LS-DYNA® Belted Occupant Model

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Abstract

The seat belt is one of the most critical components in automotive crash safety. The three-point belt system has been around for fifty-eight years, belt pretensioners for thirty years and retractor torsion bar load limiters for eighteen years. Though the belt system has been around for so long, CAE correlation to physical test is still limited and far from having high confidence predictive capability. There are numerous CAE parameters and all their values have to be carefully determined, to represent the physics of crash testing and for the CAE models to have good predictive value. How well the belt system is modeled in CAE can directly affect occupant correlation and our predictions. There is an increased need to correlate and predict occupant results in various crash modes, from the ever changing USNCAP, FMVSS and IIHS to the other NCAP updates from outside the United States. Through this study, the belt modeling has been greatly improved leading to much better occupant CAE results. Like airbags, one of the challenging parts of modeling the seatbelt is the modeling of the fabric and other related devices (like pretensioners). To validate CAE models, different levels of component and subsystem testing are required. These test procedures, setups and fixtures have to be carefully designed to create a controlled environment, which will determine the properties of the components in focus. What we have done in this particular study is to follow certain precise steps to exclusively determine the seatbelt properties and parameters, which can later be applied with fullest confidence.

Introduction

As the abstract above briefly outlines, the purpose of this entire study was to improve the modeling of seat-belts in occupant CAE. In such an effort, not only is it important to determine accurately the fabric material properties of the belt but also to determine energy managing retractor (EMR) and pyrotechnic-pretensioning characteristics, together with belt friction coefficients at D-rings and buckles and as they slide over dummies. The broader aim is that once these parameters are discovered and verified through "controlled environment tests", they can be used later in different models with the fullest confidence, instead of each individual analyst continuously tuning them to achieve a desired result in a specific situation. With this goal in mind, we have used a progressive and a systematic approach to improve occupant CAE models in frontal crash scenarios.

There were essentially three steps that we took and they are:

- Step 1 → Determination of belt fabric properties via *dynamic webbing test*; an FE model built & correlated later.
- Step 2 → Rigid Body Belted Sled Test (RBBS); CAE correlation using belt properties from Step-1 above.
- Step 3 → Sled Test with Belted Hybrid III 50th on rigid seat; CAE correlation using parameters from Steps 1&2.

It can be noted that the first of the three above can be termed a "component level" test, while the next two can be called a "sub-system level" test. Our *purpose* was to first determine all the properties and parameters possible from the tests at each level and then carry them over to the next level with practically no alteration (if possible at all), in order to check out how the model correlations *automatically turned out to be* at each subsequent step. With that in mind we move on to the descriptions of the tests themselves at each step, the results obtained from them and how our attempted model correlations turned out to be for each one of them.

Step 1: **Dynamic Seat_Belt Webbing Test (using an Impactor) and Equivalent Model Correlation**

The setup for this test is shown in **Figure 1**. The dynamic test procedure in our study simulates the average loading rate under NCAP test conditions. The fixture as shown in Figure 1 had been used at the Ford Component Lab. Two load cells on each side of the webbing were attached, close to the fixed ends. A pretension in the range 4-5 lbf was applied to the webbing before the test. The impactor displacement was calculated by using the double integration of the impactor deceleration. A switch was used to signal the contact between the impactor and the webbing. Four feet of webbing was needed for each test and four tests were conducted to establish the average properties of the webbing. The fixture deformations in the setup itself turned out to be insignificant.

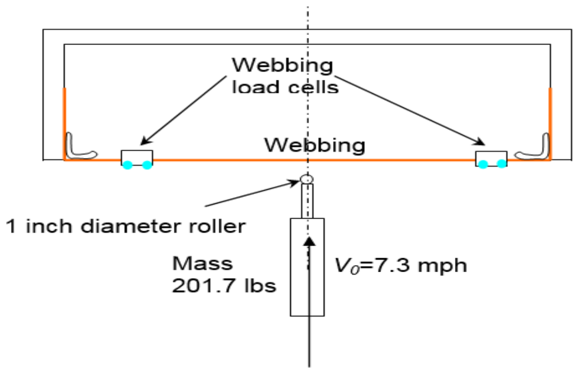

Figure 1: ***Fabric Test setup*** An Impactor of mass of **201.7-lbs** moved initially at **7.3-mph** toward the middle of the webbing. The webbing sample had **5-lbf** of pretension. Webbing load cells were used on both sides of the sample. The mass and speed were chosen such that the webbing load can rise to about **2000-lbf** in **40-msec**. This corresponds to the average NCAP webbing loading rate without torsion bars.

A *finite element model* of the same test configuration was created, as shown in **Figure 2** below. A fabric material model based on past experience was initially used to start the simulation process. Through the process of correlation of the CAE model and the test results (using the seatbelt force and impactor displacement of each respectively), we were able to accurately determine the different parameters of the seatbelt material. Once determined, *the seat-belt material properties were never altered in future steps of this study*. The various material properties have been shown in **Table-1** on the following page.

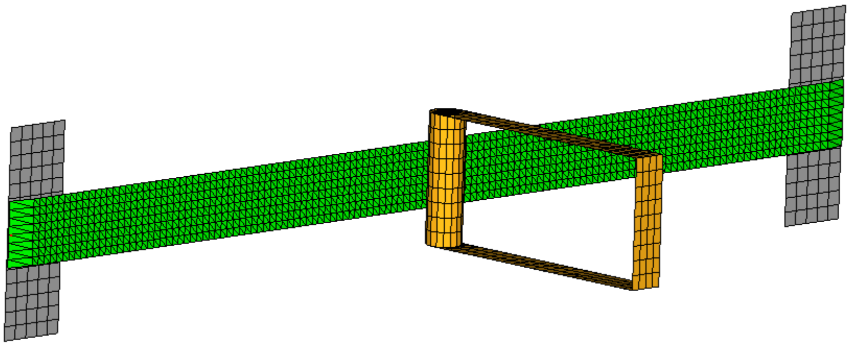

Figure 2: Seatbelt webbing test CAE model. Note the *8-element triangular mesh* in the lateral direction.

Figure 3 shows the *belt cross-section force* as recorded during the test by the load cells at the two ends of the belt and the *impactor displacement*, both being with respect to time. **Figure 4** shows the *average belt force* plotted with respect to *impactor displacement*. The "green curves" in all of these are equivalent model simulation results.

As we can see, the fabric model showed remarkable correlation with respect to the test results, differing slightly only in the "unloading phase". The webbing test correlation provided significant direction in finalizing the seatbelt material properties like Young's Modulus, "force vs. strain" characteristics in loading and unloading in both the longitudinal and lateral directions, damping, liner properties, etc. Our hope was that this could in turn improve the "system level" CAE models such as those for RBBS, regular sled and barrier.

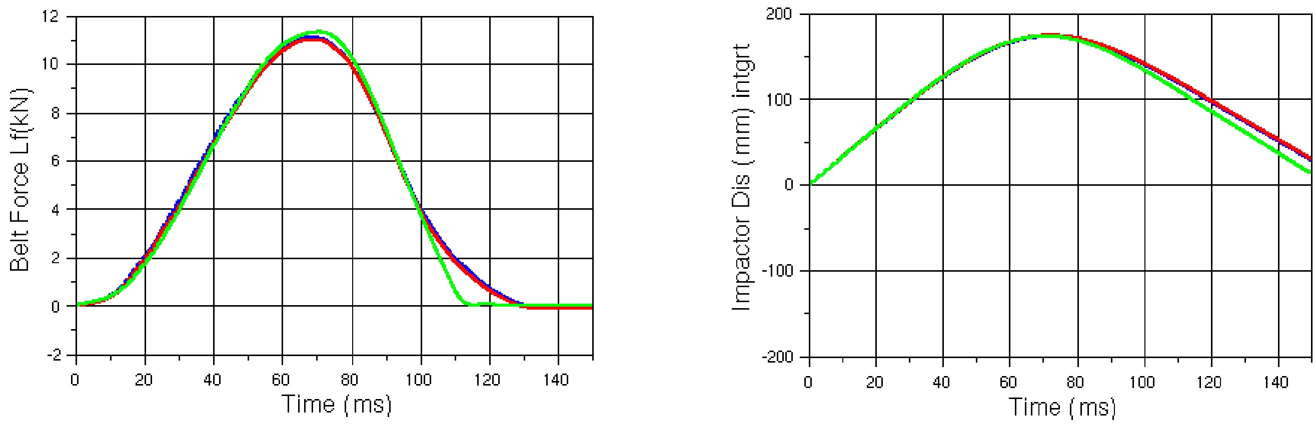

Figure 3. Seatbelt Force & Impactor Displacement. Note: The "green curves" are from the model.

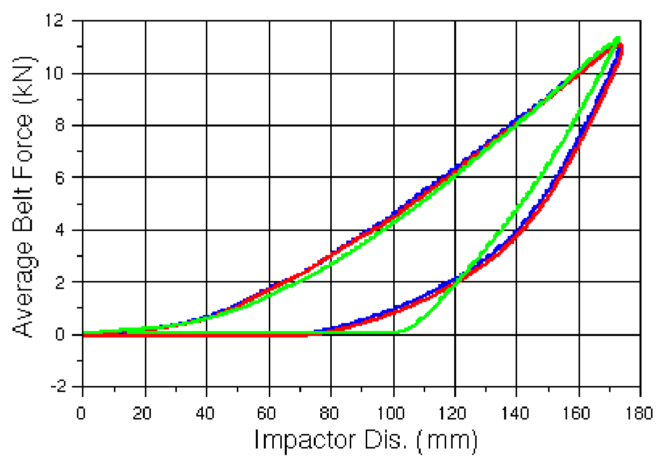

Figure 4. Force vs Impactor Displacement. The "green curve" is from the model.

In the following two pages we have displayed what the final "Section Properties" and "Fabric Material Model" we chose were, to achieve the above correlations to test. Obviously, these are in LS-DYNA format. Not only are the necessary curves shown overlaid on each other but the values themselves have been tabulated to make it easy for those who wish to use this very fabric material model directly in their own models to try out. Here we would like to add that the fabric belt we modeled had "8" triangular elements across the width, instead of the default "4" which most people normally use. We have found that the performance of an 8-element belt model is superior to that of a 4-element model. Currently LSPP gives the option of not only generating an 8-element belt when we start from scratch but also gives us the possibility of "refining" our existing 4-element belts to 8-element belts.

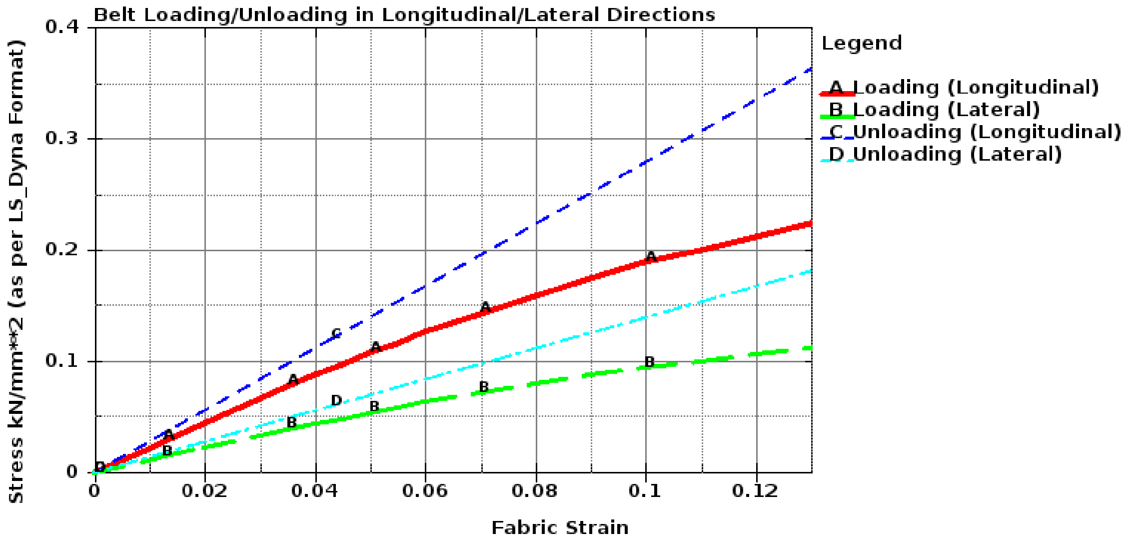

Figure 5. Belt Fabric Material Model "Stress vs. Strain" Curves (as per LS-DYNA requirement for Fabrics)

Figure 5 shows the belt fabric loading and unloading curves in the longitudinal and lateral directions of the belt. It is to be noted that LS-DYNA expects "stress vs. strain" curves for the fabric material model (not "force vs. strain"). We can convert the same curves back into a "force vs. strain" curve by simply scaling the "Y" by the cross-sectional area of the belt. Since a typical belt has a width of about 47-mm and a thickness of 1.2-mm, scaling the "Y" by "47.0*1.2" (i.e., by 56.4 mm**2) would give us each of the above back as a "force vs. strain" curve. The latter can then be used for "single line segment belts" in a "mixed belt system" (requiring only the "longitudinal curves" from the above and not the "lateral ones").

The "Section Properties and Material Models" of the fabric used are given below:

```
*SECTION_SHELL
$
$#     secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
          11         9       0.0         2       1.0         0         1         1
$#        t1        t2        t3        t4      nloc     marea      idof    edgset
         1.2       1.2       1.2       1.2       0.0       0.0       0.0         0
$#        bi        bi        bi        bi        bi        bi        bi        bi
        90.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0

*MAT_FABRIC
$
$#       mid        ro        ea        eb        ec      prba      prca      prcb
           8  1.062E-6       2.0       2.0       2.0       0.3       0.3       0.3
$#       gab       gbc       gca       cse        el       prl    lratio      damp
       0.769     0.769     0.769       1.0       0.3       0.3       0.1       0.2
$#      aopt       flc       fac       ela      lnrc      form     fvopt    tsrfac
         0.0       0.0       0.0       0.0       0.0        14       0.0       0.0
$#    unused    rgbrth    a0ref        a1        a2        a3        xd        xl
           0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
$#        v1        v2        v3        d1        d2        d3      beta    isrefg
         0.0       0.0       0.0       0.0       0.0       0.0       0.0         0
$#       lca       lcb      lcab      lcua      lcub     lcuab        rl
     1000058   1000059         0   1000070   1000071         0       0.0
$
```

The “tabulated values” of the loading curves in the longitudinal and lateral directions of the belt and the corresponding unloading curves are shown below. These are curves 1000058, 1000059, 1000070 and 1000071 in the material model shown above.

Curve **1000058** (Loading Longitudinal)

Strain	Stress (kN/mm**2)
0.00e+00	0.00e+00
1.44e-02	3.25e-02
2.89e-02	6.48e-02
4.33e-02	9.46e-02
5.78e-02	1.23e-01
7.22e-02	1.47e-01
8.67e-02	1.70e-01
1.01e-01	1.91e-01
1.16e-01	2.07e-01
1.30e-01	2.25e-01

Curve **1000059** (Loading Lateral)

Strain	Stress (kN/mm**2)
0.00e+00	0.00e+00
1.44e-02	1.63e-02
2.89e-02	3.24e-02
4.33e-02	4.73e-02
5.78e-02	6.15e-02
7.22e-02	7.36e-02
8.67e-02	8.51e-02
1.01e-01	9.54e-02
1.16e-01	1.04e-01
1.30e-01	1.13e-01

Curve **1000070** (Unloading Longitudinal)

Strain	Stress (kN/mm**2)
0.00e+00	0.00e+00
13.00e-02	3.62e-01

Curve **1000071** (Unloading Lateral)

Strain	Stress (kN/mm**2)
0.00e+00	0.00e+00
13.00e-02	18.17e-02

Table 1. Pairs of Stress-Strain values of the Fabric in Loading/Unloading, in Longitudinal/Lateral directions.

NOTES: The stresses in the lateral direction above are about 50% those in the longitudinal direction. We used the unit system of “mm, kg, ms and kN”, which is widely used all over the world in vehicle crash safety models.

As stated earlier, we have published the sectional and material properties of the fabric seatbelt in our model so that people can use them directly in their own models, in case they do not have any better data to begin the process with. It should surely be a very good place to start.

As mentioned shortly before, please remember that for “single line segment seatbelts” Dyna expects “Force-Strain” curves instead of “Stress-Strain” and therefore, the “Y” values have to be appropriately changed. This can be easily implemented by using the appropriate scale factor as “sfo” in the load-curves of the segment seatbelts, while continuing to use the exact same data pairs. Only the “longitudinal loading/unloading curves” are required for these segment belts (there being no “lateral direction” for these).

Now we move on to Step-2 of the process, carrying over the knowledge of material parameters and other general ideas from Step-1 above and applying them directly as far as possible.

Step 2: Rigid Body Belted Sled Test (RBBS Test) and Equivalent Model Correlation

The next step was the RBBS test and the equivalent CAE model correlation. The RBBS was specifically designed to eliminate almost all other restraint system variables except those belonging directly to the seatbelt (and perhaps friction), thereby validating the seatbelt material properties and parameters as determined from

"Step 1" above. The scheme has been shown in **Figure 6**. Two rigid blocks were designed to represent the *human upper body* and the *pelvis*, having approximate shape and mass. The lower block could slide on cylindrical rails with very little friction. The upper block on the other hand, could "bend over" much like the H-III dummy can through its own lumbar rotation (made possible by the three inline rotational joints connecting the upper and lower blocks). One shoulder guide was built in the upper block top frontal surface so that the shoulder belt would not slip off.

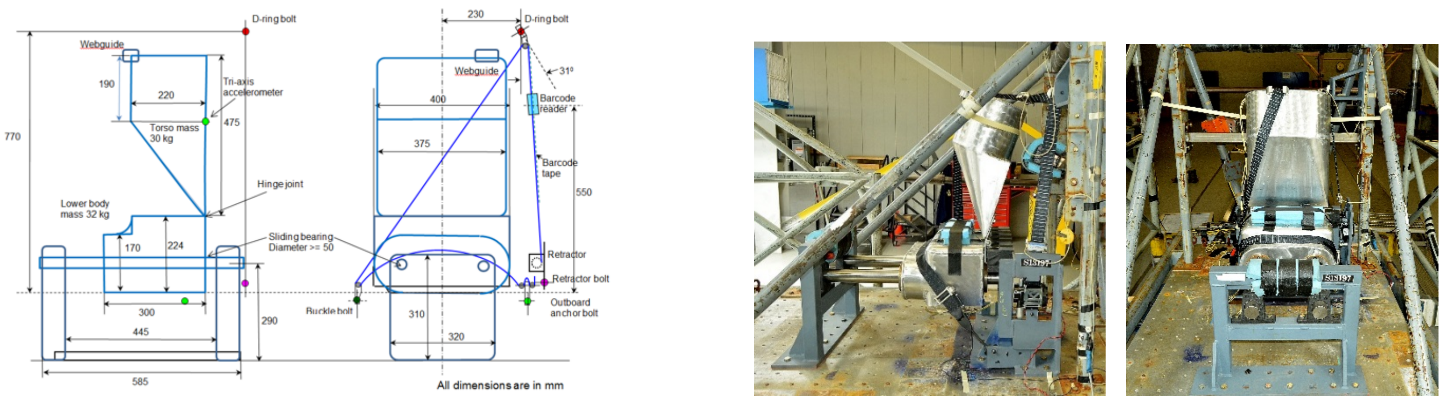

Figure 6: ***RBBS Test setup*** Upper rigid body mass was **46-lbs** and lower rigid body mass **75-lbs**. The sled initial velocity was **35-mph** with no pitch and drop angle.

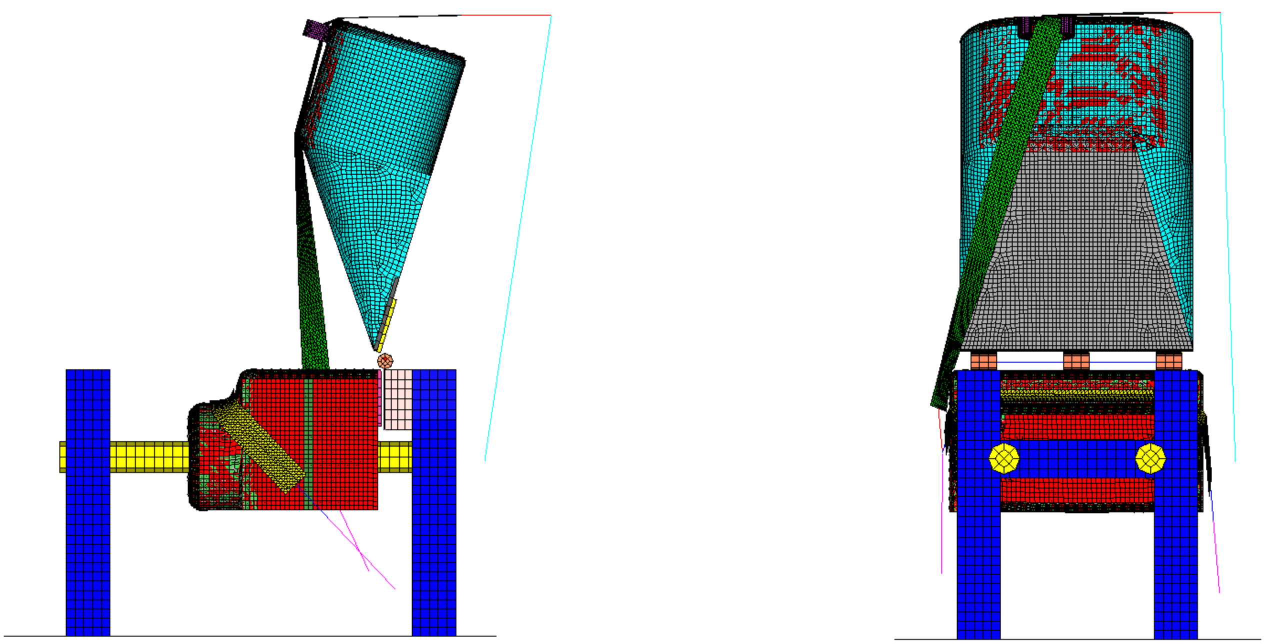

Figure 7. RBBS CAE sled model

In this step, we conducted four repeat test runs. The seatbelt had a one way CLT (Crash Locking Tongue) at the buckle, which after locking up only allows the belt to move from the lap side to the chest side (thus increasing lower body restraint). There was also a *retractor pretensioner* with a fire time of 12-ms. As in the previous step, we built a simulation FE model as closely as we could and tried to see how good the correlations to test were, in the different channels for which data had been collected. The important thing to note here is that during the model correlation, we used the *same seatbelt material properties which were obtained in Step-1*; there were no changes in that respect within the FE model at this step.

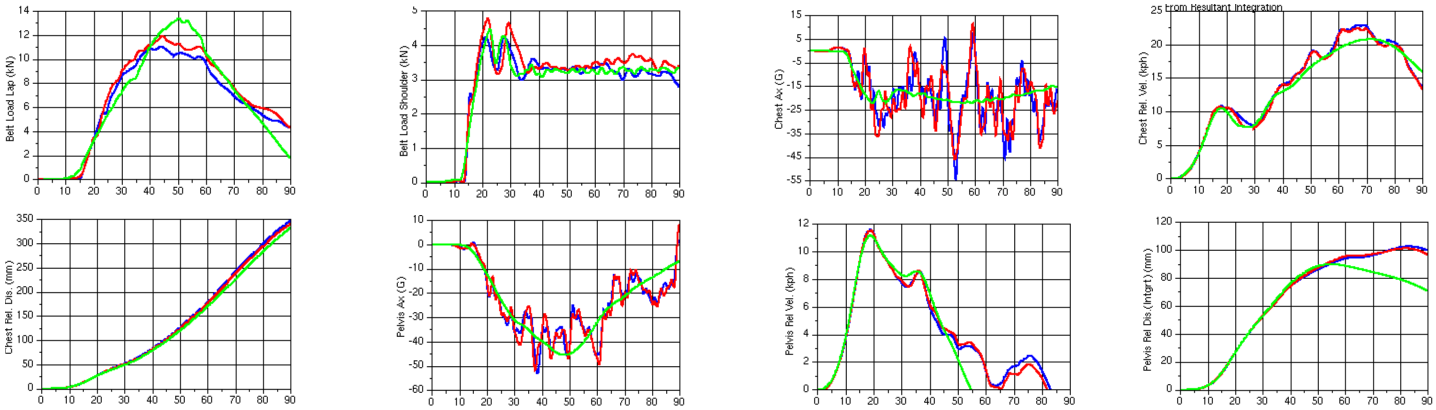

Figure 8. RBBS Correlations **Note**: The "green curves" are all from the model.

Figure 8 above shows the RBBS test to model correlations at different channels, all being with respect to time. As we can see, here too we had obtained very good correlations.

The most important additional parameters which were determined at this step to be carried over to Step-3 were merely the friction coefficients of the seatbelt at the *D-ring* and the *Buckle*. Everything else was *particular to this test* and hence were unimportant to Step-3. In Table-2 below, we have listed these friction coefficients.

	Dynamic Friction	Static Friction	Decay
Buckle	0.21	0.247	2
D-ring	0.15	0.176	2

Table 2. Seatbelt D-ring and Buckle parameters for RBBS

Please note that the relation between the "static" and "dynamic" friction coefficients and the "decay" coefficient were not determined by us via actual testing. We searched published data on this issue and finally concluded that the *ratio of the dynamic to the static friction coefficient* is around "*0.85*" and the *decay coefficient* is about "*2.0*". Based on that, we decided to use this ratio and coefficient not only at this step but use them in all our future applications as well. The values of the friction coefficients given in the table above have the ratio of "0.85".

This is a matter in which different engineers may differ in opinion and the matter is open to debate (of course). However, unless one has valid data which differ from the above, one might use the values we have tabulated above simply to start their own process of simulation (like most other things we have published in this paper).

Summarizing, we froze the seatbelt retractor and pretensioner properties and the D-ring and buckle frictions at this step. These and whatever other parameters we thought important were then carried over to Step-3.

Step 3: 50th% H-III Belted Sled Test and Equivalent Model Correlation

In the third step, a *belted Humanetics 50th% H-III dummy* was used in a sled environment (essentially replacing the belted rigid body of the previous step). As before, a pulse representative of a 35-mph full-frontal crash was used on the sled. Here too, four repeat tests were conducted to verify consistency.

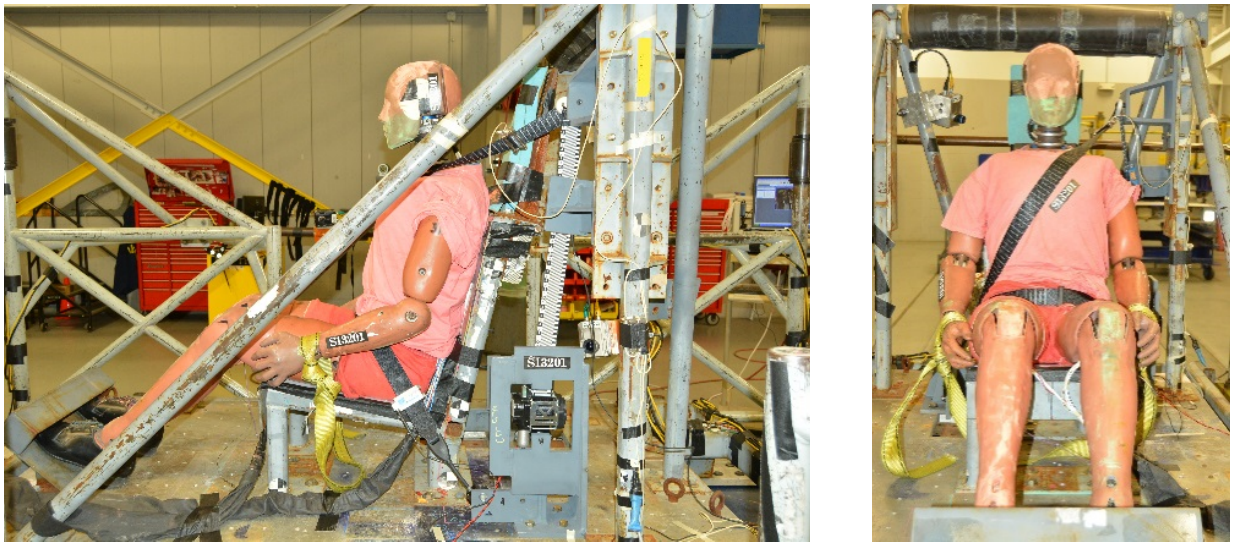

Figure 9. Sled Test setup using a recent 50th% Hybrid-III Dummy.

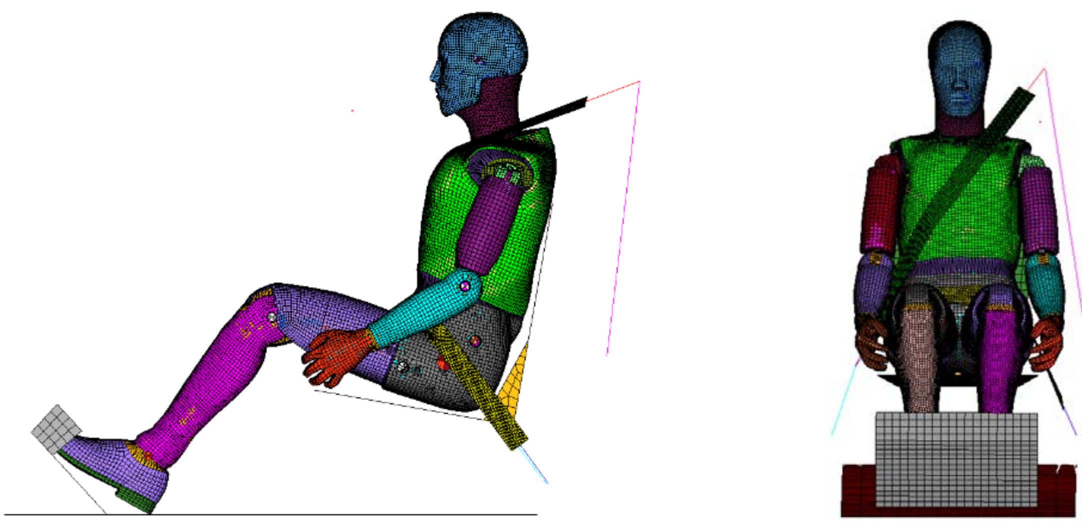

Figure 10. The most recent 50th% H-III Dummy from Humanetics was used in the sled model.

The *most important* takeaway from Step-3 are the "seatbelt to dummy" friction coefficients and other contact related parameters/formulations. We are detailing those below, so that all users can use them as a "starting point":

FS (static)=0.294 FD (dynamic)=0.25 (Note: FD/FS = 0.85) Decay coefficient=2.0 VDC=20.0
SFS=SFM=1.0 SST=MST=1.0 SOFT=2 SBOPT=3 DEPTH=5

Note: The above can be used in "Surface to Surface" contact definitions between the seatbelt and dummy.

Displayed below are the correlations of mostly the *head*, *chest* and *pelvis* responses, having used the above parameters in the general model we had built. We have also shown a couple of the *seatbelt force* responses.

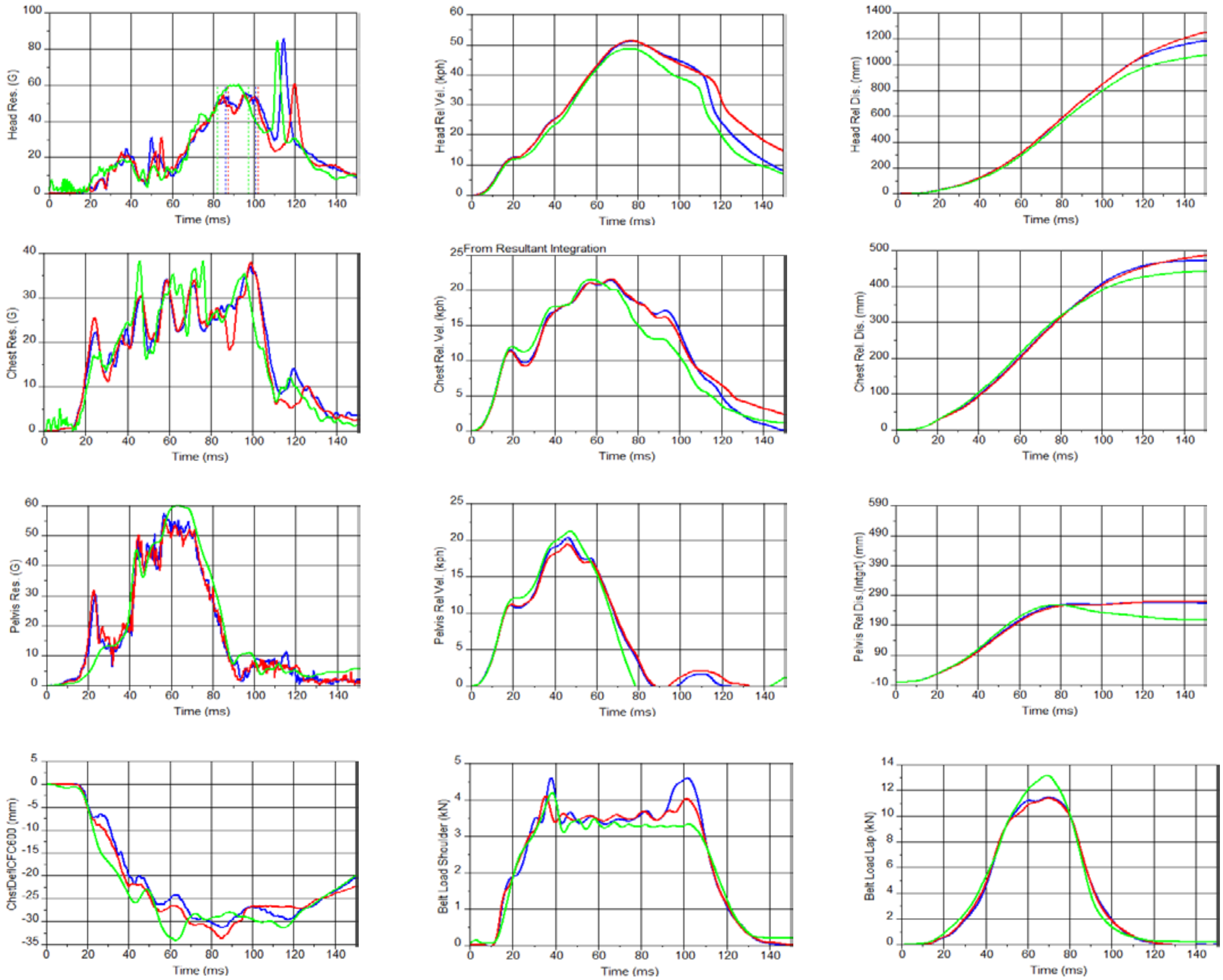

Figure 11. Model correlations with Test results (using the latest 50th% H-III Dummy from Humanetics)

Note: The “green curves” all belong to the model. The other colors represent any one of the repeat tests.

As we can see, almost all model channels show correct trends and curve shapes, with respect to test. Even the correlations are excellent in many of the cases.

The *head relative velocity* is almost line-on-line to 65-ms and though it falls slightly short at the peak and later, it does maintain the same basic *shape* of one of the test curves. The *head relative displacement* is almost perfect to at least 80-ms, though it falls off slightly after that. The *chest relative velocity* shows all the peaks, valleys and even magnitudes right to 60-ms, while the *chest relative displacement* is close to being line-on-line till about 90-ms. The *pelvis relative velocity* shows exactly the same trends to about 70-ms while the *pelvis relative travel* is perfect to 80-ms. The *chest deflection* also shows sufficiently good trend and magnitude. The *shoulder belt force* shows the *first peak* clearly and then displays EMR action correctly to at least 70-ms, while the *lap belt force* shows remarkable correlation both in loading and unloading, though it does show a higher peak in the middle.

Displayed below are quite a few other correlations connected with the Upper Neck and the Femurs.

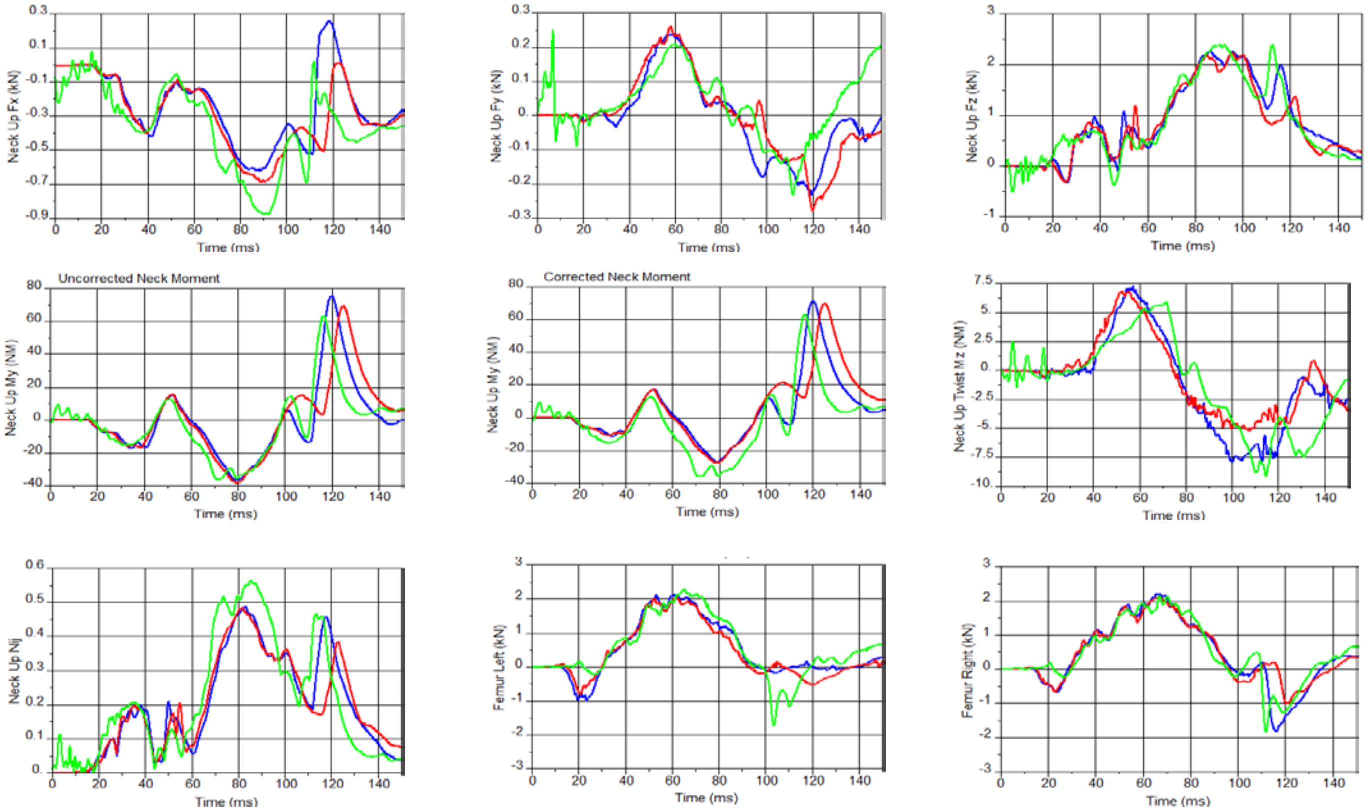

Figure 12. Model correlations with Test results (using the 50th% H-III Dummy from Humanetics)

Note: The "green curves" all belong to the model. The other colors represent any one of the repeat tests.

Anyone working in the simulation of occupant safety knows that the *upper neck channels* are the most difficult to correlate. However, here too we find that almost all the model neck channels have shown exceptional trends and magnitudes when compared directly to test. The *uncorrected upper neck My* is the first one we would like to point out because it literally hugs one of the test curves (the "blue curve"), distinctly showing all the peaks and valleys. The *upper neck Fz* shows almost identical trends. We would have been happier with a slightly better correlation of the *upper neck Fx* magnitude between 80-ms and 100-ms, even though the general trend is still well represented. We are still quite satisfied with the *upper neck Nij* even though it does show a little deviation in the 70-ms to 95-ms range. Even the *upper neck Fy & Mz* show trends which are likely to satisfy the most demanding of simulation engineers and analysts. The last two plots are those of the *left and right femurs* and in these also we have very little left to ask for, both being as good as they can perhaps get; they not only hug the test curves all the way to 100-ms but in the case of the right also shows the negative peak at 110-ms, thereby replicating the *blue test curve* almost exactly.

Humanetics has been at the forefront of FE dummy model development since the early '90s and the correlations of *figures 11 & 12* above demonstrate how far they have truly come. However, we have always maintained that the *quality* of a dummy model can only be ascertained *either way* when the *rest of the model – especially the restraint system* – has also been modeled to near perfection. The same Humanetics 50th% H-III dummy model coupled with a not too good restraint system and sled/vehicle model, might show totally different results, thus creating a false impression of the performance characteristics of the dummy model. We believe that the high standard of our *total model* has brought forward the best aspects of the *Humanetics dummy model* as well.

The quality of our correlations lead us to our conclusions regarding the three-step approach we had taken to validate our *seatbelt CAE methodology*. Those, together with a future outlook, have been summarized below.

Summary, Conclusions and Future Outlook

To recapitulate, our purpose was to determine certain *essential parameters* by means of carefully designed and very controlled tests and then take those same parameters to the *next step* and apply them *without any further alterations*. These parameters could be essential parts of the *material model* of a seatbelt, the parameters we use frequently to define *belt slippage at buckles/d-rings* or the parameters used to define *contact between the belt and the dummy surfaces*.

That is really what we had done. At **Step-1** we determined the *belt fabric properties* and developed the specific *material model* which we could use directly in an LS-DYNA seatbelt model. At **Step-2** we took those *same fabric properties* (and the *material model*) from Step-1 and applied them to our *rigid-body sled model*. Having sufficiently correlated this model we took the *buckle/d-ring friction coefficients* and moved over to **Step-3**, in which we used all the parameters from Steps 1 & 2 and applied them directly to the model involving the belted dummy. At this last step we wanted to see how the correlations turned out to be *automatically*. We still might have tuned it a bit just to be sure of the *belt to dummy friction coefficients*, though the *initial values* of those themselves came from past experience (thus drastically reducing the tuning runs at this stage).

Of course, our real goal in the matter was to encourage all simulation engineers to take the parameters we have openly published and try them out directly in their models without alterations. Our belief is that if *everything else* in a new and independent model is correct (such as dummy position, vehicle pulse, pitch, drop, etc.), then the correlations to test of a *purely belted sled or vehicle model* should be remarkably close to test *even in the first run*. That is truly the hope we are expressing as a group, having conducted this study.

It would be tremendous if users tried out our suggested seatbelt material model and other parameters directly in their purely belted dummy sled models and then published their correlations and other findings in the future. We would then have a clearer picture as to where we stand in the matter.

We do have plans in the near future to conduct similarly *controlled driver & passenger airbag tests* and correlate simulation models at each step of the process, exactly as we have done in this study series. The *final objective* of all this would be to come to a stage where *all material models and parameters* derived from all of these tests and model runs can essentially be *frozen* to a certain degree, so that users can apply them directly in not only their sled models but also in their full vehicle models. To be able to *reduce parametric tuning to a minimum* in different model runs is a goal worthy of pursuing by all simulation engineers. We are also sure that *exchange of information* in such matters *openly* amongst the larger community worldwide, would greatly advance the progress of CAE.

Acknowledgements

The authors would like to acknowledge the tremendous help provided by *LSTC of Michigan* with respect to all of the CAE model development & correlation and that extended by *Humanetics of Michigan* with any issue related to their latest H-III 50th% physical and FE model dummies.

References

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