Methods for Modeling Solid Sports Ball Impacts

Derek Nevins[1], Lloyd Smith[1]
[1]*Washington State University, Pullman, WA 99164-2920, USA*

Abstract

Finite element modeling of dynamic sports ball impacts presents a substantial challenge. This is because, rather than displaying linear-elastic behavior, many sports balls are predominantly non-linear, inelastic and rate dependent. This is true of both softballs and baseballs, which exhibit strong rate-dependence and large energy dissipation characteristics in collisions occurring under play-like conditions. The development of finite element models of these balls is further complicated by the difficulty in measuring materials properties at strain rates and magnitudes representative of play. This work describes the development of novel ball models from data obtained under play-like conditions. Ball models were implemented in LS-DYNA® using the Low-Density Foam material model. Simulations were compared to empirical data collected over a range of ball speeds. Models displayed good agreement with experimental measures of energy dissipation and impact force and represent an improvement over commonly used viscoelastic models.

Introduction

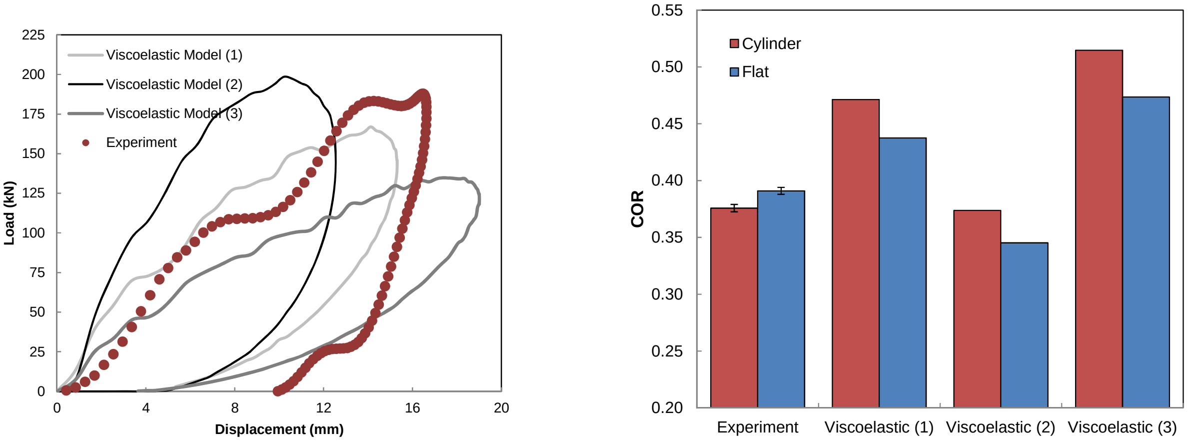
Finite element analysis (FEA) has been widely implemented in the simulation of sport balls including golf, cricket, baseball, tennis, and softball. Compared to the nearly elastic behavior of bats and clubs however [1], sports balls have been difficult to model due to their non-linear and time-dependent material response [2]. Recently, sophisticated finite element models of sports ball impacts have been developed for various sports. Tanaka et al. simulated golf ball-club collisions using multiple layers and both hyperelastic and viscoelastic material models [3]. Likewise, robust finite element models have been developed to describe the dynamic performance of hockey and soccer balls [4,5].

Models of softball collisions are especially challenging due to the relatively low coefficient of restitution (COR) and associated large magnitude of energy dissipation observed during collisions occurring under play-like conditions [2]. Previous work by Duris [6], Faber [7] and Bryson [8] produced finite element models of softballs in LS-DYNA using a linear viscoelastic material model.

While these models reasonably capture experimentally observed peak contact force or displacement, the generally oval-shaped load-displacement curve generated by these models suggests a different mechanism of deformation than occurs with the polyurethane softball foam (Figure 1A). Perhaps a greater challenge for softball models has been capturing COR. Impacts on a flat surface have less deformation and less energy loss than impacts on a cylindrical surface and, as a result, experimental flat surface COR is larger than the cylindrical coefficient of restitution (CCOR). Viscoelastic models do not correctly capture this effect of impact surface geometry, and show CCOR to be greater than COR (Figure 1B).

Recently, Burbank and Smith [9] developed a finite element model of dynamic softball impacts using a foam material model (MAT#57, Low Density Foam). This model produced substantially improved agreement with experimental data for peak contact force, peak displacement, loading and unloading behavior, and coefficient of restitution over a range of impact speeds.

A unique aspect of softball is the wide variation in ball stiffness and elasticity used in play. The following is an extension of Burbank and Smith's foam softball model to describe the dynamic response of both stiffer and more compliant polyurethane ball types, and a cork-cored softball. All models are compared to experimental measures of dynamic impact response over a range of speeds.



(A) (B)

Figure 1. Load-displacement (A) and COR (B) of experimental measures and prior viscoelastic models. Experimental measure were obtained by Burbank and Smith; viscoelastic models were from (1) Bryson, (2) Faber and (3) Duris.

Ball Impact Tests

Instrumented ball impacts were performed on an impact apparatus as shown in Figure 2 [10]. The test consisted of firing a ball from an air cannon against a fixed, solid-steel, half cylinder (57 mm diameter). Load cells (PCB, model 208C03) were placed between the impact surface and a massive support where load was recorded at a sample rate of 100 kHz. Light screens, placed between the cannon and impact surface, measured the inbound (v_i) and rebound (v_r) ball speeds. Cannon alignment with respect to the impact surface was adjusted to maintain a rebound path within ±10° of the inbound path.

The cylindrical coefficient of restitution (CCOR) was calculated as the ratio of inbound and rebound ball speed from a flat plate impact. Impulse is the change in ball momentum and was calculated from

$$I = \int_0^T f(t)dt \tag{1}$$

where $f(t)$ was the measured load at time t over an impact duration of T seconds. Displacement of the ball center of mass was calculated using

$$d(t) = \int_0^T \left(v_i - \int_0^T \frac{f(t)}{m} dt \right) dt \tag{2}$$

where m was the ball mass.

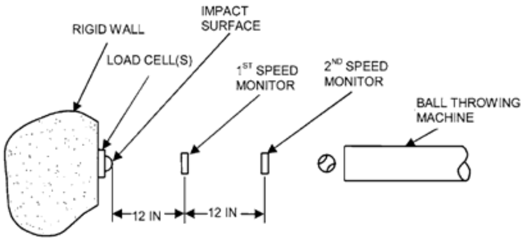


Figure 2. Instrumentation diagram of the ball dynamic stiffness test apparatus.

Force, displacement and CCOR data were obtained from four different softball types. Balls A and B were from different manufactures but of the same type (44/375) and approved for adult slow pitch play. Results for ball A were obtained by Burbank and Smith while the properties for ball B were found as part of the current work. Ball C was a Reduced Injury Factor (RIF) ball composed of more compliant foam than ball A, and ball C was composed primarily of cork.

To determine an average ball response, at least three new balls of each type were impacted four times on a cylindrical surface at 26.8, 42.5 and 53.6 m/s. A single ball response was selected at each speed which had a loading curve, weight and CCOR that was representative of the group of balls and used to train the finite element models.

Finite Element Models

Most softballs consist of a solid, uniform PU core (which tends to govern its response) and a thin leather cover. The softball and cover were, therefore, modeled as a single isotropic homogeneous sphere as done elsewhere [6-8]. The cylindrical impact surface was modeled using 4,864 linear solid elements and was elastically characterized. The softball was modeled using 7,168 solid elements and the low density foam material model (MAT_057). Simulations used two symmetry planes and an orthogonal impact (Figure 3).

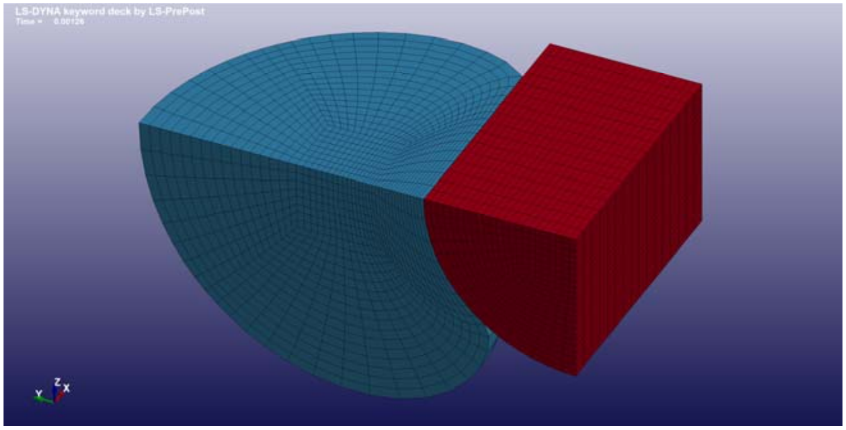


Figure 3. Finite element model of softball (Ball Type B) impact on cylindrical surface.

The master stress-strain curve for ball A, used to control the compressive loading response of the Low Density Foam material, was based on the master curve experimentally derived by Burbank and Smith [9]. For simulations of impact for the other ball types, the ordinate axis of the master curve was scaled to achieve agreement with experimental measures of load-displacement data.

Likewise, the hysteretic unloading factor (HU) and "shape" factors, which control unloading response, and the damping factor (DAMP) which controls viscous effects were adjusted to achieve agreement with experimental unloading response. Master curve scaling and unloading parameter identification for balls B, C and D was accomplished using the optimization package LS-OPT® (Version 4.2 LSTC, Livermore, CA).

The Curve Mapping approach in LS-OPT was used to minimize the difference between the measured and simulated force-displacement curves. The optimization included three test speeds (26.8 m/s, 42.5 m/s and 53.6 m/s) to ensure that rate effects were properly accounted for [9]. Models were evaluated by their contact force, peak displacement of the ball center of mass and CCOR between simulations and experimental observations. Rate dependence of ball response was further characterized by the slope of a linear best fit line of CCOR results at each impact velocity. The slope of best fit lines from experimental and simulated impacts were compared to assess rate sensitivity of models of each ball type.

Ball Impact and Modeling Results

Substantial differences in measured peak force, peak displacement and CCOR across ball types were observed during impact tests. Simulation results displayed good agreement with force-displacement data, and the foam material model was able to describe the linear loading and unloading of the higher stiffness ball types A and B, and the non-linear unloading of the more compliant ball types C and D (Figure 3).

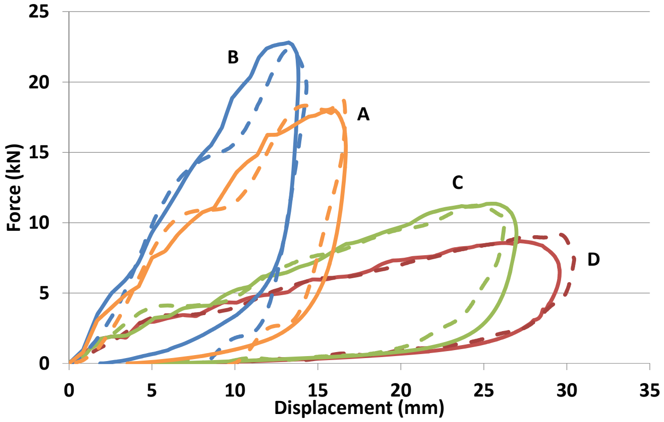


Figure 4. Comparison of experimentally observed (dashed) and simulated (solid) load-displacement responses of ball impacts on a cylindrical surface at 42.5 m/s for ball types A (orange), B (blue), C (green) and D (red).

Simulated peak force and peak displacement displayed excellent agreement with experimental measures over the range of impact speeds, while agreement with CCOR results was more modest (Table 1).

Table 1. Average difference between experimentally observed and simulated peak force, peak displacement and CCOR across impact speeds for each ball type.

Ball Type	Peak Force	Peak Displacement	CCOR
A	4.8%	2.7%	3.6%
B	3.8%	4.3%	18.8%
C	1.4%	3.9%	13.0%
D	7.2%	3.3%	7.6%

Consistent with prior work, CCOR was rate dependent in impact tests (Figure 5). At higher test speeds, greater deformation occurs, leading to increased heat production and energy dissipation. Therefore, to model the general response of a softball to dynamic impacts the finite element model must capture rate dependence of energy dissipation.

Models of ball types A, B and C under estimated the rate sensitivity of CCOR by approximately 52.2%, 29.5% and 45.8%, respectively. For ball type D, simulation CCOR rate sensitivity was over estimated by 9.4% (Figure 6).

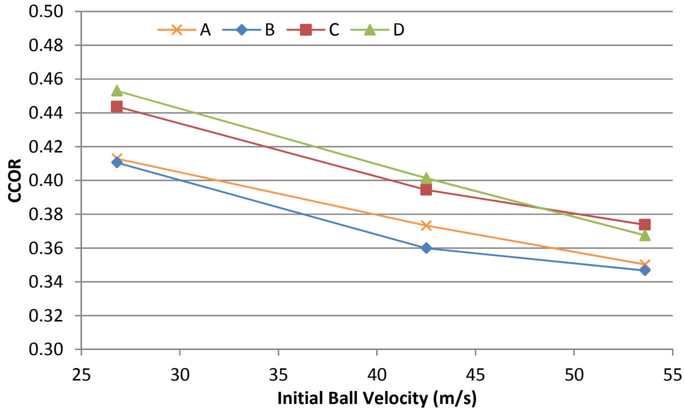


Figure 5. Experimentally measured CCOR over the range of initial ball velocities investigated.

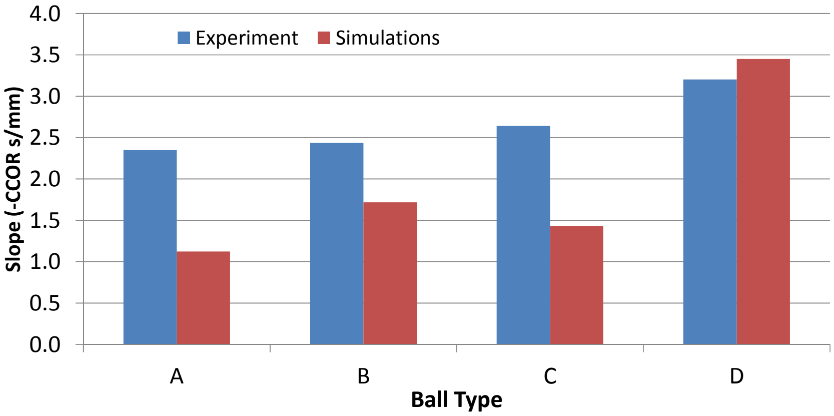


Figure 6. Experimental and simulated CCOR Rate sensitivity for all ball types.

Discussion

The foregoing considered the modification of a leading finite element softball model to simulate impacts of various softball types with a wide range of stiffnesses. Experimental measures of dynamic ball response were obtained from a test method developed to characterize ball material response at strain rates and magnitudes that are representative of play conditions. Finite element models of these impacts were constructed in LS-DYNA using the low density foam material model (MAT_057).

Tuning of foam material parameters for each ball type achieved good agreement between experimental and simulated peak force and displacement results, and modest agreement was obtained for CCOR. This is likely a result of the foam material parameter tuning method. Parameter identification was conducted using the Curve Mapping approach in LS-OPT, with experimental force-displacement data as the target curve. Explicit inclusion of CCOR into the objective function of the LS-OPT routine may improve parameter identification results in future work.

Despite being approved for the same level of play, balls A and B displayed substantially different stiffness. This presents a challenge for players and federations, because deviation from accepted ball performance standards can affect both the integrity of the game and player safety.

Previous viscoelastic and foam modeling efforts have not been able to accurately capture both magnitude and rate dependence of the softball CCOR in dynamic impacts. The model developed by Burbank and Smith provided good agreement with CCOR magnitude, though modest agreement with experimental measures of CCOR rate dependence. While previous viscoelastic models more accurately captured CCOR rate dependence, the foam model was able to accurately capture the effect of impact surface geometry [9].

In general, capturing CCOR magnitude and rate dependence in finite element softball models continues to be difficult. That shortcoming is also observed in this work, with some exception for the model of ball type C. For this ball type, tuning of material parameters resulted in a difference of less than 13% for both CCOR magnitude and rate dependence. This may be due to the combination of the relatively lower stiffness of ball type C and similar CCOR magnitudes compared to the other ball types.

Parameter identification conducted using the LS-OPT curve mapping approach achieves good agreement with experimental measures of dynamic loading and unloading behavior. The low density foam material model captured this behavior despite large energy dissipation and strain magnitudes. Accurate description of response rate dependence remains a challenge, and will need to be addressed in future work to improve finite element models of softball impacts.

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