IMPACT BEHAVIOUR OF THE BASEBALL WITH IMPLICATIONS FOR PLAYER SAFETY

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Fatalities amongst baseball pitchers occur primarily as a result of impact by the batted ball (Adler & Monticone, 1996). It was hypothesized the material properties of the baseball would affect ball exit velocity after bat-ball impact, and thereby the available time for the pitcher to take evasive action. Material behaviour of the baseball under conditions representative of those during bat-ball impact have not been previously investigated. The results of quasi-static compression testing were used to develop a mathematical model of the nonlinear viscoelastic behaviour of the baseball as the basis for dynamic analysis of the bat-ball impact.

KEY WORDS: baseball, material properties, infielder injury.

INTRODUCTION: In 1997, baseball had the highest fatal injury rate of the 13 sports undertaken by men in US colleges, exceeding that of both spring football and ice-hockey (Dick, 1999). Impact from the batted ball is the primary cause of deaths among baseball pitchers (Adler & Monticone, 1996). The use of increasingly sophisticated metal bats has been proposed as a factor in ball exit velocities which exceed the reaction time of pitchers in the field (Crisco, Hendee & Greenwald, 2001). However, the material properties of the ball also affect the dynamics of the bat-ball interaction, and thereby the ball exit velocity and subsequent time available for the pitcher to take evasive action. This highlights the need for investigation into the behaviour of baseballs under maximal impact conditions. During bat-ball impact, a baseball is compressed to 50% of its original diameter (Adair, 1994). Previous investigations of baseball material properties using a quasi-static uniaxial design have typically tested to 10% compression (Cross, 1999; Heald & Pass, 1994; Hendee, Greenwald & Crisco, 1998), as the force-displacement relationship is linear in this range and ball stiffness can be determined as the gradient of the curve (Hendee *et al.*, 1998). However, such data cannot guarantee the validity of results at 50% ball compression. In order to predict baseball impact response and behaviour under such maximal conditions, this research undertook extensive compression tests to obtain realistic measures of material behaviour as a basis for future analysis to predict baseball response during impact with both wood and metal bats.

METHODS: Seventy new baseballs from 7 models (A-G, Table 1) were selected for testing, representative of balls used in professional and college baseball. Baseballs are constructed in four layers, consisting of a cork or rubber core wound in grey and white wools encased in two stitched pieces of cowhide. Variations in material properties were expected between models as previous coefficient of restitution (COR) measurements have indicated inter-model differences (Crisco *et al.*, 1997). Uniaxial compression testing was conducted using the Instron 8501 (Instron Corp., Canton, Massachusetts). Each ball was positioned between two circular stainless steel platens: the upper platen was attached to a calibrated 100 kN load cell and lowered toward the stationary lower platen. Testing was conducted at 1 mm/s as pilot testing at speeds of 0.1 and 0.01 mm/s produced no verifiable differences in curve shape or peak force. The onset of the loading phase was indicated by the first non-zero force reading, and terminated at 50% of baseball diameter (35.86 mm). Only one loading cycle was completed for each ball due to the destructive nature of the test. Force-displacement data were sampled at 5 Hz using LABTECH Notebook software with DAS8 type boards and EXP16 multiplexors. The data were normalised to 100 data points (as a percentage of maximum displacement) in Excel spreadsheets (Microsoft Corporation, Seattle). A distinct directional effect was evident when the ball was compressed on the cover as opposed to when oriented on the seams (Figure 1).

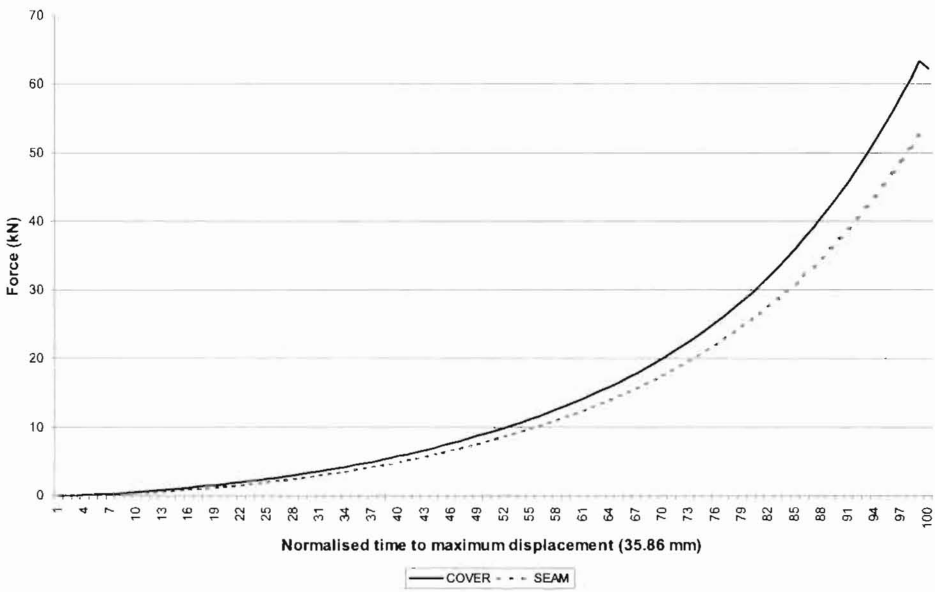

Figure 1. Force – displacement curves for Model B in cover and seam orientations.

The model showing the steepest mean curve and greatest peak force in cover orientation was selected as indicative of the "worst-case scenario" - that likely to produce greatest ball exit velocity. Increased peak force has also been linked to decreased deformation during impact, increased stress transmitted to bone and increased chance of and severity of head injury (Heald & Pass, 1994; Viano & Lau, 1988).

RESULTS AND DISCUSSION: Static tests have previously shown poor correlation with dynamic properties of the baseball such as COR, which is used as a performance indicator by professional baseball regulatory bodies (Hendee *et al.*, 1998). Although some quasi-static properties of baseballs have been correlated with ball impact characteristics (Crisco *et al.*, 1997), such conclusions were derived from compression experiments to 10% of ball diameter in which ball behaviour was assumed linear elastic - and therefore cannot guarantee the validity of results at 50% compression. Ours is the first experimental study to measure elastic and time-dependent properties of balls as a basis for future approximations of ball behaviour under maximal impact conditions. Results are presented only for the loading phase. The nonlinear behaviour of baseballs under compression to 50% of original diameter is evident in Figure 1. The coefficient of variation (standard deviation divided by the mean) for normalised force-displacement curves of four randomly selected balls, ranged between 0.03 and 0.09 for each models when tested on the cover, and 0.03 - 0.11 for seam orientation. The surface of the baseball is assymmetric due to its pattern of raised seams. Repeated measures ANOVA for normalised force indicated a distinct directional effect was evident when comparing data from the two ball orientations (cover and seams) ($p=0.000$), with cover orientations being steeper with greater peak force (Figure 1). Some quasi-static properties of baseballs have been previously correlated with ball impact characteristics, particularly peak force and stiffness (Hendee *et al.*, 1998). Modification of the procedure adopted by Hendee *et al.*, (1998) was used to estimate ball stiffness for compression to 50%. Data from four balls in each model were selected at random and averaged to represent that model. Linear least-squares fit was applied to the 10 (normalised) data points preceding maximum displacement for each ball model. Maximum stiffness was determined as the gradient of this fit line (Table 1). These values are significantly higher than those reported by Hendee *et al.* (1998) for 10% compression (mean 2340 ± 441 N/cm, n=8). The distinct directional effect is also verified, with mean peak force and stiffness in cover orientation exceeding that of seam orientation for each model.

Table 1. Mean peak force and linear fit stiffness data for seven baseball models during compression to 50% of ball diameter (35.86 mm).

	Cover			*Seam*		
Model	**Mean peak force (kN)**	**Stiffness (N/cm)**	**R^2**	**Mean peak force (kN)**	**Stiffness (N/cm)**	**R^2**
A	61.29 ± 2.56	18004	0.9912	47.85 ± 2.52	12977	0.9641
B	63.37 ± 5.56	20039	0.9898	52.72 ± 3.02	15813	0.9894
C	55.68 ± 2.13	17541	0.9919	43.99 ± 2.85	12751	0.9760
D	60.64 ± 6.12	19769	0.9954	48.08 ± 4.58	14438	0.9799
E	56.36 ± 3.04	16175	0.9877	48.61 ± 3.38	13853	0.9890
F	57.35 ± 4.20	17187	0.9924	47.96 ± 3.93	13575	0.9840
G	55.97 ± 1.43	18089	0.9930	47.24 ± 1.61	14128	0.9794

Variation in the time-dependent properties of the ball may be one method for reducing ball exit velocity to safer levels. In tests using NOCSAE protocols on humanoid heads, baseballs stiffer than 700 N/cm have shown 50% increased risk of head injury for a 60 mph blow to the temple (Heald & Pass, 1994). Crisco *et al.* (1997) demonstrated that decreasing baseball stiffness by a factor of 15 decreased peak impact force by 66%. The directional effect evident above may indicate a possible avenue for modifying ball internal structure to reduce both peak force and ball stiffness, and thereby ball exit velocity. This would increase the time available for the pitcher to take evasive action against a ball hit directly at him or her. However the demonstrated nonlinear material behaviour indicates a mathematical solution is required to approximate ball time-dependent behaviour before assumptions can be made about impact response (Miller, 2000). It is proposed a single-phase material model be developed according to the data described above, and explicit dynamics analysis employed to fully quantify the behaviour of the baseball under maximal impact conditions.

CONCLUSIONS: This research is the first to experimentally measure time-dependent properties of baseballs under conditions representative of those during bat-ball impact. Baseball stiffness during compression to 50% of initial diameter has been determined, giving assurance for the validity of results beyond the 10% compression tests previously undertaken in published research (e.g. Hendee *et al.* (1998)). Baseball behaviour is highly nonlinear during compressive loading. A distinct directional effect between compression on the ball seams and cover has implications for future baseball design. The reduced peak force and stiffness during compression on the seams indicates a potential control strategy for ball performance. These results are important in determining permissible ball behaviour to maximise safety of baseball pitchers. Manipulating the material properties of the baseball may assist to reduce batted ball velocity to safer levels. Baseball behaviour is highly nonlinear during compressive loading and a mathematical model to predict the behaviour during high-speed impact must be developed.

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