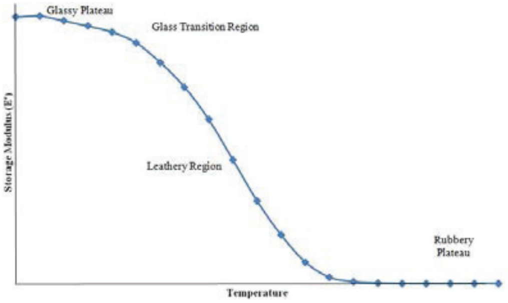


Fig. 3 Regions of viscoelastic behaviour for a representative softball sample

In the DMA test, samples undergo a “temperature-step frequency sweep” test where the test starts at very low temperature and increases to a “high” temperature in user-specified increments, e.g. 10°C increments. At each temperature, the sample undergoes a frequency sweep from 1-100 Hz. For this characterization, several clamp configurations were considered, including the shear sandwich and the compression clamp, but these did not yield useful data—probably due to the sensitivity of the clamp to the damping nature of the samples. The tension film clamp, as shown in Fig. 4, was the most successful in withstanding the wide temperature and frequency ranges required for the characterization.

The storage modulus was then plotted as a function of frequency for each temperature as shown in Fig. 5. The axes scales and temperatures are not given due to the sensitivity of the data at this time. The lines progress from top to bottom in the figure with increasing temperature. Thus, the modulus decreases as the temperature increases, and this trend corresponds to the trend shown in Figs. 2 and 3. Similar to Fig. 3, the decrease in stiffness is gradual with the increase in temperature.

Each of the temperature curves was transformed to the time domain and “shifted” along the time axis to construct the master curve. Fig. 6 is the master curve constructed for one of the softballs. The ultimate goal of the DMA testing of the softball foam is to construct such a master curve so the shear modulus G as a function time is known and can be used to find the material constants for implementation in the Prony series. This master curve is also used to identify the T_g.

Fig. 4 Tension clamp of the TA Instuments Q800 DMA

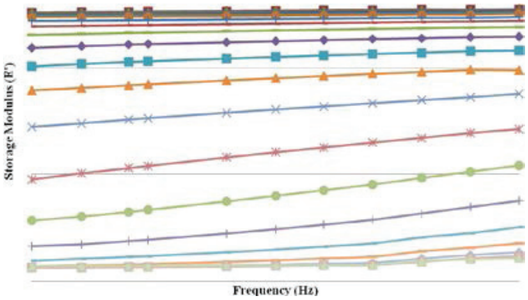


Fig. 5 Storage Modulus as a function of frequency for each temperature step. The curves with the highest storage modulus are the coldest temperatures.

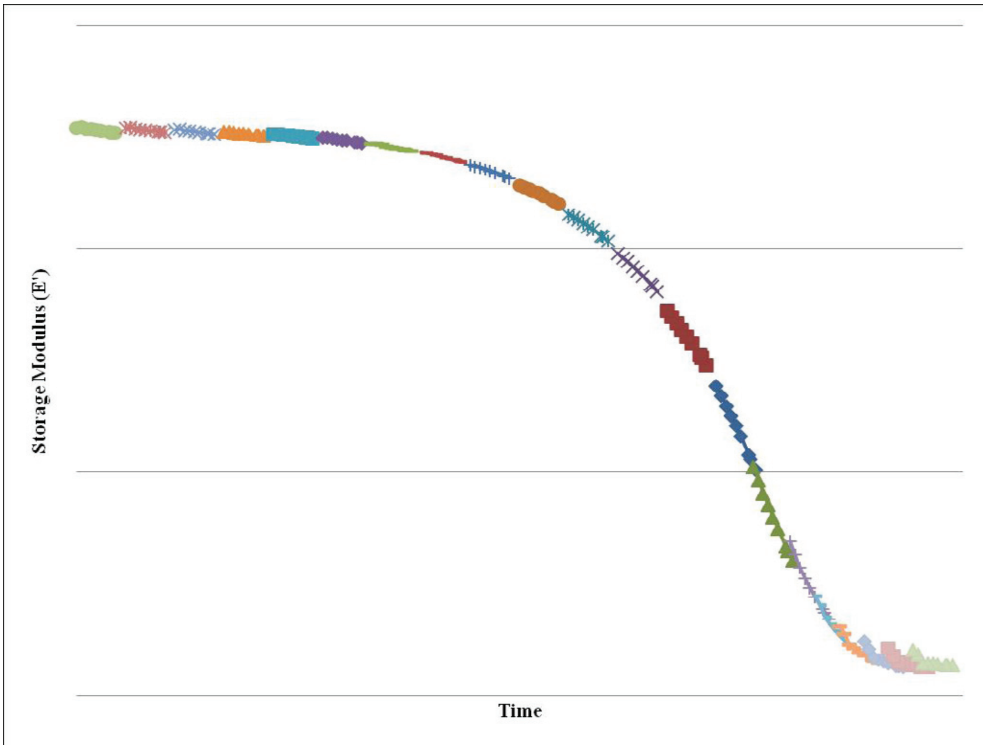


Fig. 6 Master curve constructed from experimental DMA data.

To determine the T_g of the sample, one can use the master curve and identify the inflection point, or plot tan δ as a function of temperature as shown in Fig. 7. The T_g occurs when tan δ is at a maximum [6,7]. If the test was run successfully, then the two methods (master curve and tan δ curve) of determining the T_g will correlate well with each other.

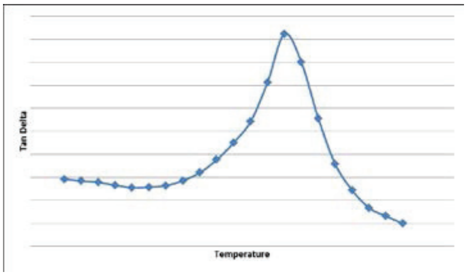


Fig. 7 Tan δ as a function of temperature. The T_g is indicated by a maximum in tan δ.

With these DMA data now available, the next task is to use the master curve to find the constants to be used to define ABAQUS Prony series, which will capture the material behavior over a range of speeds to model the softball COR and compression. Future experimental data collection is planned to correlate the results with the ongoing development of the FE model. COR and dynamic stiffness testing at different speeds are needed to check for the robustness of the new FE model. If the softball models are demonstrated to be successful, performance testing and modeling can then be done to observe the interaction between bat performance and ball characteristics.

5. Conclusion

Experimental results for COR, quasi-static compression and dynamic stiffness were accumulated. Attempts to build an FE model in LS-DYNA were unsuccessful in tuning to the material model to be applicable over a wide range of impact speeds. It was concluded that more terms are needed to model the ball behavior over a range of speeds. DMA was shown to be an effective tool to characterize the viscoelastic behavior of the polyurethane foam core. The DMA tension clamp configuration was best suited to subject the sample to the wide range of temperatures and frequencies. A master curve was constructed to identify the T_g, as well as to observe the stiffness in the glassy and rubbery regions of viscoelasticity. These data will be used to build an FE softball model in LS-DYNA and ABAQUS.

Acknowledgements

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