A Complementary Experimental and Modeling Approach for the Characterization of Maple and Ash Wood Material Properties for Bat/Ball Impact Modeling in LS-DYNA

Joshua Fortin-Smith[1], James Sherwood[1], Patrick Drane[1]
and David Kretschmann[2]
[1]University of Massachusetts Lowell Baseball Research Center,
1 University Avenue, Lowell, MA, 01854, USA
[2]U.S. Forest Products Laboratory, U.S. Forest Service,
1 Gifford Pinchot Drive, Madison, WI, 53726, USA

Abstract

To assist in developing LS-DYNA finite element models of wood baseball bats that can be used to explore the relationship between bat profile and bat durability, an experimental program was conducted to characterize the mechanical behavior of maple and ash woods for the range of densities used to make major-league quality baseball bats. The test program included four-point bend testing to determine the elastic moduli and breaking strength and Charpy impact testing to determine strain to failure as a function of strain rate. The MAT_WOOD material was used to describe the mechanical behavior of the wood, and the input parameters were calibrated by comparing the results of LS-DYNA finite element simulations of the Charpy tests to the experimental test data. This paper describes the experimental characterization program, summarizes the material parameters and presents a comparison of the finite element simulations of the Charpy testing and bat/ball impacts to experimental results.

Corresponding Author Email: james_sherwood@uml.edu

Application Area(s): **Impact and Drop Testing**
Modeling Techniques

Introduction

Research efforts have been pursued to explore how finite element modeling can assist in understanding how bat profile and wood quality relate to bat durability [1]. These finite models have been found to be valuable tools for providing insight into the mechanical response of wood baseball bats over a range of impact speeds. However, the description of the material properties to date has been limited to what can be extracted from quasi-static four-point bend testing and the Wood Handbook [2]. To further improve the level of correlation between finite element models and real bat/ball impacts and thereby have a credible prediction tool, the material behavior for these wood species must also be characterized at strain rates comparable to those experienced during on-field bat/ball collisions.

In the current research, Charpy Impact tests of ash and maple were completed to characterize the high strain-rate behavior of ash and maple. By following the testing methodologies that were used by the Federal Highway Administration [3] to characterize southern yellow pine and applying them to maple and ash, the current high-speed testing characterized the material behavior of these wood species beyond what is currently available. Once characterized, the resulting material properties can be prescribed using the MAT_WOOD (Material Model 143) material model in LS-DYNA [4] for use in the finite element analyses of bat/ball impacts. This paper describes the experimental characterization program, summarizes the material parameters and presents a comparison of the finite element simulation results to the Charpy test data and to bat/ball impacts over a range of collision speeds.

Mechanical Behavior of Wood

To develop a set of properties for the material characterization of maple and ash wood species, quasi-static and dynamic material testing was conducted. Four-point bend testing of wood dowels was explored to develop an understanding of the relationship between wood density, MOE (modulus of elasticity), and MOR (modulus of rupture, i.e. failure stress). Charpy Impact testing was conducted to characterize wood behavior during dynamic impact.

Impact Location

The wood surface associated with the ball impact plays a measurable role in bat durability. For ring-porous woods, such as ash, impact is preferred to occur on the edge-grain (see Figure 1) because this face is parallel to the dense latewood growth rings of the wood, allowing impact forces to be transferred across the bat diameter. For diffuse-porous hardwoods, such as maple, contact is desired along the flat-grain face of the bat which has been demonstrated to exhibit better durability in experimental testing than impacts on the edge grain.

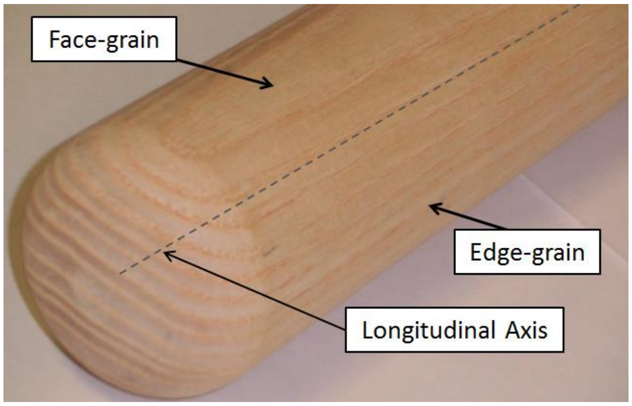


Figure 1: Grain faces of an ash bat.

Existing test data

In 2009, four-point bend testing of ash and maple dowels was completed at the FPL in Madison, WI [5] to see how the MOE and MOE varied as a function of density for each of these wood species. The density range was chosen to correspond to the range of wood densities that are permitted by MLB. Figures 2 and 3 show the MOE and MOR results, respectively, as a function of density. The slope of grain (SoG) angles for each of the samples was less than or equal to 3^o, which is the current range of allowed SoGs for MLB bats. It is clear from the results that the MOE and MOR for each of the wood species increase with increasing density.

Dynamic high-rate material testing

For the current research, the Charpy Impact test was utilized for the high strain-rate material testing. A standard Charpy test involves the use of a pendulum swinging a hammer to impact a specimen of known geometry per the ASTM Standard D6110-10 Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics [6]. To help in the extraction of the strain-rate for each test, high-speed video was used to capture each test event. The video was then postprocessed to measure the maximum deflection of the sample during impact. Once the max deflection was known, the strain to failure of the sample and the effective strain-rate were calculated. Figure 4 depicts how samples were cut from wood blocks for use in testing. The edge (radial) and face (tangential) SoGs were measured for each sample.

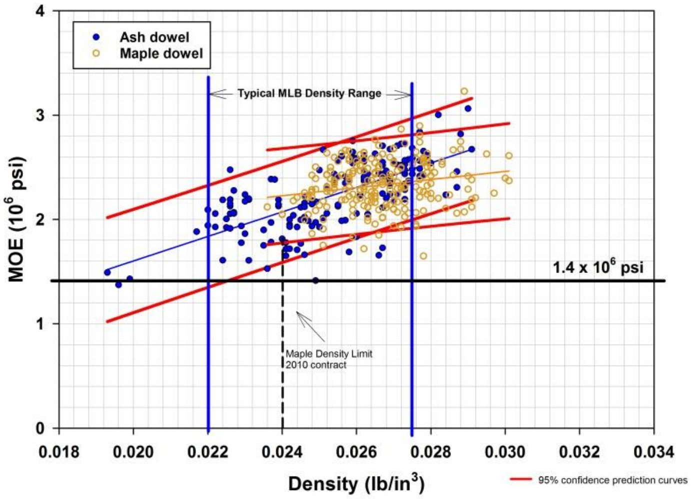


Figure 2: Test results for ash and maple dowel Moduli of Elasticity (MOE) with SoG < 3^o**.**

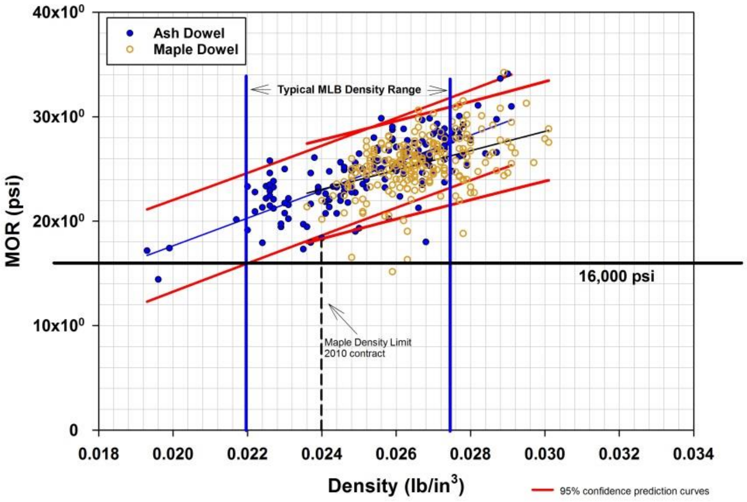


Figure 3: Test results for ash and maple dowel Moduli of Rupture (MOR) variance with SoG < 3º

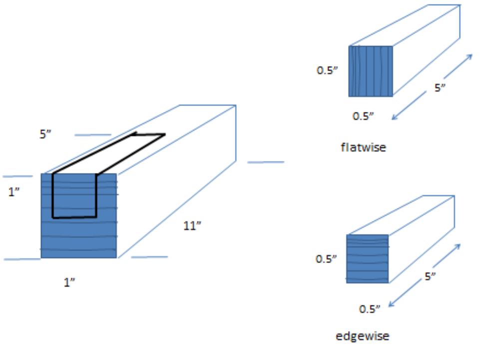


Figure 4: Sample selection process

Test procedure

Charpy Impact testing is used to determine the resistance of a material to breakage by flexural shock. The shock in this test is induced by a pendulum of specified weight to break a test specimen in a single swing. The output of the test is the energy required to break a specimen of a specified size. A photograph of a typical Charpy Impact test is presented in Figure 5. Samples were impacted with a 13.56 N-m (10 ft-lb) hammer on the edge grain and face grain to determine the effect of edge vs. face grain impact within each wood species.

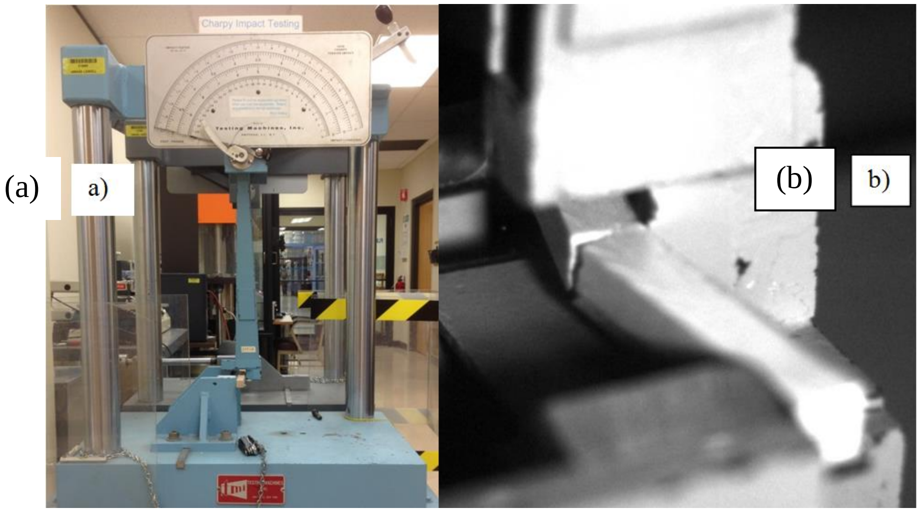


Figure 5: Charpy testing. (a) Test setup and (b) Example of wood specimen at fracture during test

Results

Table 1 summarizes the results of the Charpy testing. The results show that maple exhibited a lower failure energy, a lower max-deflection and a lower strain-to-failure for both edge and flat-grain loadings relative to ash. Maple performed better when loaded in the face-grain direction compared to edge-grain impacts. This difference was expected because maple is known to exhibit better durability (higher relative bat/ball impact speed) when impacted on the face grain compared to impacts on the edge grain for baseball bats. Ash performed better for deflection and for strain-to-failure when impacted on the edge grain, but it had superior failure energy when impacted on the face grain. From a strain-to-failure perspective, the ash samples performed better when impacted in edge-grain loading vs. face-grain loading, which is consistent with the preferred impact face of ash bats.

Table 1: Summary of average values for Charpy Impact testing

Wood Species	Impact Surface	Number of Samples	Average Energy N-m (ft-lb$_f$)	Average Max Deflection cm (in.)	Average Strain to failure
Ash	edge	23	8.79 (6.48)	0.378 (0.149)	0.0267
Ash	face	15	9.75 (7.19)	0.371 (0.146)	0.0259
Maple	edge	21	8.54 (6.30)	0.338 (0.133)	0.0236
Maple	face	33	8.69 (6.41)	0.356 (0.140)	0.0250

Density

Some distinct trends and differences were noted amongst the data for each of the wood species as a function density. For both species, the Charpy failure energy increased with increasing density. For the maple sample set, the strain-to-failure increased with increasing density (Figure 6).

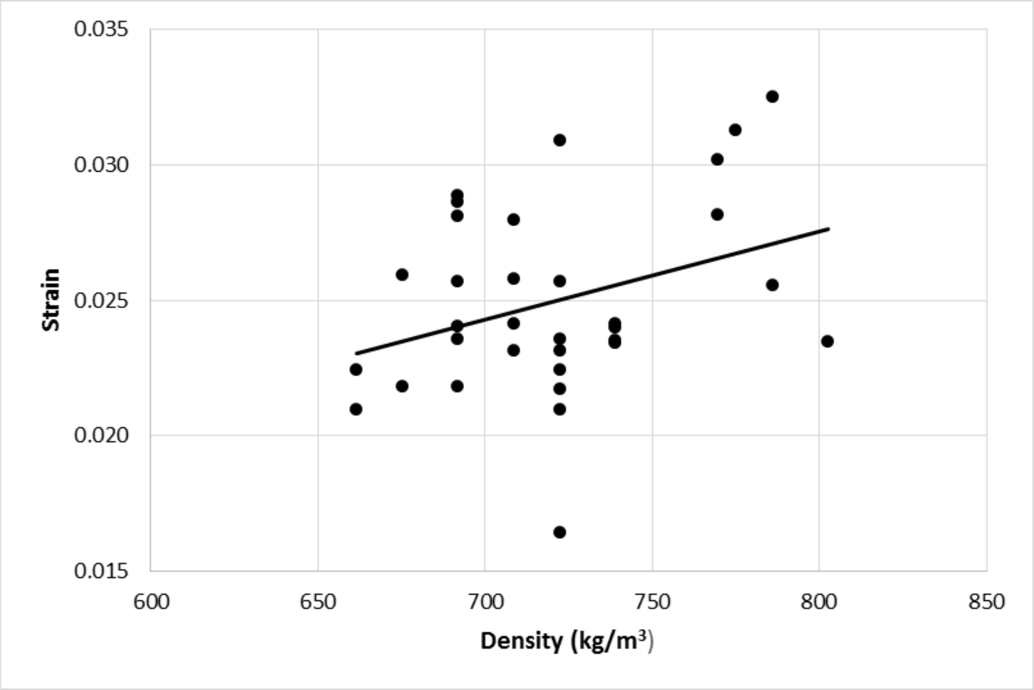


Figure 6: Strain-to-failure for maple samples impacted on the face-grain

Finite Element Modeling

Finite element models of the Charpy impact tests and of a bat/ball impact were built for processing in LS-DYNA. The material parameters as determined from the static (four-point bend tests at the FPL), the dynamic (Charpy impact tests at UMass Lowell) and the Wood Handbook [2] were used to determine the inputs to the MAT_WOOD material model. To facilitate fracture, the maximum-principal-strain-at-failure criterion in the ADD_EROSION option for material models was used in conjunction with MAT_WOOD. The material parameters were then “tuned” through an iterative process of comparing the Charpy test finite element model and test results until good correlation was achieved between the model and the experiment. These final constants were then used in a simulation of a bat/ball impact.

Material parameters

MAT_WOOD (Material Type 143) is the only exclusively wood-based material model available for use in LS-DYNA [4]. The user prescribes the material input parameters for modulii, strength, and fracture properties of the wood species under consideration. The scope of the modeling presented in this paper is limited to the modeling of maple.

The material parametrs were developed through a combination of experiemtal tests and base values in the Wood Handbook [2]. The MOE and MOR were calcualted using the results of the FPL quasi-static testing on maple and varied as a function of wood density. The remaining strength input parameters were based on the strength relationships published in Table 5-3 in the Wood Handbook. The Card 4 fracture parameters for Mode 1 parallel fracture energy were based on the values published in Table 5-10 of the Wood Handbook of 480 KPa-$m^{1/2}$ (430 lbf/in^2-$in^{1/2}$) as this is the failure mode seen during a Charpy impact test. The remaining parameters were left as default. The input parameters for 692.0 kg/m^3 (0.0250 lb/in^3) maple wood are shared in Table 2.

Table 2: MAT_WOOD inputs (SI units of Kg, m, s)

Card 1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	MID	RO	NPLOT	ITERS	IRATE	GHARD	IFAIL	IVOL
Values	A8	6.47E-05	1	0	0	0	0	1
Card 2	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	EL	ET	GLT	GTR	PR			
Values	2.28E+06	148070	252858	80642	0.476			
Card 3	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	XT	XC	YT	YC	SXY	SYZ		
Values	22513	11227	2163	2107	3341	4677		
Card 4	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	GF1||	GF2||	BFIT	DMAX||	GF1⊥	GF2⊥	DFIT	DMAX⊥
Values	430	2000	30	0.9999	430	1500	30	0.99
Card 5	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	FLPAR	FLPARC	POWPAR	FLPER	FLPERC	POWPER		
Values	0	0	0	0	0	0		
Card 6	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	NPAR	CPAR	NPER	CPER				
Values	0.5	400	0.4	100				
Card 7	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	AOPT	MACF	BETA					
Values	2	1	0					
Card 8	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	XP	YP	ZP	A1	A2	A3		
Values				0	0	1		
Card 9	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Variable	D1	D2	D3	V1	V2	V3		
Values	1	0	0					

Model Correlation

A finite element model of the Charpy Impact is shown in Figure 7. The test specimen rests on a pair of rigid support brackets. A wood density of 719.7 kg/m^3 (0.026 lb/in^3) and failure strain of 0.025 were chosen for the model as these are the average density and strain-to-failure of the maple samples tested. The resulting maximum deflection of the model before failure occurs is 0.348 cm (0.137 in.), which corresponds to the maximum deflection of sample M307B, a 719.7-kg/m^3 (0.026-lb/in^3) density maple sample that failed at a strain of 0.0241. The model can be seen in Figure 8 (right) with a high speed image of the Charpy test for comparison in Figure 8 (left). A summary of charpy impact models and corresponding sample IDs for correlation of maximum deflection is presented in Table 3.

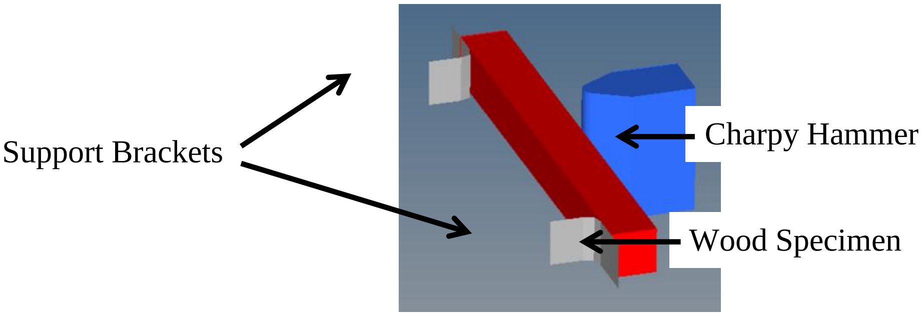


Figure 7: Charpy Impact Finite Element Model

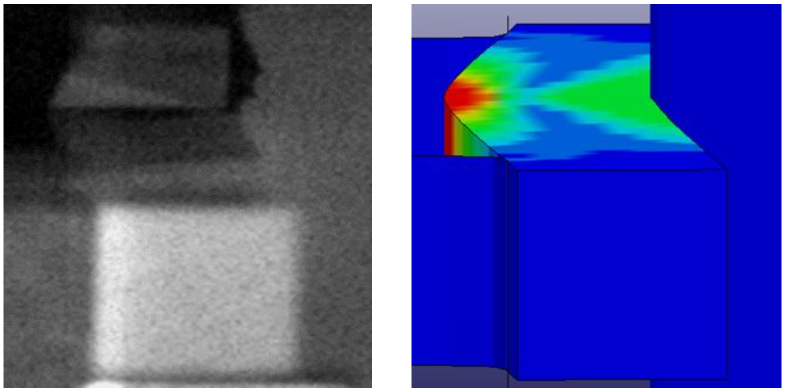


Figure 8: Charpy impact of maple from high-speed imaging (left) and Charpy Impact model (right)

Table 3: Charpy Impact Model Deflection Correlation Results

Density kg/m^3 (lb/in^3)	Sample ID	Deflection cm (in.)	
		Experimental	Model
664.3 (0.024)	M35B10	0.318 (0.125)	0.320 (0.126)
692.0 (0.025)	M36C	0.338 (0.133)	0.335 (0.132)
719.7 (0.026)	M307	0.350 (0.138)	0.348 (0.137)
747.4 (0.027)	M306	0.386 (0.152)	0.378 (0.149)

Bat Model

The principals described for modeling maple wood in the Charpy Impact model were applied to the finite element model of a bat/ball impact. A model of a baseball bat of a known professional bat profile that was tested in the ADC durability machine at the UMass Lowell Baseball Research Center (UMLBRC) was built. The bat model was 86.4 cm (34 in.) in length and prescribed a wood density of 692.0 kg/m^3 (0.0250 lb/in^3) to simulate a 0.879-kg (31-oz.) bat, matching the size and weight of the bat tested in the durability machine. An impact velocity of 63.9 m/s (143 mph) at an impact location of 35.6-cm (14-in.) as measured from the barrel tip was used to mimic test conditions. The strain-to-failure used in the model was 0.0241 and was derived from the relationship between wood density and strain-to-failure results of the Charpy impact testing. A comparision of a high-speed image taken of the bat during the ADC durability testing and the finite element model is presented in Figure 9. The model shows excelent correlation for the mode of fracture and the extent of the crack propoagation along the length of the bat.

In an effort to further demonstrate the capabilities of the bat model, the impact velocity was varied to observe the bat response as a function of impact speed. Through ramp-up durability testing at UMLBRC, it is known that bat profiles will be able to withstand impacts up to a distinct speed threshold and then fracture in either a single-piece or multi-piece fashion. Three impact velocities were chosen; 53.6 m/s (120 mph), 58.1 m/s (130 mph), and 64.8 m/s (145 mph). The wood properties and strain-to-failure were unchanged from the 86.4 cm (34 in) 0.879 kg (31 oz.) bat shown in Figure 9. The results of the modeling are shown in Figure 10. It can be seen from the model results that there is a clear threshold transition from a single- to a multi-piece failure between 58.1 (130) and 64.8 m/s (145 mph). By refining the impact velocity further, the exact failure impact speed threshold for the bat can be estimated.

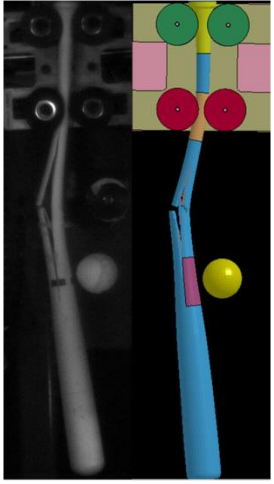
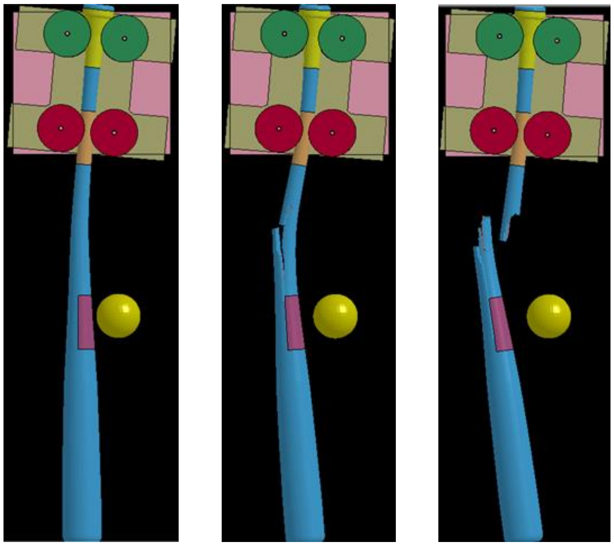


Figure 9: 86.4 cm (34 in.), .879 kg (31 oz.) professional bat profile impacted at 63.9 m/s (143 mph.) and 86.4 cm (34 in), 0.879 kg (31 oz.) bat finite element model impacted at 63.9 m/s (143 mph).



Impact Speed [m/s] (mph)	**53.6 (120)**	**58.1 (130)**	**64.8 (145)**
Failure	**No Break**	**SPF**	**MPF**

Figure 10: Bat model failure modes at varying impact velocities

Conclusions

The following conclusions may be drawn from the results of the mechanical testing performed.

- The MOE, MOR and failure energy increase with increasing wood density for maple and ash wood species.
- The strain-to-failure increases with increasing density for maple, but the strain-to-failure remains constant over the range of densities considered in this study for ash.
- On average, ash samples exhibit higher failure energy and greater strain-to-failure than maple samples of the same density.
- Ash exhibits a higher strain-to-failure in edge-grain loading in comparison to face-grain loading and maple exhibits the opposite response to impact surface.
- The material characterization program where the Charpy impact test was used to examine the high strain-rate response of maple and ash provided a set of material parameters that could be used for modeling the fracture response of wood bats during a bat/ball impact condition.

Acknowledgements

The financial support of the Office of the Commissioner of Baseball and the MLB Players Association is appreciated.

References

[1] Ruggiero, E. 2013. Investigating Baseball Bat Durability Using Experimental and Finite Element Modeling Methods. MS Thesis, University of Massachusetts Lowell.

[2] Forest Products Laboratory. 2010. Wood handbook—Wood as an engineer¬ing material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

[3] Y.D. Murray, J.D. Reid, R.K. Faller, B.W. Bielenberg, and T.J. Paulsen (2005), Evaluation of LS-DYNA Wood Material Model 143, PUBLICATION NO. FHWA-HRT-04-096.

[4] Manual for LS-DYNA Wood Material Model 143. U.S. Department of Transportation Federal Highway Administration, AUG 2007.

[5] 2009 Interdisciplinary Team. 2009. *Options for Reducing Multi-piece Bat Failures in the 2010 Season*, Presented to the MLB/MLBPA Safety and Health Advisory Committee November 6, 2009. MLB Offices in New York, New York. Final Report.

[6] ASTM D6110-10. Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA.