Applying the Dynamic Relaxation Step to Determine Influence on Global Model Response from Shock Tube Loading for Mounted Hybrid III Head Neck Assembly

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Abstract

Blast-induced traumatic brain injury (bTBI) is a critical issue for warfighter protection. Since bTBI has many features in common with injuries due to impact loading, the Hybrid III crash test dummy can be used to study many aspects of this injury, and the head-neck assembly of the Hybrid III dummy can provide a relevant initial bench test for computational studies of traumatic brain injury. LS-DYNA® has provided finite element models (FEM) of various Anthropomorphic Test Dummies (ATDs), and in this study the head-neck subassembly from the LSTC-NCAC 50th% Full FE H-III Dummy was used. To study the effects of blast on the head a shock tube experiment was simulated and the relevant loading conditions were applied to the head-neck assembly of the Hybrid III dummy FEM. The results were then compared to similar experimental test data. Since the initial tension in the neck cable of the Hybrid-III head-neck assembly is a key factor in the experimental response, simulating the initial tension in the neck cable is required in order to maintain a consistent boundary condition for the model. The neck cable definition in the Hybrid-III FEM was modified to include an initial stress, which was implemented using a dynamic relaxation step applied to initialize the model. The dynamic relaxation step is applied using explicit techniques and a sensitivity study is explored to understand impact of the initialization on the global response. The relative influence on the resulting global behavior response depends on the loading conditions.

Introduction

Blasts related to improvised explosive devices (IEDs) have become an important threat to military personnel in asymmetric warfare, and numerical simulations have become an important tool for developing countermeasures to them. Since there are substantial similarities between blast and impact loading, the tools that have been developed to study automotive impact can offer a useful starting point for the study of blast injury.

The head-neck assembly of the Hybrid III dummy has been used for years for head impact studies related to crash, so it is reasonable to use the head neck assembly to benchmark the response to blast loading condition and in this case shock tube loading conditions. As the simulated environments become increasingly complex in nature or boundaries are crossed with respect to the intended use of test devices, Finite Element Models (FEM) become important to study varying influences and can help determine importance of numerical techniques for certain loading conditions. Dynamic relaxation is one of those techniques used to better define problems for improved model response in comparison to experimental response. Dynamic relaxation in LS-DYNA provides the means to preload the system to a steady state prior to dynamic loading for the explicit transient analysis. For this study, the application of a dynamic relaxation step to initialize the neck cable stress is examined for the shock tube loading condition.

Methods

The head-neck subassembly of components and definitions from the LSTC-NCAC 50th% Full FE H-III Dummy was used in the LS-DYNA simulations to examine the dynamic relaxation step influence on response [1,2]. The number of components from the full dummy was reduced to include only the head and neck components and their definitions. The neck cable from the reduced FEA model was then modified to simulate the initial tension in the cable, as well as the initial compression in the surrounding neck parts.

Finite Element Model Modifications

The neck cable was modified from its original definition for this study to better represent an equivalent experimental set-up and allow a study of dynamic relaxation. The cable on the Hybrid III dummy neck is 5/16" diameter 7x19 galvanized wire rope with a 1/2-20 threaded hex nut at the end to tighten the cable to a torque specification of 112.98 kN-mm (12 in-lb)[3]. The calculated area using the cable diameter of 7.9375 mm(5/16") is 49.5 mm^2, while the original model defined the cable cross sectional area to be 30 mm^2. The 30 mm^2 cross-sectional area takes into account that the cable is comprised of many smaller diameter wire ropes and therefore the entire cross section does not encompass the area calculated by the diameter. This study uses both cross-sectional area properties. All of these parameters determine the initial stress applied to the cable and will provide the stress needed to determine the equilibrium state that is defined by the dynamic relaxation step. The following equations and parameters were used to determine the initial stress in the neck cable to establish the baseline from which to work:

The torque equation (1), based on design rules for a standard screw sizes rearranged (2) to solve for force:

$$T = k \cdot F \cdot d \qquad (3)$$

$$F = \frac{T}{(k \cdot d)} \qquad (3)$$

Applying the known values for the 1/2-20 threaded bolt:
Nominal Torque, T = 112.98 kN-mm (12 in-lb)
Coefficient, k ≈ 0.20
Diameter, d = 12.5mm(.5 inches)
Yields a calculated force of .5338 kN (120 lbs)

Apply the calculated force to the stress equation (3) while using the cross-sectional area (49.5 mm^2) of the cable to calculate the stress that is applied the cable.

$$\sigma = \frac{F}{A} \qquad (3)$$

The calculated initial stress in the neck cable is .01 GPa

The neck cable was modified from a Belytschko-Schwer resultant beam element with an initial stress definition to a truss resultant beam element. The truss resultant beam has two parameters, the initial stress (STRESS) and ramp up time (RMPT) that are used to generate the uniform stress state of the cable when the dynamic relaxation step is activated. Figure 1 shows the original model definition and Figure 2 shows the modified neck cable definition. The original configuration using the *INITIAL_STRESS card allows the neck cable to have the appropriate cable stress state but does not include the effect to the assembly by having this imposed stress.

```
*PART
NeckCableBeams
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
  50200008  50200008  50200008         0         0         0         0         0
*SECTION_BEAM
$#   secid    elform      shrf   qr/irid       cst     scoor       nsm
  50200008         2 0.000E+00         0 0.000E+00 0.000E+00 0.000E+00
$#       a       iss       itt       irr        sa
 3.000E+01 7.200E+00 7.200E+00 1.440E+01 2.700E+01 0.000E+00 0.000E+00 0.000E+00
*MAT_ELASTIC
  50200008 7.890E-06 9.600E+01 3.000E-01 0.000E+00 0.000E+00
*INITIAL_STRESS_BEAM
$#     eid      rule      npts     local
  50207805         2         4         1         0         0         0
$#   sig11     sig22     sig33     sig12     sig23     sig31       eps
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 ...
$#     eid      rule      npts     local
  50207825         2         4         1         0         0         0
$#   sig11     sig22     sig33     sig12     sig23     sig31       eps
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
 1.000E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
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Figure 1 Original neck cable definition

```
*PART
NeckCableTruss
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
  50200008   50200008  50200008
*SECTION_BEAM
$#   secid    elform      shrf   qr/irid       cst     scoor       nsm
  50200008         3       1.0         1
$#       a     rampt    stress
      49.5      10.0      0.01
*MAT_ELASTIC
  50200008 7.8900E-6 96.000000  0.300000
```

Figure 2 Modified neck cable definition

<u>Loading and Boundary Conditions</u>

To set the model conditions for simulation, the model was fixed at the base of the neck bracket and a temporal pressure field was applied to the outside surface of the Hybrid III dummy head. The pressure field was generated from a CFD simulation of a rigid head form positioned 6 inches from the exit plane of a shock tube. This was done to mimic a relevant experimental test set-up [5]. The temporally and spatially accurate pressures were then mapped to the outside surface of the Hybrid III head FEM using MATLAB® and the loading conditions for the simulations were set [4,6]. A pressure contour plot of the CFD simulation can be seen in Figure 3 alongside the similar experimental test.

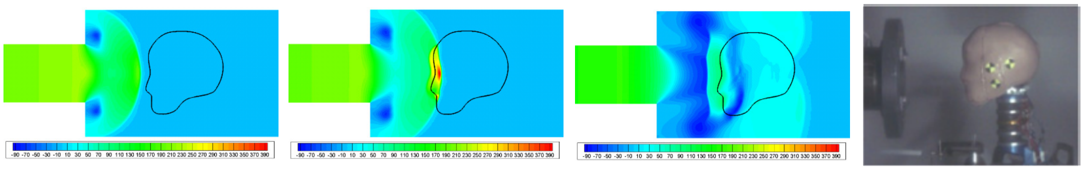


Figure 3 CFD provides input for the LS-DYNA simulation shock tube generated pressure loading on the Hybrid III Head Neck assembly similar to the relevant experimental test [5,6].

The temporal pressure loading condition was only applied to the head form surfaces. The representative model configuration with boundary and loading conditions can be seen in Figure 4.

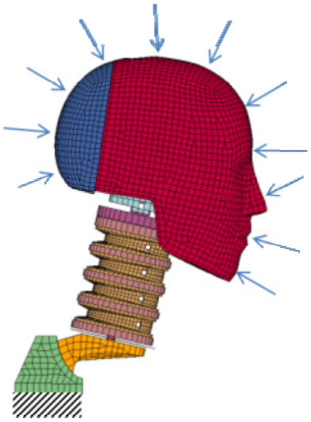


Figure 4 Model configuration

The effect of gravity was removed from the models to explore only the initialization of the neck cable.

Dynamic Relaxation Study

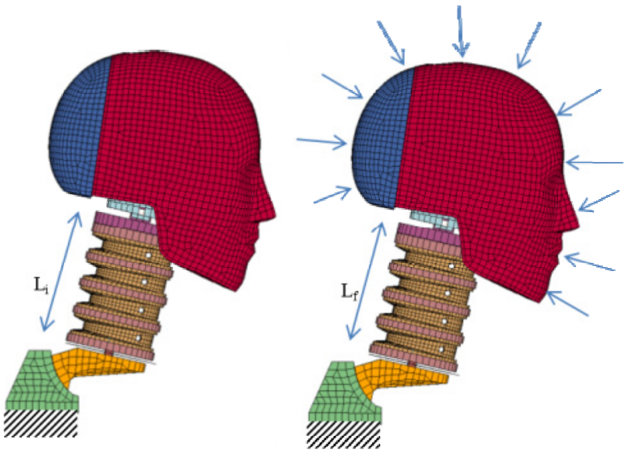
Three simulations were run including a dynamic relaxation step, in which the initial stress was varied while maintaining the cross-sectional area of 49.5 mm^2 constant (Table 1, cases C through E). In an experimental setting, this is equivalent to changing the applied torque on the cable. Two additional simulations were run to see the effect of changing the cross-sectional area to the original defined 30 mm^2 while either maintaining the same applied torque or the same cable stress (Table 1, cases F and G). Two baseline simulations were run without dynamic relaxation; one including the original Hybrid-III neck cable configuration and another including the modified neck cable configuration (Table 1, cases A and B). All of the models discussed in this paper have the CFD generated shock tube blast loading condition and clamped neck bracket boundary conditions applied. The explicit transient simulations were completed to 100 ms. In cases where dynamic relaxation was used, this time interval was measured from the end of the dynamic relaxation step. Table 1 shows the Simulation configurations and the parameters or definitions that were varied. Global displacement will be examined to show the effect on the global response of the model.

Table 1 Parameters

Simulation	*Cable Elements Formulation*	*Explicit Dynamic Relaxation Step*	*Equivalent Torque [kN-mm]*	*Applied Cable Stress [GPa]*	*Cable Cross-Sectional Area [mm]*
A	2	No	N/A	.01	30
B	3	No	N/A	N/A	49.5
C	3	Yes	1.3559	.01	49.5
D	3	Yes	.4746	.0035	49.5
E	3	Yes	.6101	.005	49.5
F	3	Yes	.8813	.01	30
G	3	Yes	1.3559	.018	30

Results and Discussion

To understand the effect of using the dynamic relaxation step to set the equilibrium state, the resultant displacement of the head center of gravity (CG) was studied. When the dynamic relaxation step was activated it calculated the model position prior to the transient analysis. Therefore, the relaxation step imposed a displacement on the model that was the initial position of the FEM for the transient analysis. Also, the dynamic relaxation step calculated an initial stress state in the model that influenced the reaction to imposed loading.



(a) (b)

Figure 5 Position of FEM after dynamic relaxation is applied (a) LSTC-NCAC Hybrid III Head-Neck assembly (b) Dynamic Relaxation step applied to initialize model for shock tube loading simulation [$L_f = L_i - L_{DR}$]

The peak resultant displacement increased for all the simulations in which the dynamic relaxation step was active (Figure 6). The time of peak displacement shifted when the neck cable stress changed (i.e. when the applied torque on the cable end bolt changed). This can become important when trying to understand the impact of the boundary conditions on the experimental setup. A summary of the tabulated results can be seen in Table 2. Also included in the table of summary of results is the response of a similar relevant experimental test.

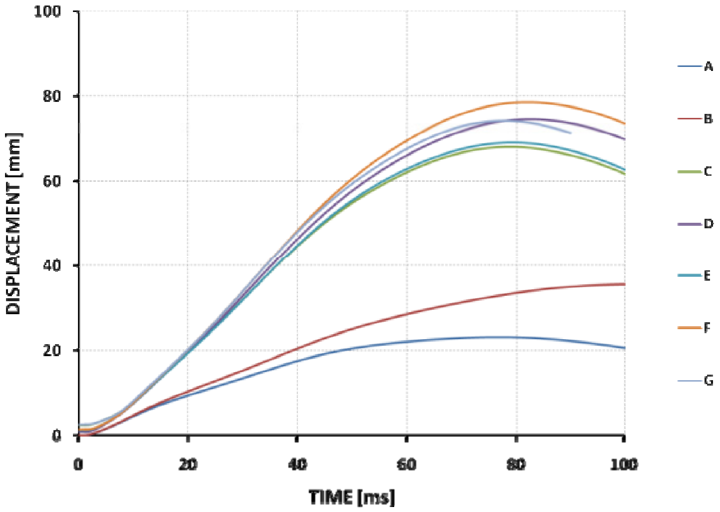


Figure 6 Global Displacement Results
A - Original Cable, No DR
B - Modified Cable, No DR
C - Modified Cable, Stress = .01, CA = 49.5
D - Modified Cable, Stress = .0035, CA = 49.5
E - Modified Cable, Stress = .005, CA = 49.5
F - Modified Cable, Stress = .01, CA = 30
G - Modified Cable, Stress = .018, CA = 30

Table 2 Summary Results

Simulation	L_{DR}, *Total displacement of Head CG after Dynamic Relaxation [mm]*	*Peak Resultant Global Displacement [mm]*	*Time [ms]*
A	-	23.10	76.90
B	-	35.6	100+
C	2.5	68.11	78.6
D	.899	74.57	81.8
E	1.296	69.17	79.4
F	1.4258	78.63	81.9
G	2.618	74.12	77.6
Experiment [5]	unknown	43.519	71

When the dynamic relaxation step is applied to the model, the resulting response appears to be counter intuitive. The global peak displacement was larger when the dynamic relaxation step was applied, but the neck system was expected to be stiffer due to a reinforcing effect. The effective decrease in stiffness in the neck may have been due to the tensile preload on the central truss elements, which placed the rubber disc components of the neck in compression. Figure 7 shows the Von Mises stress in an anterior and posterior element from the second rubber disc on the neck for simulations B and C. The initial stress (time = 0 ms) seen in the rubber elements after the dynamic relaxation step for simulation C of the neck is about 100 KPa as compared to zero stress for simulation B run without the preload on the system.

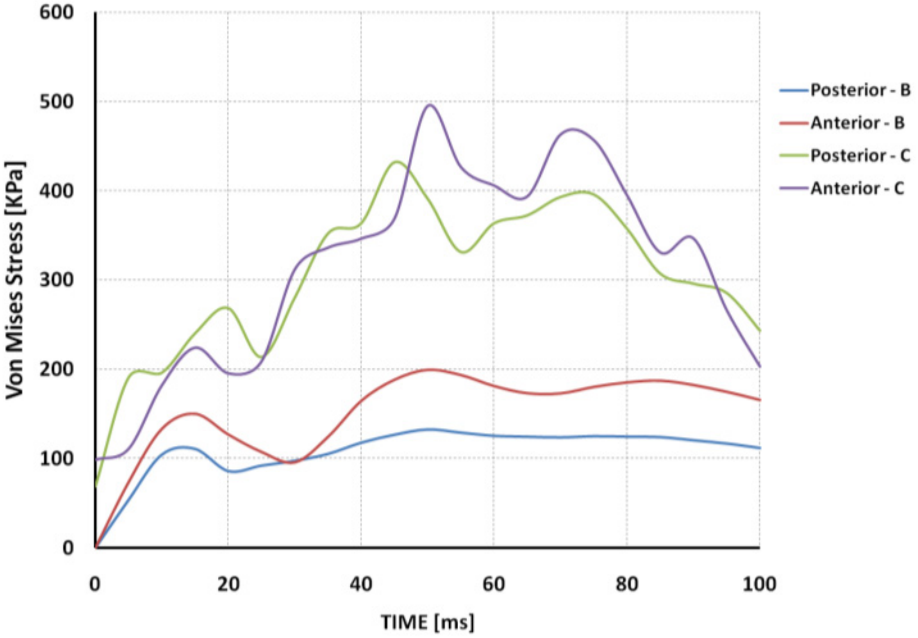


Figure 7 Von Mises stress in an anterior and posterior rubber neck element for simulations B and C

The overall stress seen in the rubber neck component for the simulation with dynamic relaxation step applied is greater than the overall stress for the simulation with no dynamic relaxation step applied. This pre-compression and ensuing dynamic response may have amplified the rearward bending of the neck and resulted in higher rearward displacements. This aspect will have to be explored further for confirmation. Regardless, applying the relaxation step to allow the model to start the transient analysis from a preloaded steady state position yielded a more compliant system as can be seen in Table 2 for simulation configurations C through G.

Conclusions

The results show that applying the dynamic relaxation step to initialize the model prior to the explicit transient simulation is important and significant for this application. The dynamic relaxation step generates a pre-loaded state of the model that was shown to be significant to model response for this shock tube simulation environment. The application of the dynamic relaxation step increased the peak global displacement in the finite element model response in comparison to simulations that were exercised without the applied preloading condition. The results show that the time and magnitude of peak global displacement were affected by varying the parameters that influence the applied stress on the cable. For FEM validation and experimental comparison, it is important to identify all quantitative values pertaining to the experimental set-up in order to best represent it as finite element model. For this study, the applied torque allows for a consistent experimental set-up, as well as a quantitative value that is imposed on the model of which can be replicated in simulation. This study shows that the initialization is important to the dynamics of this model.

Recommendations

Future dynamic simulations should explore initializations that may affect the dynamics of the system. For this particular study, the increased neck compliance after applying the preload shows that further exploration is needed to understand the specific dynamics leading to this counter intuitive response. Conditions that can be quantified in an experiment will be best able to be represented numerically. In this example the torque specification to which the neck cable bolt be applied is that quantifiable value that will help to improve the response of the FEM. However, not all dynamic simulations will require the dynamic relaxation step, so the technique should be explored and ruled out to be insignificant.

References

1 LS-DYNA® Keyword User's Manual, Version 971

2 LSTC_NCAC Full_FE Dummy (50th Percentile H-III), LSTC_NCAC.H3.50th.061609_Alpha

3 Backaitis, Stanley H., and Harold J. Mertz. Hybrid III: The First Human-Like Crash Test Dummy. Warrendale, PA: Society of Automotive Engineers, 1994.

4 Matlab (Version R2009b), The Mathwork, Inc, Copyright 1984-2009

5 Merkle, A.C.; Wing, I.D.; Armiger, R.A.; Carkhuff, B.G.; Roberts, J.C.; " Development of a Human Head Physical Surrogate Model for Investigating Blast Injury," IMECE2009-11807, *in Proc. 2009 ASME Int'l Mech. Engin. Congr. & Expo.*, Lake Buena Vista, FL, (13-19 Nov. 2009).

6 Roberts, J.C.; Ward, E.E.; Harrigan, T.P.; Taylor, T.M.; Annett, M.A.; Merkle, A.C.; "Development of a Human Head-Neck Computational Model for Assessing Blast Injury," IMECE2009-11813 *in Proc. 2009 ASME Int'l Mech. Engin. Congr. & Expo.*, Lake Buena Vista, FL, (13-19 Nov. 2009).