Hybrid III 95th Percentile Large Male Finite Element Model Neck Alteration

Eric Day[1], Christoph Maurath Sommer[1], Jacob Putnam[2],
Chuck Lawrence[2], Preston Greenhalgh[2]
(1) Livermore Software Technology, (2) NASA

Abstract

The motivation behind the project was to update the Livermore Software Technology Corporation Hybrid III 95th percentile finite element model, such that the neck assembly response under varying simulated loading conditions equals that of the federally regulated Hybrid III 95th percentile anthropomorphic testing device (ATD). The former neck model was poorly correlated to that of the physical Hybrid III neck in corresponding tests. Adjustments were made to mass and geometry, element formulation, and element discretization to improve model durability and accuracy. Test data from a physical compression test and NASA-performed Neck Sled Tests were collated with data from simulation to adjust material properties. The neck rubber material was further calibrated according to Code of Federal Regulations (CFR) neck calibration test response requirements. The resulting neck model developed in LS-DYNA® exhibited improved dynamic characteristics and reliability under both low and high severity loading. Computational efficiency was enhanced along with model stability under excessive loading. The revised neck model will be adopted by NASA for use in predicting potential occupant injury during spacecraft landing.

Introduction

Although originally developed for automotive crash simulation, the LSTC Hybrid III models have now also been employed in predicting potential occupant injury during simulated spacecraft landing. Specifically, NASA is investigating the passenger protection capabilities of three new spacecrafts: Boeing CST-100 Starliner, SpaceX Dragon, and NASA/Lockheed Martin Orion [1]. Unlike the high severity accelerations faced during Federal Motor Vehicle Safety Standards (FMVSS) vehicle compliance testing, NASA is using the LSTC dummies in lower energy impact landing simulation.

Validity of the Hybrid III head and neck assemblies is assessed by NASA through physical and simulated sled tests. It was found that the LSTC Hybrid III 95th percentile model performance in simulation was not equivalent to the physical ATD in testing. Dissimilarity in response was due to the incorrect neck geometry of the 95th percentile model [1]. NASA performed an in-house fix of the neck model, altering geometry, mass, and material properties. On reevaluation, the updated model exhibited a more correlative response to the sled test data; however, the performance of the model was only characterized in low level loading conditions.

In this project, the NASA Updated model was evaluated in LS-DYNA under high severity loading. Adjustments to neck geometry, mesh, and material properties were consequently set to improve performance throughout the range of loading.

Preliminary Evaluation of NASA Updated Model

The NASA Updated 95th percentile neck model was evaluated under high severity loading using simulated CFR Hybrid III calibrations tests. The Neck Extension and Neck Flexion Tests are federally regulated certification tests required for dummy use in FMVSS compliance testing. The neck calibration test setup includes fixing the

Hybrid III head and lower neck assembly to the end of a pendulum. The pendulum is dropped from a specified height and strikes an aluminum honeycomb stop. Calibration of the Hybrid III 95th percentile is determined by conformance to SAE specified response characteristics, including Plane-D rotation, maximum moment about the occipital condyle, and negative moment decay. The Neck Extension Test setup specifications are available in Figure 1.

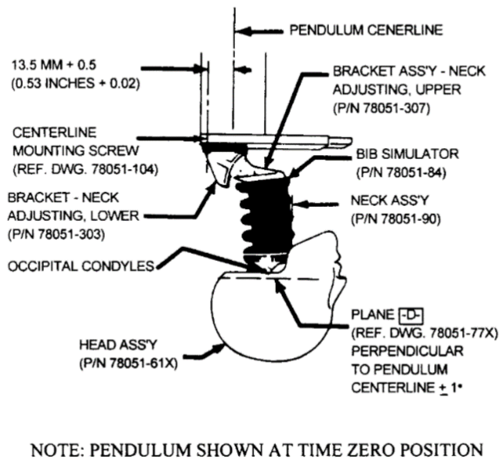


Figure 1. Neck Extension Test Setup Specifications. Adapted from 'PART 572—ANTHROPOMORPHIC TEST DEVICES' by United States, Code of Federal Regulations. Title 49, Subtitle B, Chapter V, 2019, Government Publishing Office.

The NASA Updated neck model was added to the Neck Extension and Flexion Simulation files, transformed, and constrained to the end of the pendulum. Pendulum velocity conformed to SAE regulations. A pendulum initial velocity was prescribed. The honeycomb barrier longitudinal stress curve was scaled to adjust for pendulum velocity at 10, 20, and 30ms after impact. Post processing was completed using LS-PrePost®. Table 1 compiles the NASA Updated neck response in the neck calibration simulations.

Table 1. Neck calibration simulation NASA Updated and revised model simulated results

Response Criterion	SAE Corridors		Performance
Extension Simulation:	Lower	Upper	NASA Updated Model
Plane-D Rotation [deg]	81	98	79.15
Moment During Rotation Interval [N-m]	66	84	70.51
Moment Decay to 10 N-m [ms]	100	120	107.57
Flexion Simulation:			
Plane-D Rotation [deg]	61	75	55.11
Moment During Rotation Interval [N-m]	110	130	103 N-m
Moment Decay to 10 N-m [ms]	77	97	75.62 ms

The NASA Updated LSTC 95th percentile model does not meet SAE specified standards for calibration. Although the NASA Updated model performs well under low severity simulation, adjustments had to be made to increase performance under high severity loading.

Model Re-Meshing

Before the neck model was calibrated, adjustments to the mesh were completed to improve model geometry, mass allocation, and response. Modifications to geometry were made in reference to the federally regulated Hybrid III 95th percentile drawing package. Meshing was completed by Mike Burger using TrueGrid mesh generator. The former mesh and new mesh are available in Figure 2.

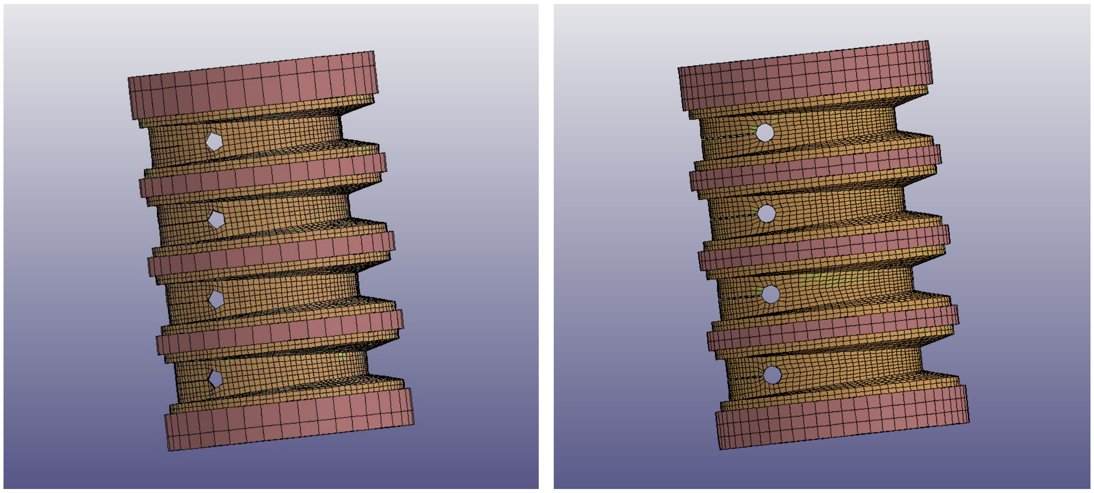


Figure 2. Former and new neck assembly mesh

A number of adjustments to the neck model were made. The neck cable through-hole diameter was enlarged from 0.31” to 0.62”. A neck bushing was added to the upper neck mount plate. The number of nodes and elements were reduced by 14.1% and 12.9% respectively. The shell elements incasing the neck rubber and neck disks were deleted. And the smallest interior angle of the elements surrounding the neck rubber hole was increased from 35° to 50°. The increased interior angle of the neck rubber hole eliminated negative volume errors which plagued the former mesh under implicit compression. The neck rubber holes of the former and new mesh are available in Figure 3.

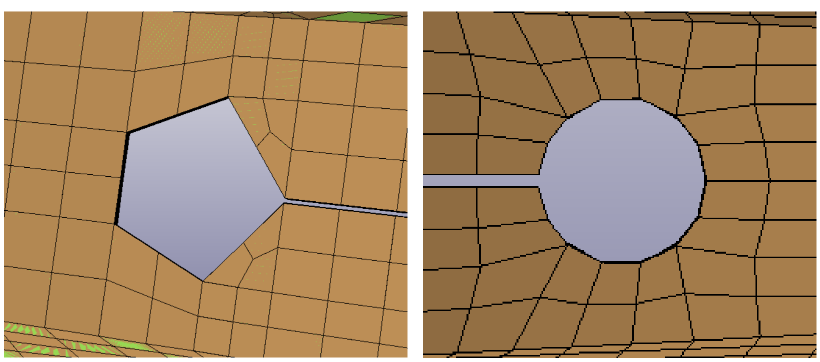


Figure 3. Former and new mesh neck rubber hole

The new mesh required further adjustments to the model. The enlargement of the neck cable hole removed mass from the model. The neck rubber density was subsequently increased to 1.175E-6kg/mm^3 in conformance to the 95th percentile drawing package neck assembly mass. The decrease in element size triggered mass-scaling in the aluminum neck pucks. 0.7kg of mass was added during explicit simulation. To resolve the issue, the neck pucks were changed from deformable to rigid. This was a viable solution because the neck pucks do not normally deform in crash testing. The substitution to MAT_RIGID removed all mass scaling in the neck because rigid bodies are bypassed during element processing [3]. Moreover, each neck puck was given its own part ID to

allow disjoint groups of rigid elements to move independently. Part, material, and section ID's were renumbered.
All node sets, contacts, and constraints were regenerated. Neck assembly constraints were made using *CONSTRAINED_RIGID_BODIES and *CONSTRAINED_EXTRA_NODES. Contacts were established using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE and *CONTACT_AUTOMATIC_SINGLE_SURFACE.

Running the new neck model in the CFR neck calibration simulations prompted errors in termination. The errors led to the substitution of the neck rubber element formulation from fully integrated to the more robust constant stress. The resulting model was able to normally terminate; however heavy hourglass modes were present, producing model instability. Hourglass control type 7 with an hourglass constant of 1.0 was introduced to reduce the hourglass energy to under 3% of the internal energy. Hourglass type 7 was selected because it is a stiffness form that works well with viscoelastic materials [3].

The resulting computational efficiency of the new model was much greater than the former model. The reduction in total CPU timing is due to the decrease in overall number of elements, the rigid neck pucks, and the substitution to constant stress elements in the neck rubber. Table 2 compiles the CPU timing of each model.

Table 2. Neck Extension Simulation CPU timing information run on 24 processers

Model	Total CPU Time
NASA Updated	1 hour, 12 min, 59 sec
New Model	20 min, 19 sec

Model Discretization Evaluation

The new neck mesh was evaluated in a mesh convergence study to understand its influence on results. The neck rubber elements of the new model were merged by a factor of eight to produce a supplemental courser model. The elements of the new model were split by a factor of eight and 64 to produce two finer models. Elements were split or merged by a factor of eight to maintain element aspect ratios. The models were subjected to the Neck Extension Simulation to select the ideal neck rubber element size based on computational efficiency and deflection-based convergence. The convergence produced during the study is visible in Figures 4 and 5. The minimum timestep was removed to observe the computation time of each model, shown in Table 3.

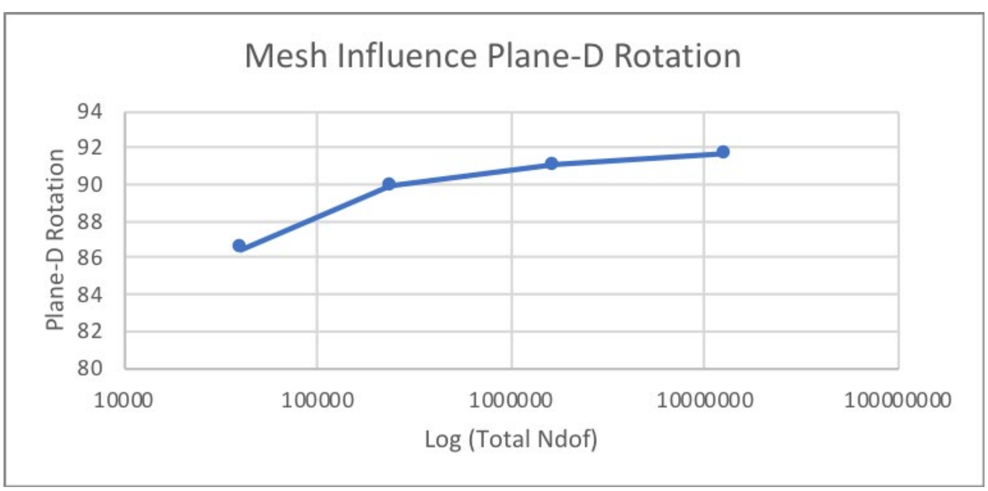


Figure 4. Maximum Plane-D rotation for models v099, v100, v101, and v102

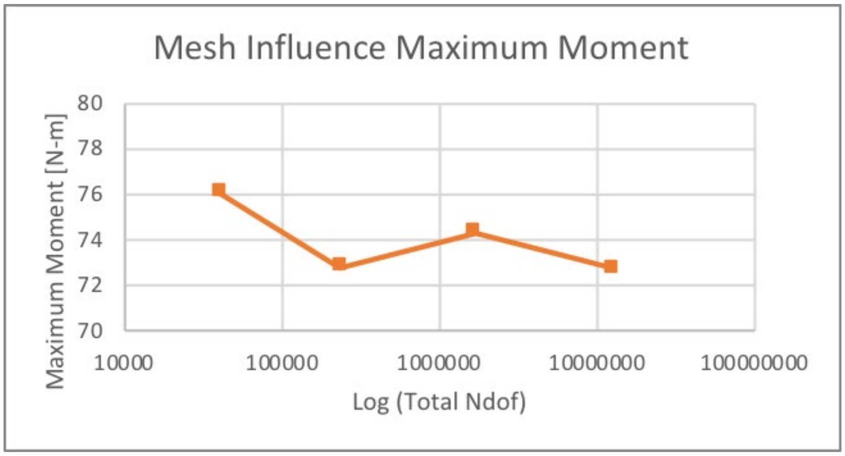


Figure 5. Maximum moment for models v099, v100, v101, and v102

Table 3. Mesh influence CPU timing information

Model	Element Count Normalized over v100	Factor of Elements per Dimension	50200001 Smallest Time step [ms]	Total CPU Time
v099	0.125	1	5.0738E-03	13 mins 12 sec
v100	1	2	1.7175E-03	20 mins 19 sec
v101	8	4	4.9164E-04	1 hr 26 min 38 sec
v102	64	8	1.6713E-04	35 hr 1 min 21 sec

Mesh v100 was selected as the model with ideal element size because it displayed good convergence, while remaining computationally efficient. The maximum Plane-D rotation differed from v100 to v102 by 1.9%. The maximum moment differed from v100 to v102 by 0.1%. The neck rubber smallest timestep shows that if the 5.0E-4ms minimum timestep was reimplemented, v103 and v104 would experience mass-scaling.

An additional evaluation was completed on the NASA Updated model and the v100 model to assess model element formulation. The neck models were subjected to extreme loads to view their individual points of failure. Each model was run in the Neck Extension Simulation with increased pendulum velocity, and the Rod Impact Simulation, which simulates neck impact with a steel rod. The new neck model in the Rod Impact Simulation is pictured in Figure 6. The results from both extreme condition simulations are compiled in Tables 4 and 5.

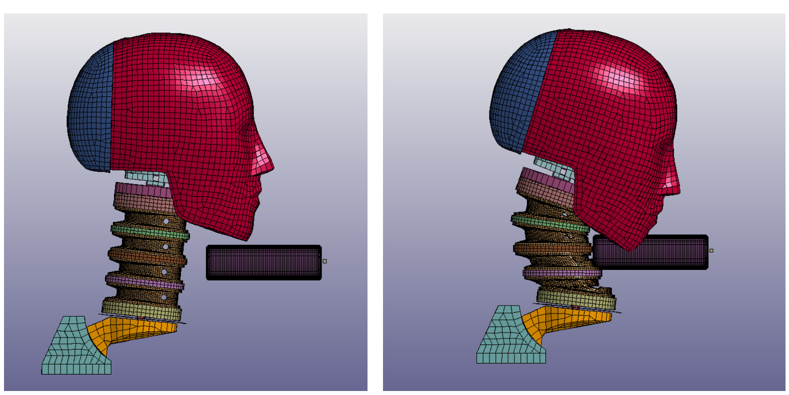


Figure 6. Rod Impact Simulation initial state and state at maximum rod deflection

Table 4. Neck Extension Simulation extreme condition testing results

Model	Velocity Multiplier	Head Maximum Acceleration [G's]	Termination
NASA Updated	1x	38	Normal
	1.2x	51	Normal
	1.5x	N/A	Error
New Model	1x	50	Normal
	1.2x	82	Normal
	1.5x	360	Normal

Table 5. Rod Impact Simulation maximum acceptable rod velocity without model failure

Model	Rod velocity at neck failure [m/s]	Rod to rubber maximum resultant force [kN]
NASA modified	12	1.26
New Model	24	4.58

Through extreme conditions testing, it was found that the fully integrated elements caused the NASA Updated model to become artificially stiff in bending. Likewise, the fully integrated elements were unable to sustain as much deformation as the constant stress elements. The newly developed neck model was shown to be more robust, as well as possessed more realistic element behavior under extreme loads.

Compression Test and Simulation

A non-destructive compression test was performed on the physical Hybrid III 50th and 95th percentile neck assemblies to measure the neck rubber resistance to compression. The force-deflection curves obtained during testing were used as a template in modeling neck response in simulated compression. The neck rubber of each percentile neck is comprised of rubber butyl 70-80 shore A durometer [4]. The neck rubber is modeled using MAT_006, Viscoelastic. The material is defined by variables: mass density, elastic bulk modulus, short-time shear modulus, long-time shear modulus, and decay constant [5].

Compression of each neck assembly was completed at a head rate of 12mm/min using a Lloyd Instruments LD50 tester. Testing conformed to ASTM standards for compression of rubber. Regulation and monitoring of the experiment were completed using NexyGen Plus software. Figure 7 displays the 50th and 95th percentile neck load curves.

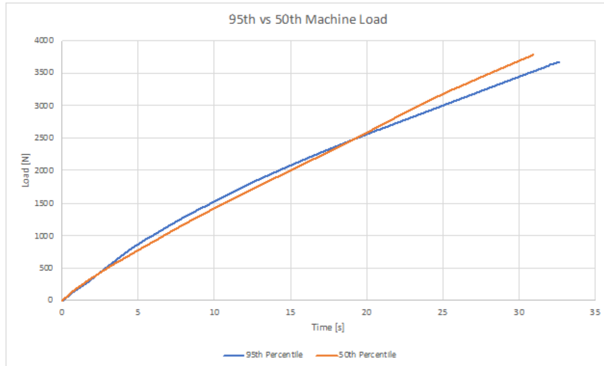


Figure 7. Compression Test 95th and 50th load curves without initial low-level loading

The compression simulations were made to replicate the compression test experiment. Neck rubber material properties were adjusted to match the simulated neck reaction force to the physical load data from experiment. An explicit and implicit compression simulation were created. Results varied based on the solver selected. The viscoelastic neck rubber material exhibits time dependent stiffness. The implicit simulation was determined as the more accurate simulation because the load rate was equal to the experiment, while time step restrictions of the explicit solver made replicating the quasi-static head rate not viable.

Material properties were adjusted to best match the implicit simulation response to the experimental load data. The magnitude of load could not be replicated. Instead, the slope, or rate of reaction force under load, was matched as seen in Figure 8.

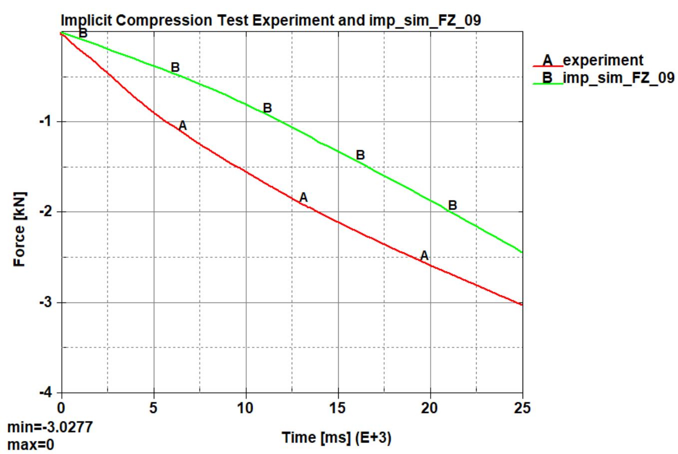


Figure 8. Implicit Compression Simulation: experiment and working model

The long-time shear modulus had the largest influence on performance in the compression simulation due to its quasi-static nature. The long-time shear modulus found in this study is equal to $0.00205 kN/mm^2$. This value represents the remaining stiffness of the material after decay. The value was kept constant throughout the remaining portion of the project.

The other three material properties: short-time shear modulus, bulk modulus, and decay constant were adjusted according to model performance in the CFR calibration simulations. The material properties were modified until the neck conformed to SAE established regulations for Plane-D rotation, maximum moment, and moment decay. Further tweaking of material properties were made to improve model performance in the low-severity Neck Sled Simulations. The aim was to maintain CFR calibration of the neck, while also achieving good performance in the Neck Sled Simulations. The resulting model would perform well throughout the range of loading.

NASA Neck Sled Test and Simulation

The working model was evaluated in the NASA Neck Sled Simulations along with intermittent evaluations in the CFR Neck Extension and Flexion Simulations to ensure model calibration. The NASA Neck Sled Tests consist of mounting the 95th percentile head and lower neck assembly on a sled that is then accelerated from zero velocity. The sensors in the Hybrid III ATD measure the head and neck reaction to the sled acceleration. Head and neck acceleration, rotational velocities, forces, and moments are pertinent during analysis. The test data for each sled test case was provided by NASA for use in this project. The NASA Neck Sled Simulation file, which modeled each sled case, was provided by NASA.

Four sled test cases were selected to evaluate the performance of the working 95th percentile neck model: Lateral 12G, Frontal 6G, Frontal 16G, and Rearward 6G. The four cases were selected because each of their individual orientations, loads, and original measured performances were well diversified. Performance of the neck model was gauged by sameness of simulation injury criterion data to its corresponding physical test data. ISO18571 ratings retrieved from CORAplus correlation and analysis software were used to quantify the sameness of data.

The NASA Updated neck model was first evaluated in the Neck Sled Simulations to collect model baseline performance. A dynamic relaxation phase was initiated by setting *sidr* to 2 in *DEFINE_CURVE to remove unwanted vibrational noise caused by the prescribed neck cable prestress. The dynamic relaxation phase replaced a 250ms simulation wait time, which occurred before the sled pulse. The NASA Updated model ISO18571 ratings for each of the four sled cases is available in Table 6.

Table 6. NASA Neck Sled Simulation 300ms ISO18571 scores: NASA Updated

Case	Head Ax	Head Ay	Head Az	Head Rx	Head Ry	Uneck Fx	Uneck Fy	Uneck Fz	Uneck Mx	Uneck My	Nij
Lateral 12 G		0.885	0.683	0.838			0.829	0.647	0.835		0.786
Frontal 6G	0.835		0.361		0.835	0.808		0.352		0.861	0.675
Frontal 16G	0.794		0.408		0.772	0.730		0.406		0.796	0.651
Rearward 6G	0.730		0.582		0.621	0.690		0.639		0.575	0.639
Average											0.688

The NASA Updated model receive a combined ISO rating of 0.688. By contrast, the working model constructed thus far received an ISO rating of just 0.663.

Finalized Neck Model

Material properties were altered until material model performance could no longer be improved. The resulting material model was named Usimcurve19, for updated simulation curve version 19. Usimcurve19 was CFR calibrated and possessed improved ISO ratings in the Neck Sled Simulations. Usimcurve19 neck rubber material properties are presented in Table 7. The ISO scores of Usimcurve19 are available in Table 8.

Table 7. Usimcurve19 MAT006 - Viscoelastic material properties

Version	Ro	Bulk	G0	GI	Beta
Usimcurve19	1.175E-6	0.0500	0.0055	0.00205	0.043

Table 8. NASA Neck Sled Simulation 300ms ISO18571 scores: Usimcurve19

Case	Head Ax	Head Ay	Head Az	Head Rx	Head Ry	Uneck Fx	Uneck Fy	Uneck Fz	Uneck Mx	Uneck My	Nij
Lateral 12 G		0.913	0.737	0.827			0.878	0.686	0.865		0.818
Frontal 6G	0.846		0.388		0.698	0.842		0.420		0.839	0.672
Frontal 16G	0.863		0.513		0.896	0.893		0.565		0.862	0.765
Rearward 6G	0.730		0.668		0.497	0.676		0.641		0.569	0.613
Average											0.717

The combined ISO18571 rating of 0.717 was the highest of all models tested. Lateral 12G and Frontal 16G correlation was greatly improved from the former model. Usimcurve19 response in the Frontal 6G sled case was equal to that of the NASA model, while response in Rearward 6G was lesser than that of the NASA model. The combined ISO rating of Usimcurve19 was 4.2% improved over the NASA Updated model. The CORAplus generated graphs for each of the Usimcurve19 injury criterion responses are available in Table 9. The red line dictates the simulation data, while the black line dictates the physical test data. All other lines are generated by CORAplus and are used in the calculation of the corridor and cross-correlation rating.

Table 9. NASA Neck Sled Simulation CORAplus generated graphs: Usimcurve19

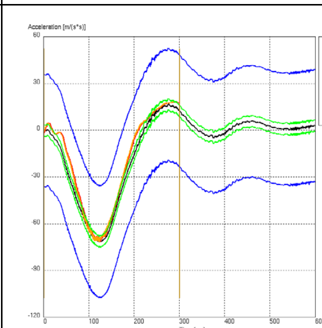
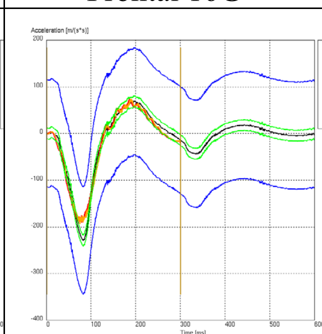
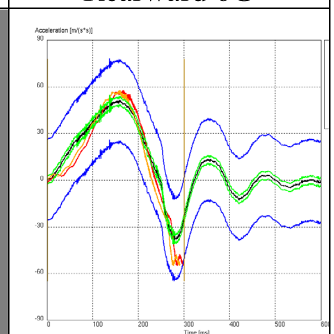
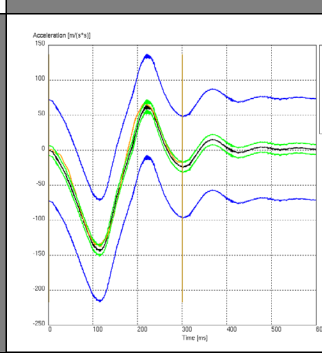
	Frontal 6G	Frontal 16G	Lateral 12G	Rearward 6G
Head Ax				
Head Ay				

Table 9. NASA Neck Sled Simulation CORAplus generated graphs: Usimcurve19, Continued

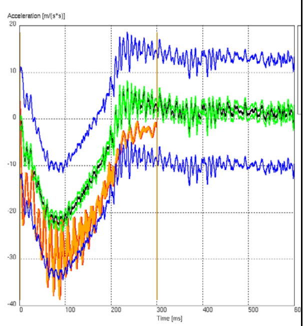
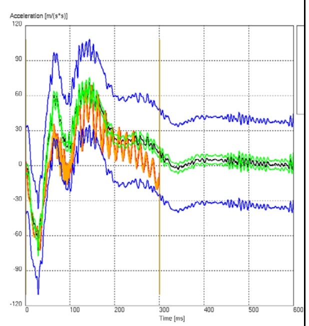
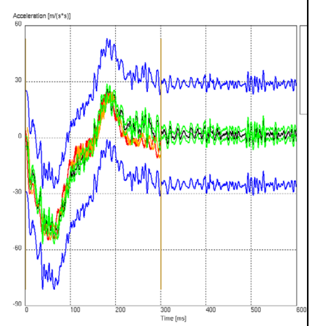
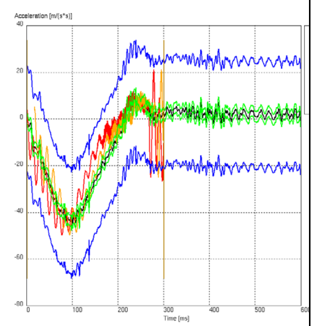
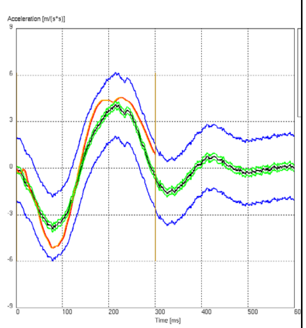
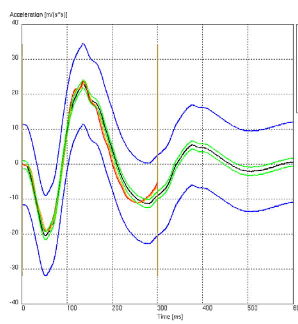
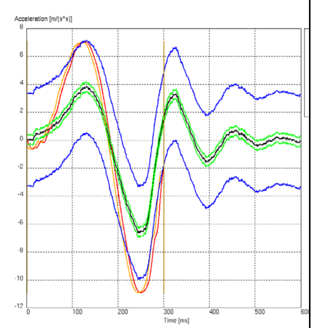
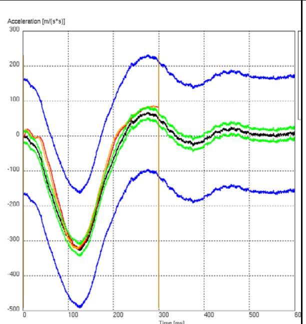
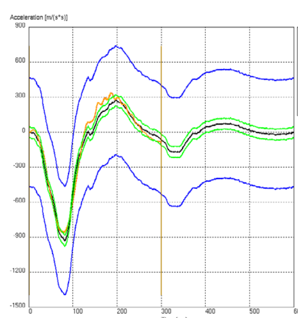
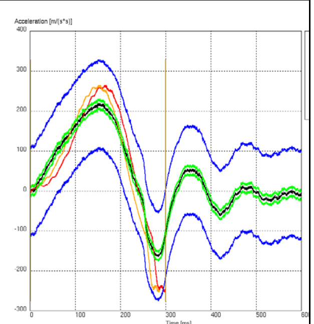
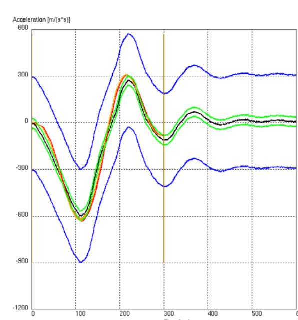
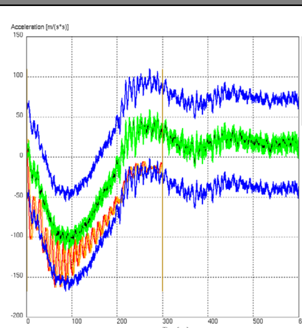
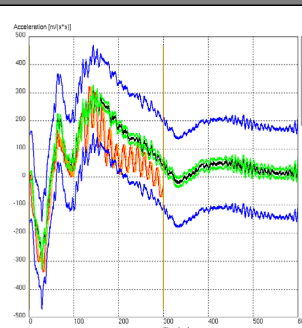
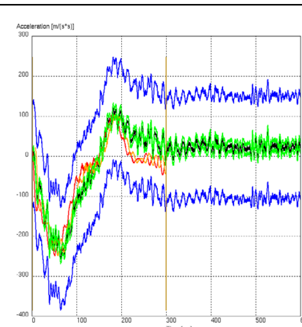
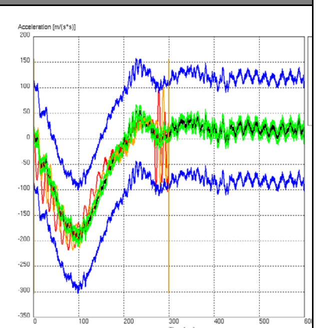
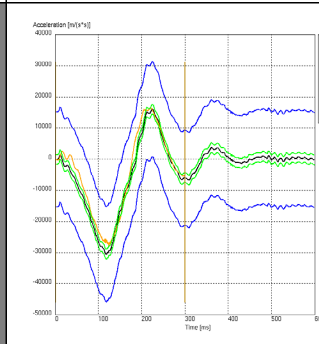
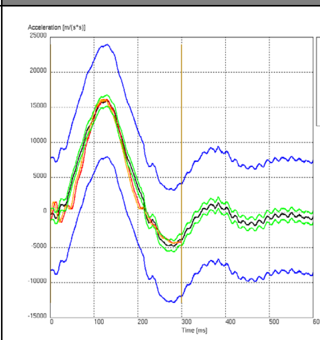
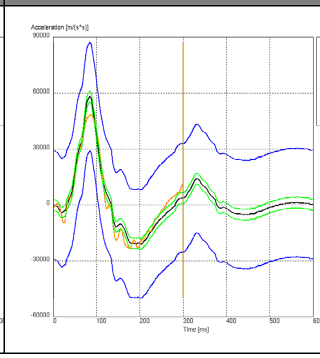
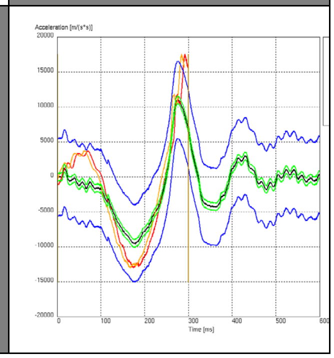
	Frontal 6G	Frontal 16G	Lateral 12G	Rearward 6G
Head Az				
Head Ry				
Neck Fx				
Neck Fy				
Neck Fz				

Table 9. NASA Neck Sled Simulation CORAplus generated graphs: Usimcurve19, Continued

	Frontal 6G	Frontal 16G	Lateral 12G	Rearward 6G
Neck Mx				
Neck My				

The Usimcurve19 material model response characteristics in the Neck Sled Simulation well match the magnitude and peak-timing response of the physical Hybrid III. The model will perform well in assessing spacecraft crashworthiness, as occupant injury is measured at the maximum value of the response sinusoidal waveform.

On top of the improved ISO rating, the Usimcurve19 material model produces a 95th percentile neck that is CFR calibrated for FMVSS compliance. Usimcurve19 performance contrasted with the NASA Updated model in the CFR neck calibration simulations is available in Table 10. The blue dashed lines represent the CFR established corridors. Model injury criterion from these simulations is presented in Table 11.

Table 10. Neck Calibration Simulation plots: NASA Updated model and Usimcurve19

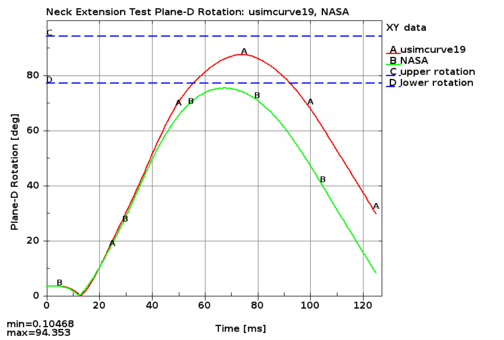
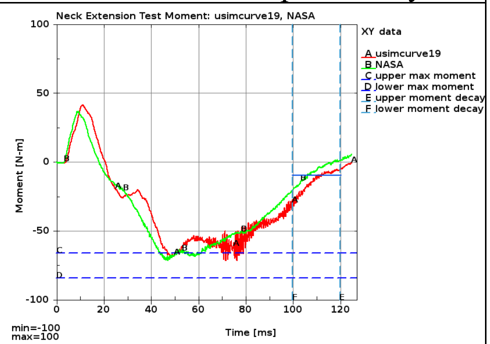
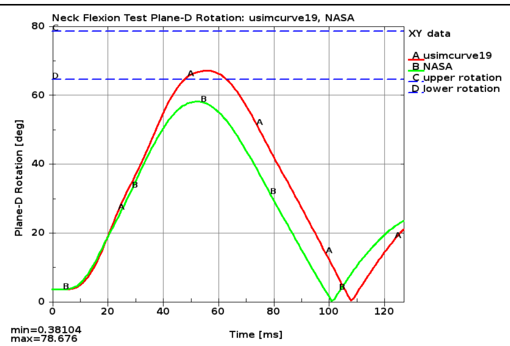
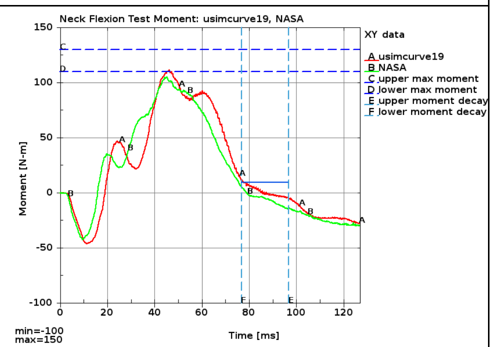
	Plane-D rotation	Moment about occipital condyle
Neck Extension		
Neck Flexion		

Table 11. Neck Calibration Simulation performance: NASA Updated model and Usimcurve19

Neck Extension	Lower Corridor	Upper Corridor	NASA Updated	Usimcurve19
Plane-D Rotation [deg]	81	98	79.15	91.29
Maximum Moment [N-m]	66	84	70.51	68.50
Moment Decay to 10 N-m [ms]	100	120	107.56	109.86
Neck Flexion	Lower Corridor	Upper Corridor	NASA Updated	Usimcurve19
Plane-D Rotation [deg]	61	75	55.11	63.52
Maximum Moment [N-m]	110	130	103	111.44
Moment Decay to 10 N-m [ms]	77	97	75.62	77.64

The newly developed model also boasts improved computational efficiency. Table 12 compares the total CPU timing between the NASA Updated and new model in the Frontal 6G Neck Sled Simulation. A simulation was submitted to the California Polytechnic State University Aerospace Bishop Symmetric Multiprocessor (SMP) cluster run on 1 node and 12 cores. Two supplemental jobs were submitted to the LSTC Barstow Massively Parallel Processor (MPP) server run on 12 and 24 cores.

Table 12. Neck Sled Test SMP Bishop Cluster CPU timing NASA model and Usimcurve27

Model	Total CPU Timing		
	Bishop SMP 1 node	Barstow MPP 12 cores	Barstow MPP 24 cores
NASA Updated (without DR)	34 hours 8 mins	N/A	N/A
NASA Updated	21 hrs 25 mins	2 hrs 22 mins	1 hrs 19 mins
New Model	10 hrs 6 mins	1 hrs 42 mins	57 mins

Timing information can be compared between like servers. In the SMP server, invoking dynamic relaxation improved CPU timing to by 37%. Switching from the NASA Updated to the new model improved computation time by an additional 33%. The CPU timing decrease from the NASA Updated model with invoked dynamic relaxation to Usimcurve19 on the MPP server was 29%.

Conclusion

The neck model revised in this project exhibits improved performance through an increased range of loading. The neck model was calibrated according to SAE standards, while having slightly improved performance in the Neck Sled Simulations. The neck rubber constant stress element formulation with hourglass control type 7 improves model stability and avoids artificial stiffness, which afflicted the former model. Total CPU timing decreased by 30% in the NASA Neck Sled Simulations and by 70% in the Neck Extension Simulation. The Usimcurve19 95th percentile neck model will be further tested by NASA before use in predicting potential occupant injury during spacecraft landing.

Model performance varied based on head orientation whether in extension or flexion. Future neck model revisions may involve introducing a new material model with the option to define a stress-strain curve. Defining the stress curve will offer an ability to adjust neck response according to if loading occurs in compression or tension, which may help correct for the bias in bending direction.

References

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