Multi-scale Validation of a Butyl Rubber Neck Model for an Anthropomorphic Testing Device Designed for Underbody Blast

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Abstract

Underbody blast is a significant injury risk for the modern warfighter, and a well-validated human surrogate for underbody loading environments can assist in preventing or mitigating injury. We present a selection methodology and hierarchical validation of the neck material model for the Warrior Injury Assessment Manikin (WIAMan) LS-DYNA® model focusing on accuracy, consistency, and robustness. All simulations were run with LS-DYNA R 8.0.0

Initially, a one-parameter Blatz-Ko material model was calibrated to constrained neck experiments. However, simulations in more biofidelic conditions (constrained at base of neck only) showed substantial oscillations that were not observed in matched experimental tests. Thus, a hierarchical validation strategy was employed. Material testing was performed with targeted strain rates of 0.01/s, 10/s, and 100/s. Seven potential Bergstrom-Boyce material models were developed, each optimized for different components of experimental material data. From the seven, a single material model was chosen based upon constrained neck-only and head-neck experimental results. These material models were evaluated using a combined metric composed of the following; Correlational Analysis (CORA), normalized peak magnitude difference and normalized time-to-peak difference. This was done to reduce shortcomings of any one objective evaluation approach. The combined single metric was then used to evaluate model performance. The best performing material model was chosen and validated in a flexed head-neck configuration which had not been tested previously. Each of the experimental conditions were tested at three different speeds.

A total of 44 simulations were run throughout all scales. The Bergstrom-Boyce material model that was fit to one compression-tension cycle was found to perform the best. It had an overall combined metric score of 13.75 out of a maximum of 18 which was 10.1% better than the original Blatz-Ko material model. In the constrained neck-only configuration, the new material was 2.1% better than the original material model, and 21.2% better in the head-neck setup. In the previously untested (head-neck, flexed) validation conditions, the overall score was 6.52 out of a maximum of 9. CORA scores ranged between of 0.612 and 0.811 depending on input pulse for all cases. CORA scores were generally higher (better match to experimental data) at higher rates.

The outlined approach, in which we validated at multiple scales demonstrates accuracy, consistency and robustness for the configurations tested. The result is based on a quantitative methodology that led to an improvement in the material response of the butyl rubber neck model of the LS-DYNA model of the WIAMan ATD.

Introduction

Underbody blast is a significant injury risk for the modern warfighter2, and a well-validated human surrogate for underbody loading environments can assist in preventing or mitigating injury.

The Warrior Injury Assessment Manikin (WIAMan) is an Anthropomorphic Testing Device (ATD) designed to be biofidelic in underbody blast. A validated numerical model of the ATD is beneficial because it enables potentially more rapid design iteration than physical prototypes and allows for investigation of scenarios that may be unsuited or impossible for use of a physical dummy; such as potential overmatch environments or pre-test predictions of environments that only exist in-silico.

Methods to validate models vary, but they usually compare responses of key channels between a physical experiment and a simulated, equivalent, experiment. Validation measures vary, each with strengths and weaknesses. Some key validation measures for dynamic tests are Correlational Analysis (CORA)1, and peak load characteristics.

We present a selection methodology and hierarchical validation of the neck material model for the Warrior Injury Assessment Manikin (WIAMan) LS-DYNA model focusing on accuracy, consistency, and robustness.

Methods

Initially, a one-parameter Blatz-Ko material model was calibrated to constrained neck experiments. However, simulations in more biofidelic conditions (constrained at base of neck only) showed substantial oscillations that were not observed in matched experimental tests (Figure 1). This is evidence that the Blatz-Ko model was over-fit for one particular condition and did not extrapolate well to new conditions.

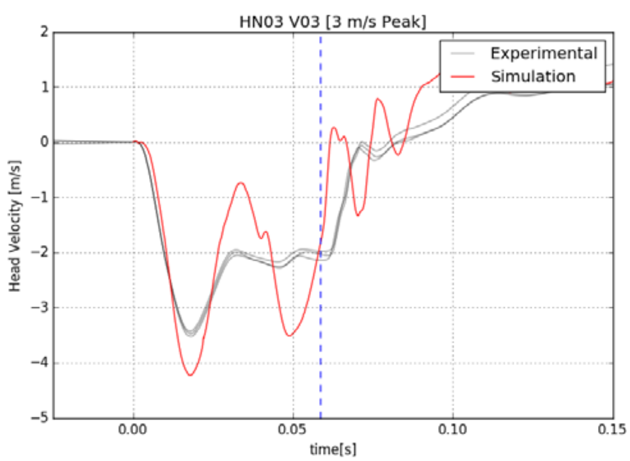

Figure 1: Initial model fit showed substantial oscillations not observed experimentally. Shown here is the vertical channel from the head accelerometer (integrated to velocity for visualization). A Blatz-Ko material model was used in this simulation.

In order to reduce over-fitting of material model, a hierarchical validation strategy was employed. This consisted of first choosing viable material models matched to coupon-level experimental stress-strain curves. Next, we then “tuned” our model by selecting the best performing material model for a neck only and head-neck setup. Lastly, we evaluated our material model against an experimental setup that was not considered during the “tuning” process.

Material testing was performed with targeted strain rates of 0.01/s, 10/s, and 100/s. Seven potential Bergstrom-Boyce material models were developed, each optimized for different components of experimental material data. MCalibrate (Veryst Engineering, MA, USA) was used to optimize the material fits. The software minimizes the normalized mean absolute deviation between the experimental stress strain response and the stress-strain response from a one-element LS-DYNA simulation.

From the seven, a single material model was chosen based upon constrained neck-only and head-neck experimental results. These material models were evaluated using a combined metric composed of the following; Correlational Analysis (CORA)[1], normalized peak magnitude difference (P) and normalized time-to-peak difference (TTP). Each of these measures are normalized from zero (worst) to one (best).

$$TTP = 1 - \frac{Peak_{sim} - Peak_{ex}}{Peak_{ex}}$$

$$P = 1 - \frac{TTP_{sim} - TTP_{ex}}{TTP_{ex}}$$

$$Total\ Score = Peak\ Magnitude + TTP\ Score + CORA$$

Peak characteristics were calculated using the first peak encountered in a channel. CORA was performed over a 150ms time interval and the corridor scores were not used. Channel-specific weights were decided *a priori* and were used to emphasize channels that would be of interest when assessing injury to risk to the warfighter.

This multi-pronged scoring system was done to reduce shortcomings of any one objective evaluation approach. The combined single metric was then used to evaluate model performance. The best performing material model was chosen and validated in a flexed head-neck configuration which had not been tested previously. Each of the experimental conditions were tested at three different speeds.

Each experiment had three conditions of increasing pulse speed (V1, V2, and V3). Neck experiments were performed by Duke University and head-neck experiments were performed by the U.S. Army Tank Automotive Research Development and Engineering Center (TARDEC).

Overall, across the three experimental setups and seven different material models, there were 44 simulations total. All simulations were run with LS-DYNA R 8.0.0.

Results

The Bergstrom-Boyce material model that was fit to one compression-tension cycle was found to perform the best (COL Bergstrom Boyce). It had an overall combined metric score of 13.75 out of a maximum of 18 which was 10.1% better than the original Blatz-Ko material model. In the constrained neck-only configuration, the new material was 2.1% better than the original material model, and 21.2% better in the head-neck setup.

In the neck validation experiment, the CORA scores for the model with the Combined One-Loop Bergstrom Boyce material model ranged from 0.699 to 0.755. Peak differences ranged from -2.6% to 32.8%; the simulations often under-predicted peak response. Time-to-peak differences ranged from -11.8% to 24.8%. A summary of the results can be seen in Table 1.

Table 1: Summary score results for the COL Bergstrom Boyce material model and the Blatz-Ko material model in the neck only setup.

Neck Only	CORA			Peak Magnitude			TTP			
	V1	V2	V3	V1	V2	V3	V1	V2	V3	Total
COL Bergstrom Boyce	0.699	0.725	0.755	0.868	0.845	0.854	0.924	0.912	0.872	7.454
Blatz-Ko	0.700	0.683	0.707	0.825	0.832	0.774	0.955	0.934	0.893	7.303

In the head-neck validation experiment, the overall CORA scores were 0.55, 0.61, and 0.72 for V1, V2, and V3 respectively. Peak differences ranged from -142% to 65%. Time-to-peak differences ranged from -200% to 18%. Kinematics showed the most variation in agreement, with head velocity consistently matched well with experiment and rotations showing poor agreement.

Table 2: Summary score results for the COL Bergstrom Boyce material model and the Blatz-Ko material model in the head neck setup.

Head and Neck	CORA			Peak Magnitude			TTP			
	V1	V2	V3	V1	V2	V3	V1	V2	V3	Total
COL Bergstrom Boyce	0.549	0.61	0.719	0.765	0.598	0.765	0.588	0.829	0.871	6.294
Blatz-Ko	0.335	0.469	0.612	0.602	0.352	0.602	0.595	0.729	0.900	5.196

In the previously untested (head-neck, flexed) validation conditions, the overall score was 6.49 out of a maximum of 9. Summarized results can be seen in Table 3.

Table 3: Summary score results for the COL Bergstrom Boyce material model in the flexed head neck setup.

Flexed Head and Neck	CORA			Peak Magnitude			TTP			
	V1	V2	V3	V1	V2	V3	V1	V2	V3	Total
COL Bergstrom Boyce	0.612	0.705	0.811	0.757	0.812	0.526	0.471	0.901	0.895	6.49

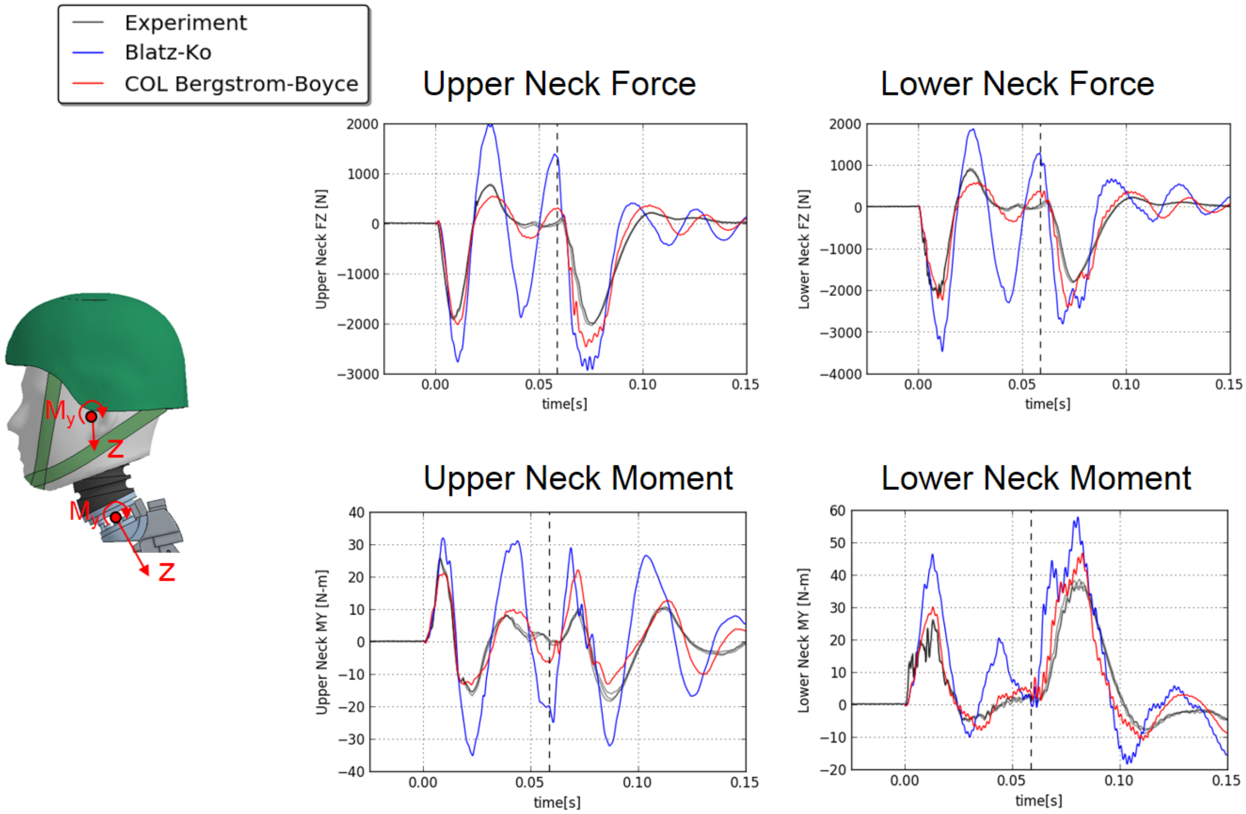

Figure 2: Improvement of material model with new COL Bergstrom-Boyce (red) and original Blatz-Ko (blue)

Discussion

CORA scores were generally higher at higher rates. This meant that the simulations matched the experiments more closely at higher rates. In highly constrained setups, the new material model showed more robustness than the previous Blatz-Ko material model. However, the performance of the new material model was only marginally improved.

In general, the neck was still underdamped at low speeds, and showed better agreement with experimental results at higher speeds. The underdamped response observed at lower speeds may be because other materials in the physical ATD can have additional damping properties that were not accounted for in the simulation model. Furthermore, the underdamped response observed at low speeds was an improvement over the existing Blatz-Ko material model –which had shown even more oscillations.

We were able to show the validity of the model with a previously untested, flexed head-neck setup. Because we did not choose our material model based on this setup, the consistency between the results from the flexed setup and the nominal position setup indicates that our model is well validated in the head-neck conditions.
The outlined approach, in which we validated at multiple scales demonstrates accuracy, consistency and robustness for the configurations tested. The result is based on a quantitative methodology that led to a substantial improvement in the material response of the butyl rubber neck model of the LS-DYNA model of the WIAMan ATD.

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