Supplemental Material

Study of Expanded Failure Modes for Two Impact Locations

Supplemental to Research Article: ***An Investigation of Wood Baseball Bat Durability as a Function of Bat Profile and Slope of Grain Using Finite Element Modeling and Statistical Analysis***

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This section outlines supplemental modeling results related to baseball bat durability at two impact locations that are commonly used in durability testing. Finite element analyses of the bat/ball impact were performed at the 2.0-in. (5.1-cm) and 14.0-in. (35.6-cm) locations for the MLB allowable SoG range of -3° to +3° in 1° increments. To capture a wider picture of failure, −5° and +5° SoG models were also considered in this investigation.

For testing in the ADC, the bat is initially at rest, so the impact velocity of the ball on the bat in the ADC is the combination of the on-field pitch speed and the bat swing speed as measured at the point of impact for that axial location on the bat. The ball impact speed was varied in 5-mph (8-kph) increments from 90 to 180 mph (145 to 290 kph). This range of speeds accounts for both a ball pitch speed and a linear swing speed. It is assumed that the pitch speed is 90 mph (145 kph), and the swing speed is also 90 mph (145 kph) at the 2-in. (5.1-cm) location for a bat rotating about a point in the handle region 6 in. (15.24 cm) from the base of the knob. For this study, it was assumed that most impact velocities fall within 80–100% of the maximum combined swing and pitch speeds.

During the post-processing of the ball impacts, it was observed that the bats fell into one of the three anticipated outcomes (i.e., NF, SPF or MPF), but there were instances where the description of the break needed to be expanded. In some cases, the bat would break in two locations but ultimately remain in one large piece of wood. This outcome was denoted as a single-piece multi-failure (SPMF) – as shown in Figure S1a. It was expected that the baseball bats would fail in tension following ball impact. Impacts at the 14.0-in. (35.56-cm) location (inside-pitch scenario) were expected to produce fail on the bat opposite side of ball impact – as shown in Figure S1b, while the bat was expected to fail on the impact-side of the bat when impacted at the 2.0-in. (5.08-cm) location. In the simulations, if the wood bat cracked in an unanticipated region of the bat, the outcome was categorized as a single-piece secondary failure (SPSF). The SPMF and SPSF outcomes are depicted in a close-up view, i.e. Figure S1c, of the unanticipated failure area location of the SPSF. As a result, there are five different classifications for outcomes from the finite element model simulations: NF, SPF, SPMF, SPSF, and MPF.

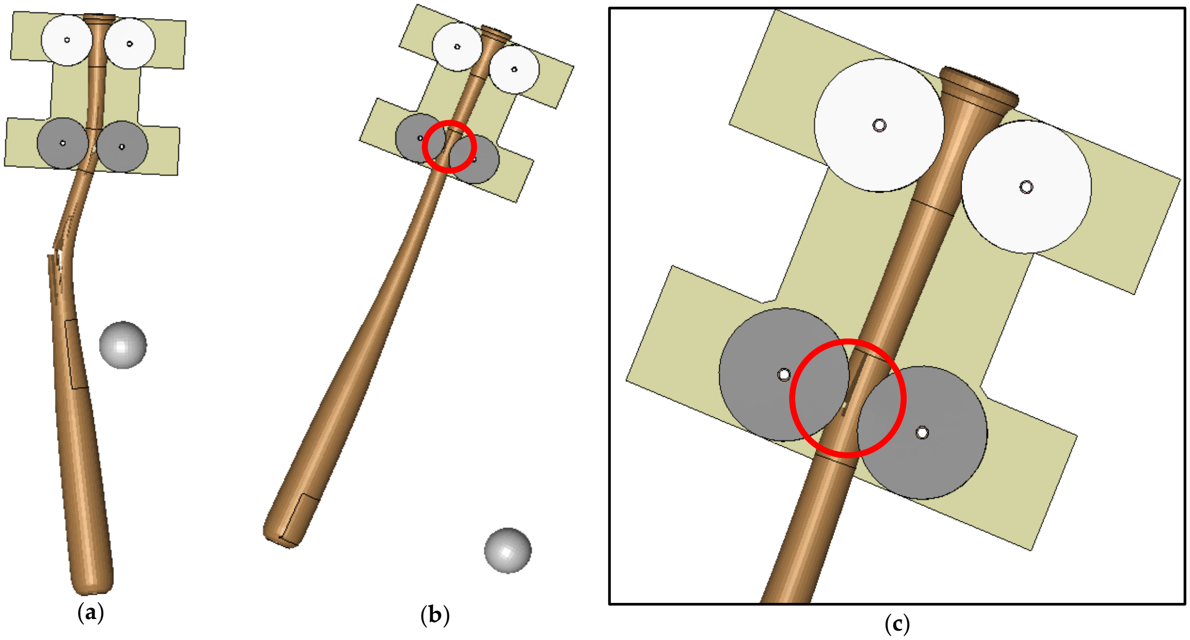

Figure S1: Finite Element Model Example of (a) SPMF, (b), SPSF, and (c) a close-up view of the SPSF outcome.

The results of the finite element models were analyzed to examine the modes of failure and to quantify the bat durability (i.e., breaking speed) with respect to each bat profile, SoG, bat/ball impact location, and ball impact velocity. The five possible outcomes are displayed in contour plots to describe the mode of failure for each combination of SoG and ball impact velocity for a given bat profile. Because the 14.0- and 2.0-in. (35.6 and 5.1-cm) impact locations have been empirically found to be two of the most vulnerable impact locations in baseball bats, they are prone to induce MPFs [23]. As a result of their vulnerability, these locations have become standard testing locations for the evaluation of baseball bat durability. Contour plots of the finite element modeling of these two critical locations are shared in Figures S2 and S3, respectively.

Within these two contour plots, the regions of color represent the finite element model outcome (i.e., NF, SPSF, SPF, SPMF and MPF) for a given combination of wood bat SoG (x-axis) and ball impact velocity (y-axis). The solid vertical line gives reference to 0° SoG, and the vertical dashed lines outline the allowable standard of ±3° SoG set by the MLB wood baseball bat standards. A velocity range of 90–180 mph (145–290 kph) with 5-mph (8-kph) increments was applied to each model. This mix of 4 profiles × 19 speeds × 9 SoGs × 2° impact locations resulted in 1368 unique combinations of simulations to capture the data shared in Figures S2 and S3.

To develop a model of the relationship among the different profiles and their respective durabilities with respect to SoG, threshold velocities between failure modes must be quantified. In this work, a threshold velocity is defined as the boundary between two different outcomes (i.e., NF, SPSF, SPF, SPMF and MPF). For example, the max NF velocity would be the highest velocity resulting in a NF, while the largest velocity resulting in a SPF outcome is defined as the MPF threshold velocity. This threshold varies with SoG, which results in the curved threshold velocity shapes shown in Figures S2 and S3.

Upon doing a visual analysis of the data shared in Figure S2, it was found that the maximum NF velocities within the SoG range of ±3° ranged from 115- to 130-mph (185- to 209-kph) while the maximum MPF threshold velocity curve ranged from 140- to 155-mph (225- to 250-kph) among the four bat profiles. The specific maximum threshold velocities and the wood SoG associated with the respective maximum values for both impact locations are summarized in Table S1. The data show that three of the four bat profiles have their best MPF durability for the 14.0-in (35.6-cm) impact location when the wood SoG is between +1° and +2°. A critical observation is Bat Profile D was found to have a maximum MPF threshold at the −1° SoG. The shapes of the contour plots also suggest that SoG effect on bat durability is profile dependent.

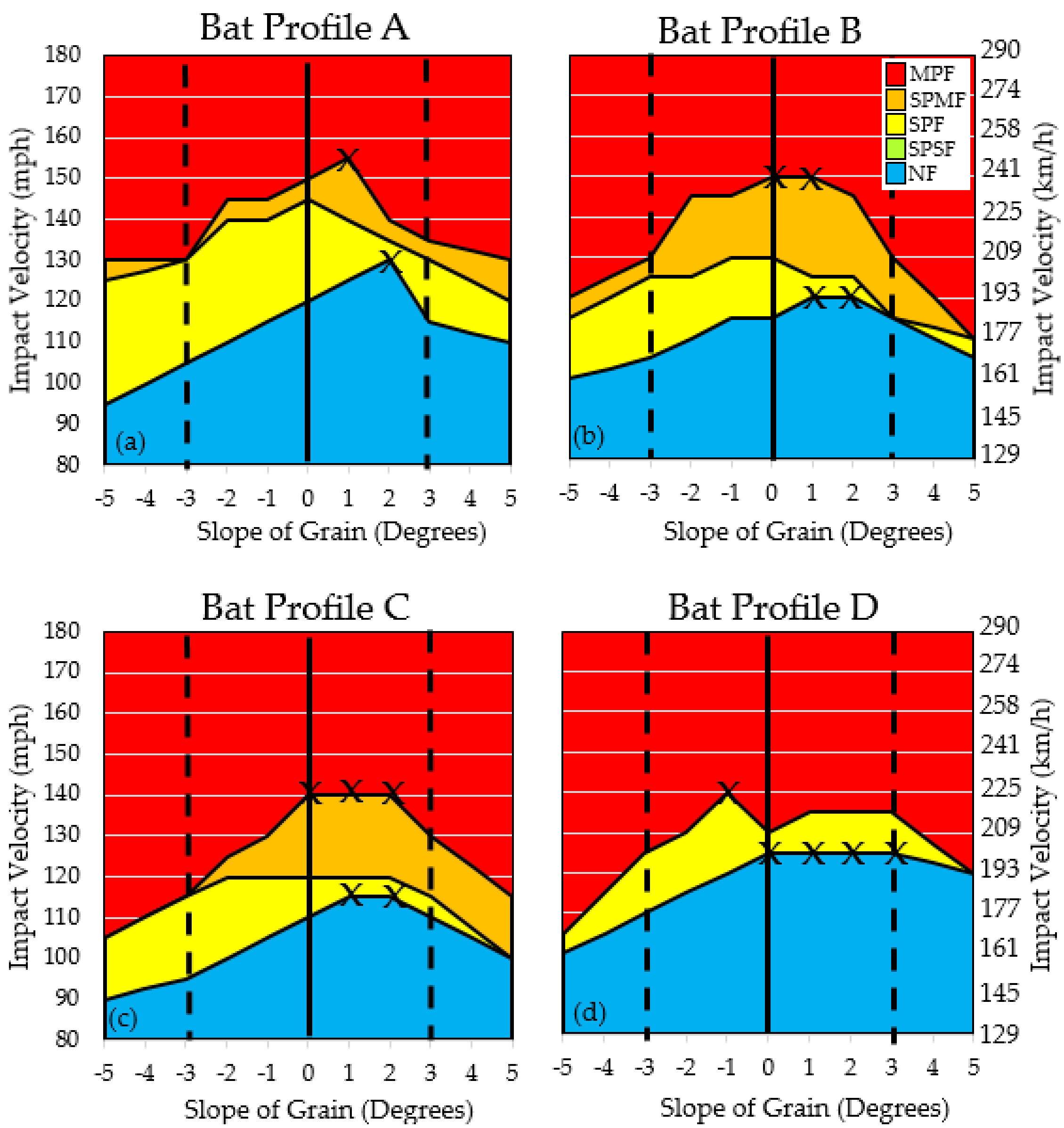

Figure S2: Contour Plots of the 14.0-in (35.6-cm) impact location model results.

Table S1: Summarized Threshold Values.

Bat Profile	14.0-in. (35.6-cm) impact				2.0-in. (5.1-cm) impact			
	Max NF Threshold		MPF Threshold		Max NF Threshold		MPF Threshold	
	Velocity mph (km/h)	SoG (deg.)	Velocity mph (km/h)	SoG (deg.)	Velocity mph (km/h)	SoG (deg.)	Velocity mph (km/h)	SoG (deg.)
A	130 (209)	2	155 (249)	1	135 (217)	−1, 0, 1	155 (249)	−3, −2, −1, 1
B	120 (193)	1, 2	150 (241)	0, 1	120 (193)	−2	175 (282)	−2
C	115 (185)	1, 2	140 (225)	0, 1, 2	105 (170)	−1, 0	135 (217)	−3, −2, −1, 0, 1
D	125 (201)	0, 1, 2, 3	140 (225)	−1	115 (185)	−3	140 (225)	1

Figure S3 shows the finite element model results of the four profiles at the 2.0-in. (5.1-cm) impact location. The maximum NF velocities at this impact location range from 105–135 mph (169 to 217 kph) while the MPF threshold ranges from 135–175 mph (217 to 282 kph). Bat Profile B was found to have the largest MPF threshold maximum value while Bat Profile C has the smallest. Specific values of the maximum threshold velocities are shared in Table S1 At this impact location, three of the four profiles were found to have maximum SPF and MPF threshold velocities less than 0° SoG. Bat Profile D shows nuanced behavior with a maximum MPF threshold velocity at +1° SoG but a maximum SPF threshold velocity at −3°.

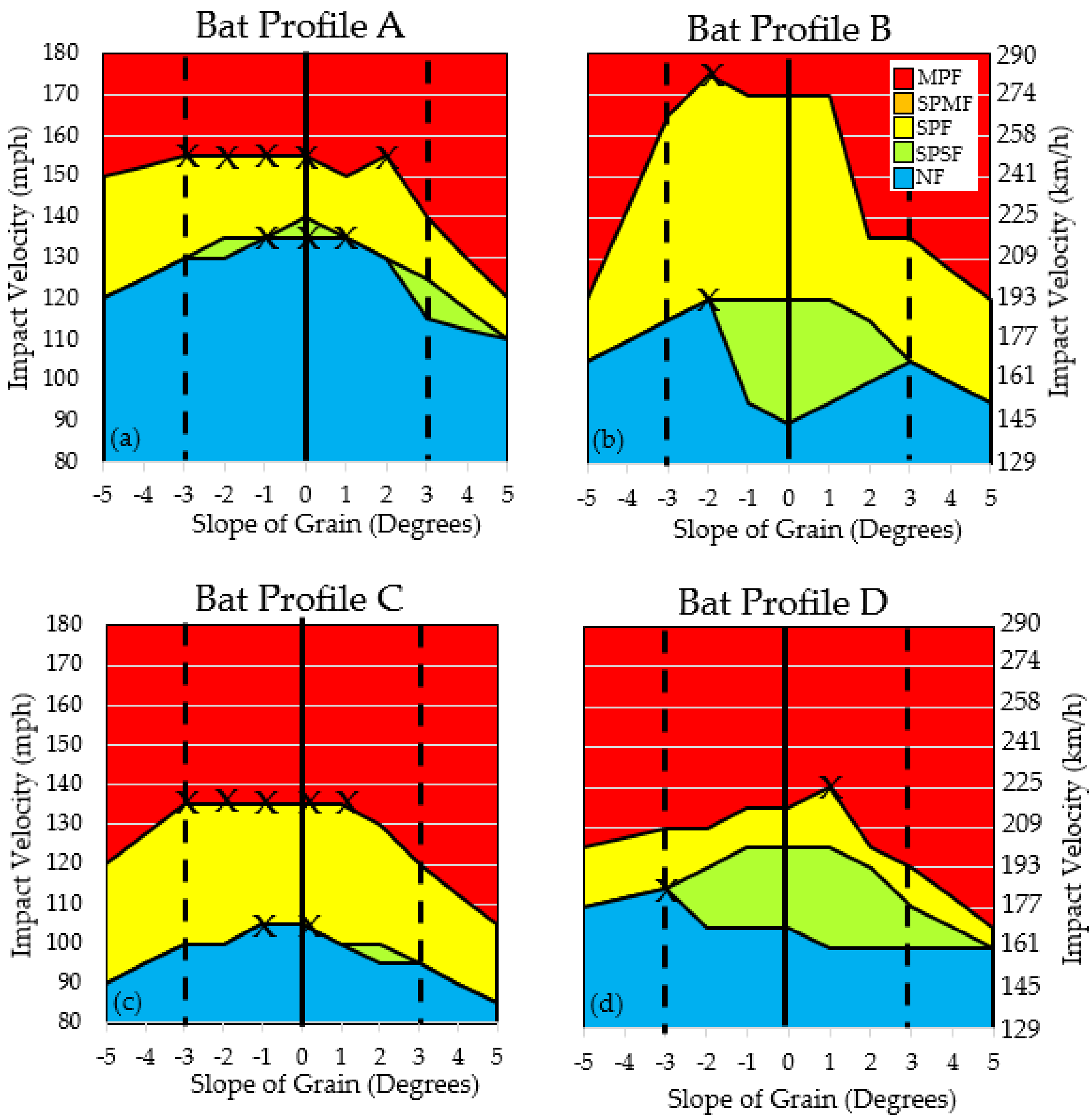

Figure S3: Contour Plots of the 2.0-in (5.1-cm) impact location model results.