Dummy Model Validation and its Assessment

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Abbreviations

FAT: German Association for Research on Automobile Technology
PDB: Partnership for Dummy development and Biofidelity
CORA: CORrelation & Analysis

Abstract

This paper describes the dummy model validation process applied in several FAT and PDB projects. The modeling activities started 19 years ago and the validation process was enhanced continuously during this period. Participants of the dummy modeling project of the FAT were engineers from:

- *AUDI AG*
- *BMW AG*
- *DAIMLER AG*
- *FORD AG*
- *ADAM OPEL AG*
- *Dr. Ing. h.c. F. Porsche AG*
- *Volkswagen AG*
- *JohnsonControls GmbH*
- *Keiper GmbH & Co*
- *TRW Automotive GmbH*
- *AUTOLIV B.V. & Co. KG*

Participants of the PDB are:

- *AUDI AG*
- *BMW AG*
- *Daimler AG*
- *Dr. Ing. h.c. F. Porsche AG*
- *Volkswagen AG.*

Members of the above companies define the quality requirements on the models and guide the development process closely. They are also involved in the definition of the validation test matrix and the appropriate load levels for the tests.

The models developed are the following side impact dummy models:

- *EUROSID*
- *ES-2*
- *ES-2re*
- *WorldSID 50%*
- *USSID*
- *SIDHIII*

and a model of the rear impact dummy:

- *BioRID II.*

All models are frequently used world-wide and regularly updated based on new validation tests and user feedback.

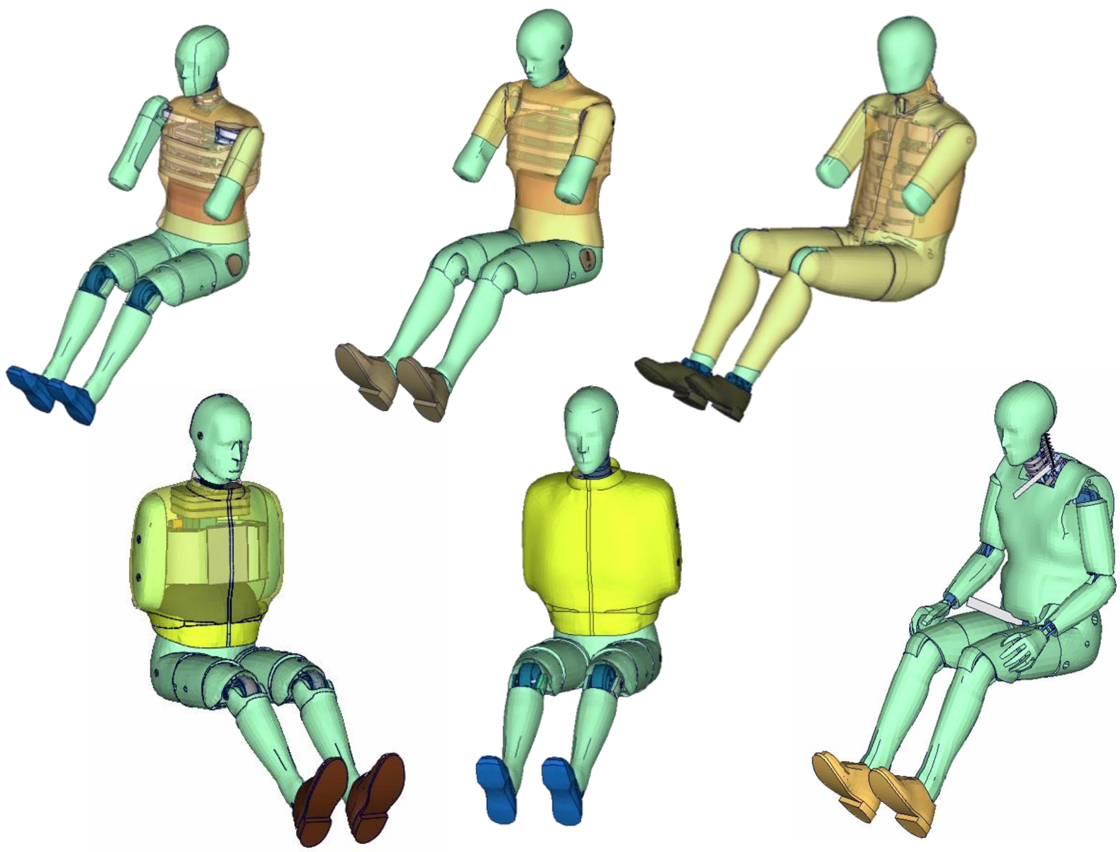

Figure 1: FAT and PDB dummy models of DYNAmore.

The design of occupant safety systems by using numerical simulations became an essential part of the vehicle development processes. Especially, the optimization of safety systems as well as robustness studies of these systems benefit from the progress of accurate simulations. Hence, the requirements for computational dummy models increased significantly over the past years. Therefore, the validation processes and the validation targets were refined continuously to meet the increasing goals.

This paper describes the four levels of tests and their role during the development process. All major tests which are used to validate a model are outlined. The paper summarizes also how a rating tool can assist to measure the correlation with test results. For this study the tool CORA is used. Finally, a rating can be used to summarize a quality of a dummy model release with one scalar value. Figure 1 describes the enhancement for different releases of the ES-2 model. Higher numbers correlate with better model quality.

	R2.0	**R4.5**	**R5.0**
PDB sled tests	0.390	0.579	0.666
FAT sled tests	0.552	0.592	0.668

Table 1: *CORA rating for different model versions of ES-2.*

The described test database is also available to generate models for other crash codes. The paper focuses on models generated for LS-DYNA. All presented models are developed by DYNAmore GmbH.

Introduction

Since many years finite element dummy models are available from several developers. The models are used by many OEMs and restraint system suppliers to develop solutions for passive safety. In the recent years the main effort in dummy modeling was to find a reliable and fast process to enhance the dummy models according to the continuously increasing requirements. Therefore, an efficient validation process is needed which ensures that the model performance is increasing or at least constant for all different load cases. The process must be able to handle design changes, new tests or load cases. In the following paper the current validation process of the FAT and PDB models is described. A more historic view how the development process evolved during the years is presented in [1]. Details on the rating scheme are presented in [2] and [3]. The development process of a particular model is described in [4] and [5]. This paper presents a general view of the lately applied methods with less focus on a complete documentation of a particular project.

Geometry and Mass

For the meshing the geometry must be available in digital format. This could be either available as CAD data or as scanned data. For the FAT and PDB models accurate CAD data was used if available. In all projects laser scans were used to adapt the model to include geometry changes due to assembly, gravity or manufacturing distortions.

During the meshing, the material stiffness of the different parts must be considered. The mesh size is generated to obtain a time-step in the range of 0.9 to 1.0 microsecond with a maximum of 1% added mass. Non-deforming parts are defined as rigid bodies. Plastic and rubber parts are meshed with hexahedron solid elements. Tetrahedron elements are only used for some soft foam parts, in many cases a hexahedron mesh is used also for the foam parts.

An important motivation for having a very detailed model, even if a part is rigid, is to have the exact inertias of each part, as there is a high influence of the inertias on the dynamic behavior of the model. In addition the mass of each component is weighted and documented carefully to allow a correct mass modeling including the masses of bolts, cables, etc.

Material Tests

The basis for the finite element models are the material tests of all relevant materials. The test specimens are usually cut out from new original parts of a dummy. Some of the specimens were taken from repair kits. Figure 2 shows the pelvis and arm flesh of the WorldSID 50% after cutting by a water jet.

Figure 2: Cut through a new arm and pelvis flesh of the WorldSID 50%.

All relevant deformable materials are tested dynamically and statically. For instance for the WorldSID the vinyl of the head, pelvis and upper leg skin, the Hyperlast materials of the upper arm and the pelvis, plastics of the arm bone and iliac wings, the foam of the pelvis and thorax rib pad and the Nitinol were tested.

Figure 3: Material specimens of the WorldSID 50%.

The main focus on the material tests is on the dynamic behavior. Thus, all parts are tested by different strain rates like 0.001 1/s, 20 1/s, 100 1/s and 400 1/s in tension and compression. Also static tension and compressions tests are performed. For rubber-like materials additional compression tests with constrained lateral expansion are carried out.

The material test results are often used after smoothing as direct input for the LS-DYNA material definitions. Therefore, material models that allow such test curves as input were preferred like *MAT_FU_CHANG_FOAM or *MAT_SIMPLIFIED_RUBBER. For many material definitions the unloading behavior is also included. This behavior is important to correlate signals that occur after a first decay of the main pulse. E.g. neck forces depend significantly on the overall kinematic behavior of the dummy, which depends on the loading as well as on the unloading characteristics of the materials.

Dummy Component Tests

In addition to the material tests the major sub-assemblies are tested on the component level. The component tests are used to ensure that each body region correlates accurately in the validation domain. All important components of the FAT and PDB models are tested and validated. The main component tests are:

- **Head** drop tests
- Pendulum tests for **neck**
- Sled test for the **neck**
- Pendulum tests on **rib assembly**
- **Partial thorax** impact tests
- Impact test on the **arm**
- Impact test on the **clavicle**
- Pendulum tests for **lumbar spine**
- Dynamic shear for the **lumbar spine**
- Dynamic torsion for the **lumbar spine**
- Sled tests for the **lumbar spine**
- Pendulum tests for the **abdominal insert**
- Impact tests for **abdomen component**
- Impact test on the **iliac wing**
- Impact tests for the **pelvis**

The main difficulty of the component tests is to find simple tests with loading conditions which are similar to the loadings in a vehicle. Therefore, a lot of pre-simulations are done to find the right test set-up and the appropriate loading levels. In the following tests for the ES-2 rib assembly and WorldSID50% rib cage are described in detail.

Example ES-2 rib assembly component test:
The ES-2 rib assembly was tested by an impacting pendulum. The assembly was fixed in space at the bearing system. A picture of the rib assembly is depicted in Figure 4.

Figure 4: Rib assembly of ES-2.

Figure 5 depicts the different pendulum target points and angles for the ES-2 rib assembly tests. For each of the impact points different pendulum masses and speeds were used to obtain tests with maximum rib deflections ranging from 10 to 50 mm.

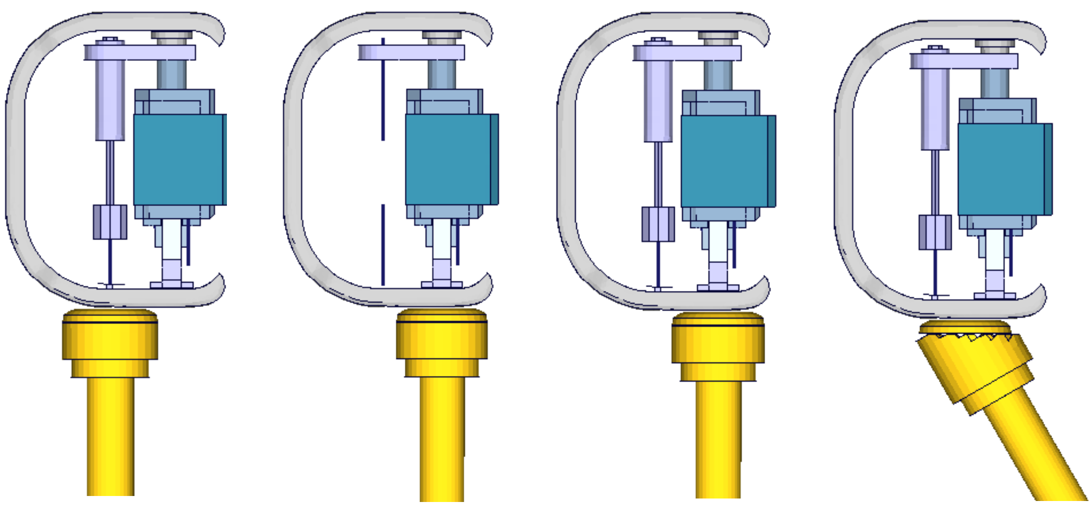

Figure 5: ES-2 rib component test configurations.

A correlation with one test series for the target point on the bearing system is shown in Figure 6. In this test different pendulum velocities are defined such that the maximum deflection is 10, 20, 30, 40 and 50 mm.

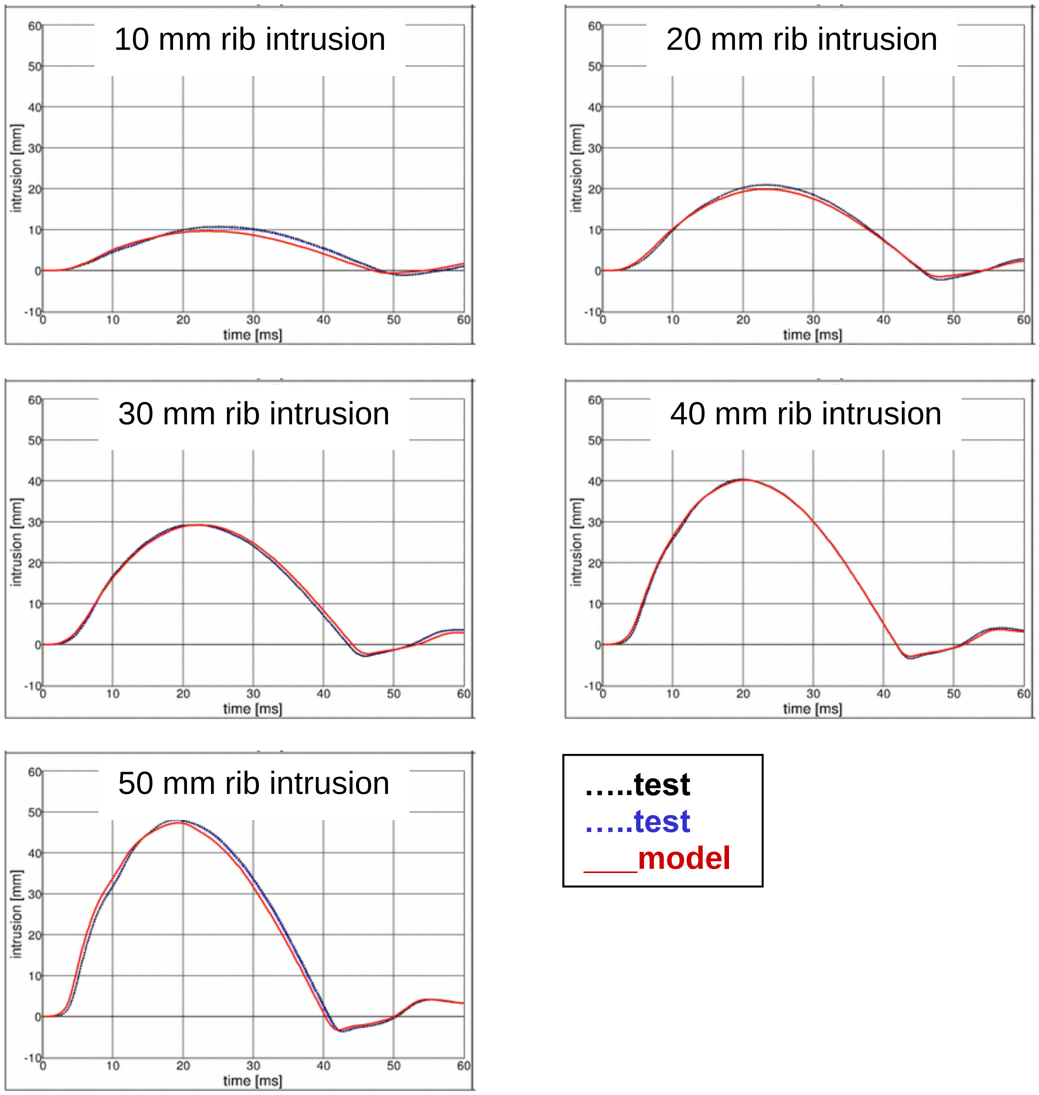

Figure 6: Rib deflection results of ES-2 for different pendulum speeds.

Example WorldSID 50% rib assembly component test:
The rib component tests for the WorldSID are done in a similar way with the completely assembled rib and with sub-sets of one rib. Since the WorldSID has four different rib designs and more oblique tests were considered the test matrix is much bigger than for the ES-2. Figure 7 depicts the spine box with the assembled third thorax rib as it is used in the pendulum test. Also the different pendulum impact angles are shown.

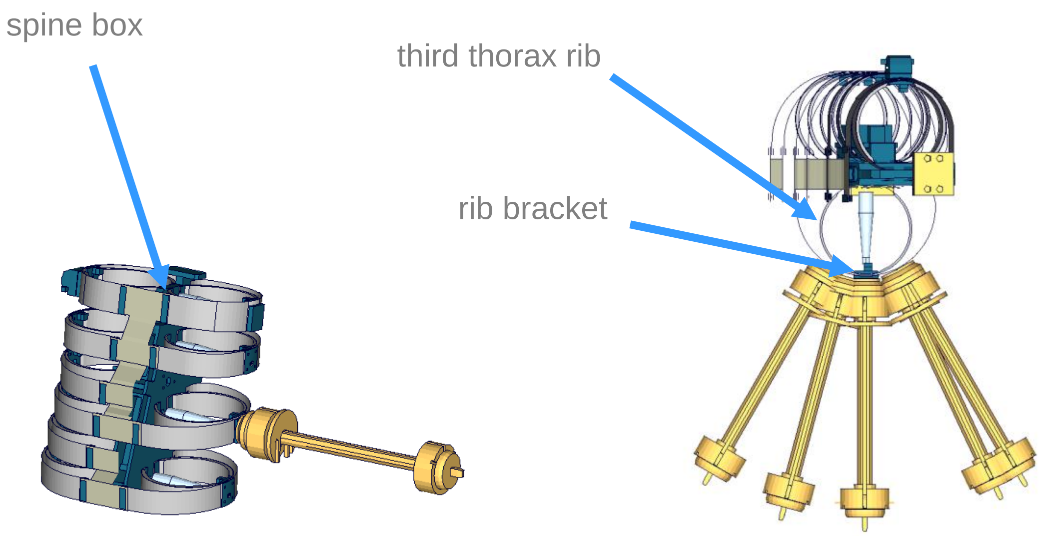

Figure 7: WorldSID 50% rib design and various pendulum angles.

In Figure 8 the results of the 90 degrees rib test for two different velocities are shown.

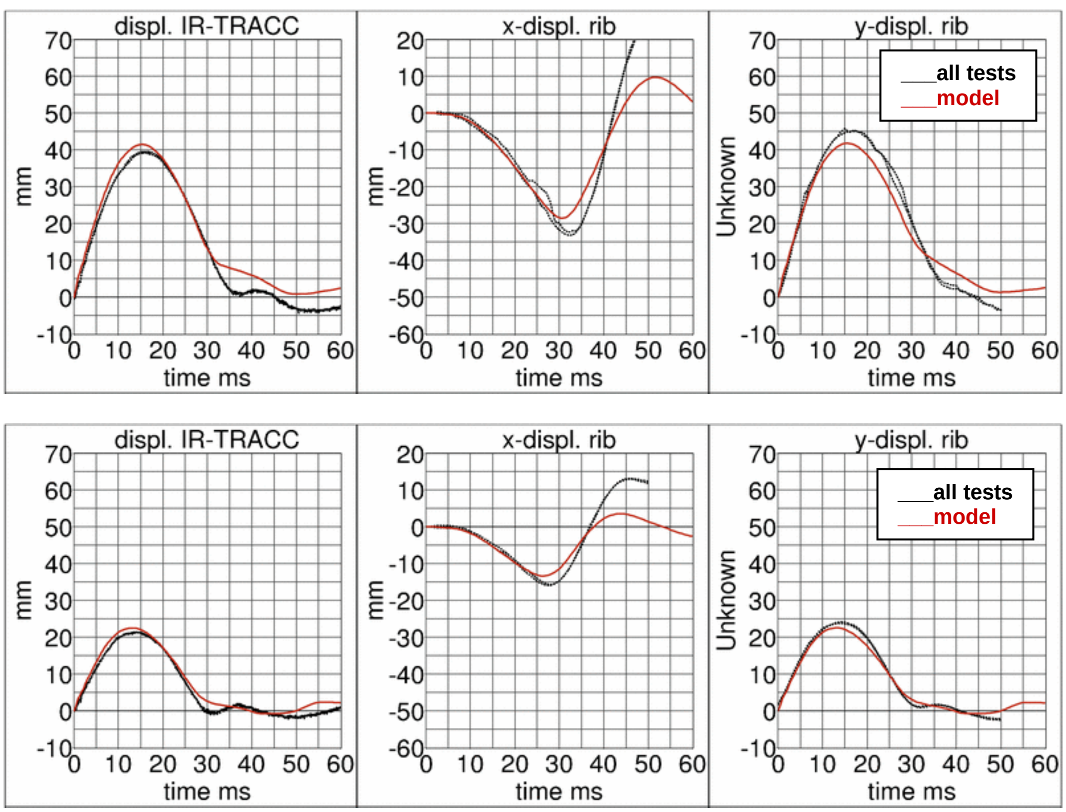

Figure 8: Third thorax rib component test of WorldSID 50%.

Top: Low velocity; Bottom: High velocity.

Fully Assembled Dummy Tests

Even if the component tests are indispensable for the validation, they are not sufficient to build a predictive model. Tests on the fully assembled dummy are needed since they include the interaction of parts, which determines the dummy behavior significantly. Two different test set-ups are used. In one set-up local impacts usually with pendulums are used to load specific body regions. In the second type of test set-ups shaped barriers are used to impact the dummy comparable to a load in a vehicle.

Pendulum Tests:

Pendulum tests are affordable and have boundary and loading conditions that can be modeled accurately. A disadvantage is that the load levels and the characteristics of a pendulum test differ from loads in a car crash. The pendulum load is very local and the impact energy is low.

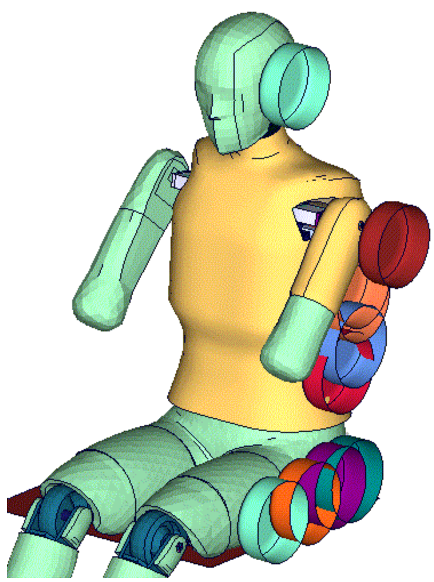

Figure 9: ES-2 pendulum test target points.

Figure 9 depicts the huge number of impact locations used for the ES-2 model development. In later projects the figure was reduced since the small variations in the impact location did not provide the expected width of the validation domain. The results for close-by impact points were too similar. As consequence the number of pendulum tests was reduced for the WorldSID 50% model development, as shown in Figure 10.

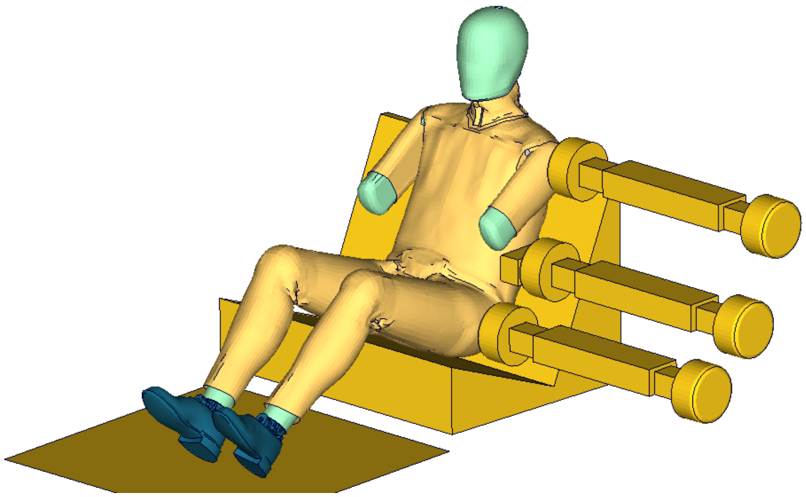

Figure 10: WorldSID 50% pendulum test target points.

Figure 11 a pendulum test on the rib extension of the ES-2re is depicted. This test was used to validate the behavior of the rib extensions which are guided by a bearing system in the back of the dummy. The aim of this test was to load the rib cage comparable to the load that might occur due a contact with a shoulder of a back rest of a seat during side impact. The results of two different speeds of this test are depicted in Figure 12.

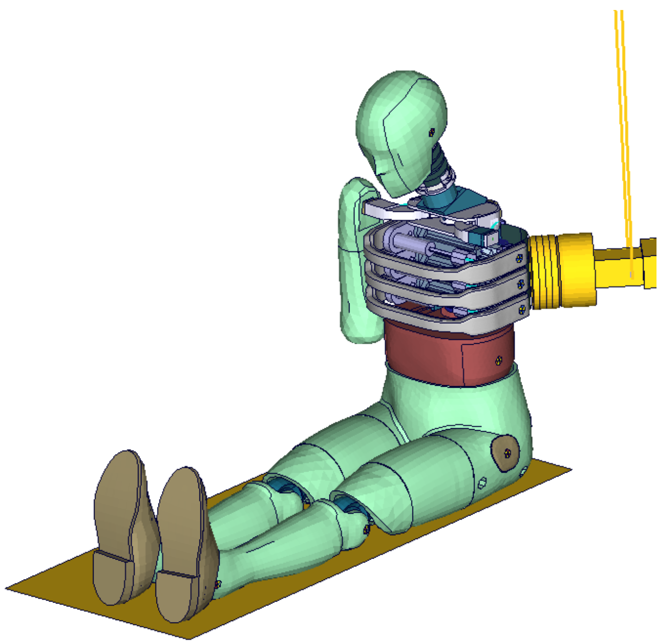

Figure 11: ES-2re additional pendulum test for rib extension validation.

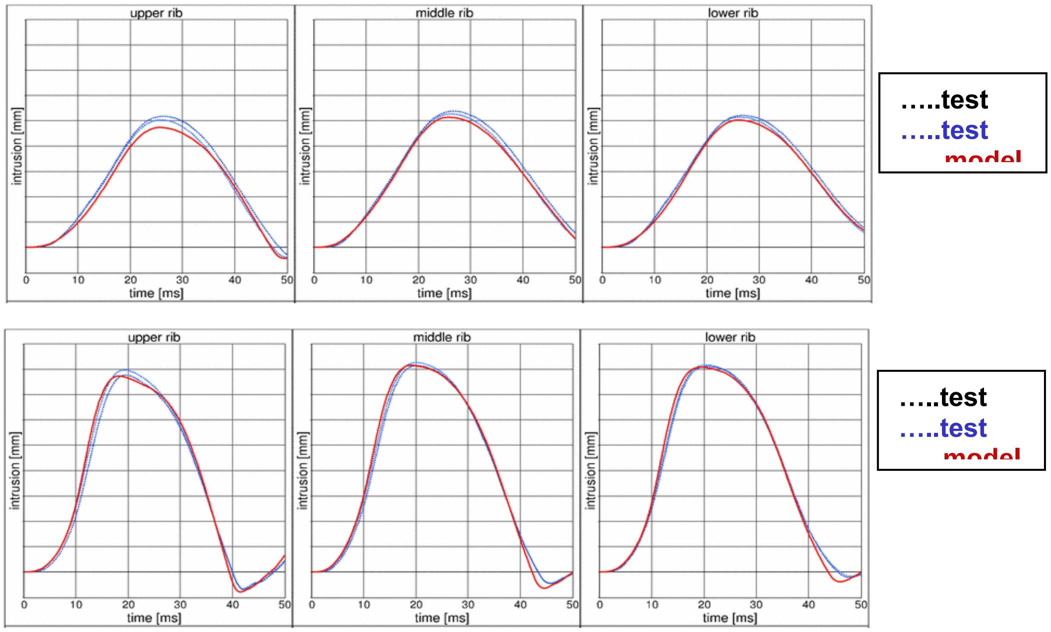

Figure 12: Results of ES-2re rib extension pendulum test.

Sled Tests:

Another type of tests for a fully assembled dummy are sled tests. In this test the seated dummy is impacted laterally by a shaped barrier. These tests give loads to the dummy which are much closer to the loadings in a vehicle load case.

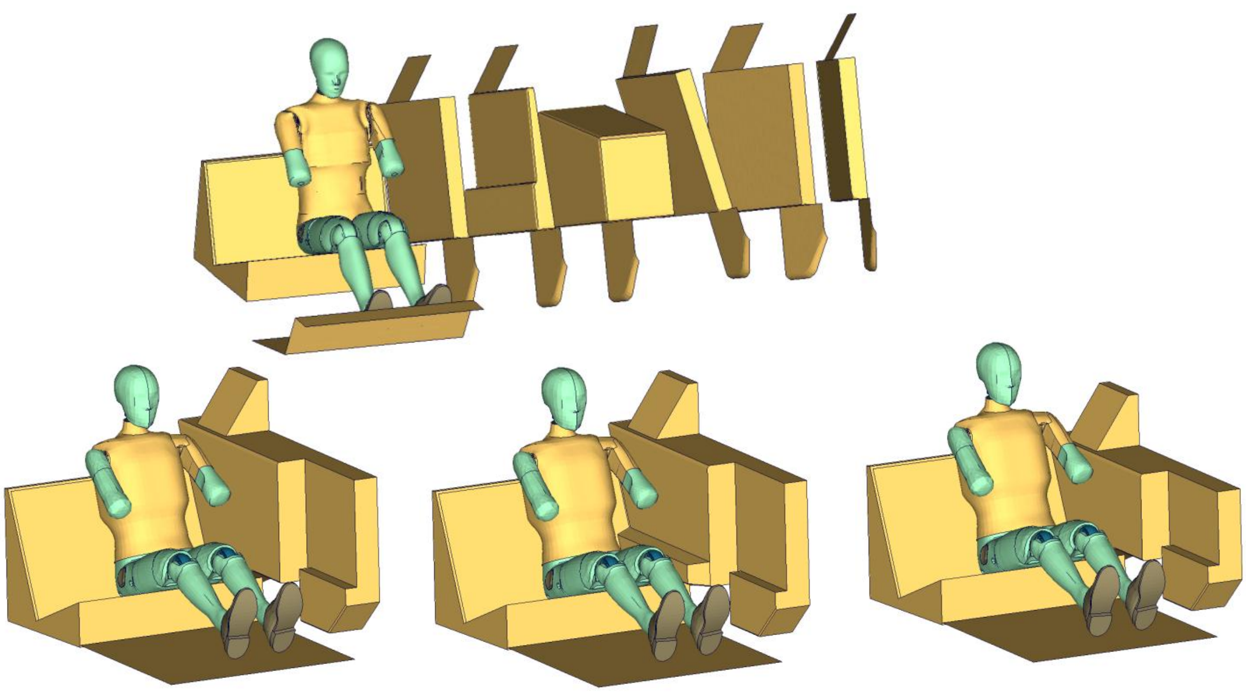

Figure 13: ES-2 / ES-2re validation sled tests.

The different shapes of the sleds are chosen to force kinematics of the dummy that can be observed in a vehicle load case. These tests are the most important validation load cases for the FAT and PDB dummy model development.

An example for different component behavior in the vehicle and in component tests is the lumbar spine of the ES-2. It is a rubber cylinder with steel disks at the top and bottom and a steel cable in the center of the rubber cylinder that connects the steel disks. Figure 14 depicts the deformation modes in a vehicle and Figure 15 depicts the deformation in a pendulum test used for the calibration of the lumbar spine.

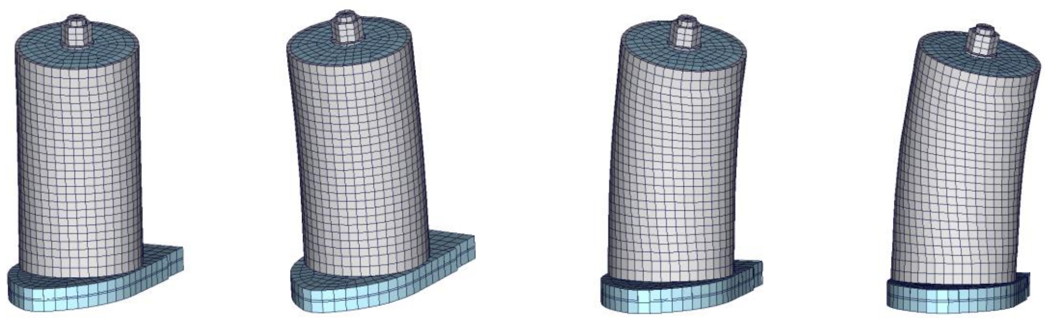

Figure 14: Deformation of lumbar spine during a vehicle side impact simulation.

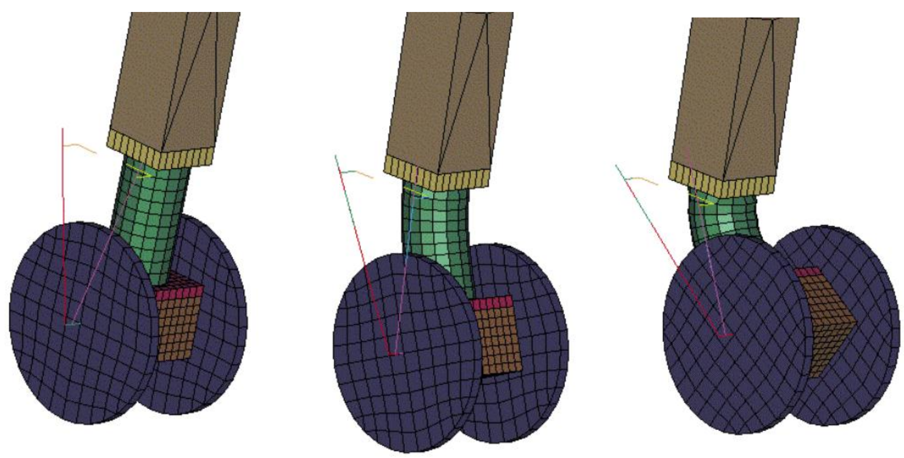

Figure 15: Deformation of lumbar spine (green) in calibration tests at different times.

In the vehicle the lumbar spine is loaded by a combined bending, torsion and shear load resulting in small elongations and angles. In the pendulum test the lumbar spine is tensioned and mainly bended with large angles. Obviously, the deformations don't have much in common and a model that behaves well in the pendulum test does not necessarily lead to a predictive dummy model. Many other parts of the dummy show similar difficulties for validation. Since the kinematics and the load level in a sled test is close to a vehicle crash this type of test is evident for a validation.

This example highlights also the importance of finding appropriate tests for the component validation. Usually, the calibration tests are not sufficient.

Validation Process

The validation process is a sequence of loops trough the above explained tests. It starts with a detailed mesh and a mass validation. In the next step the material tests are defined and the results are used to generate material cards. This leads to a first model, which can be used in a vehicle simulation to learn about the load levels and load characteristics. The model is then used to define appropriate boundary and initial conditions for a set of component and sled tests. With the test results the model can be enhanced. The new enhanced model can then be used again in vehicle simulations and the loop starts again. During each loop new test are defined and performed based on the gained knowledge where the model has to be enhanced. Defining and performing all tests in the beginning of a project is likely to lead to a weaker test database. This becomes even more obvious if we take into account that sometimes the hardware might not be totally finalized when a modeling project starts.

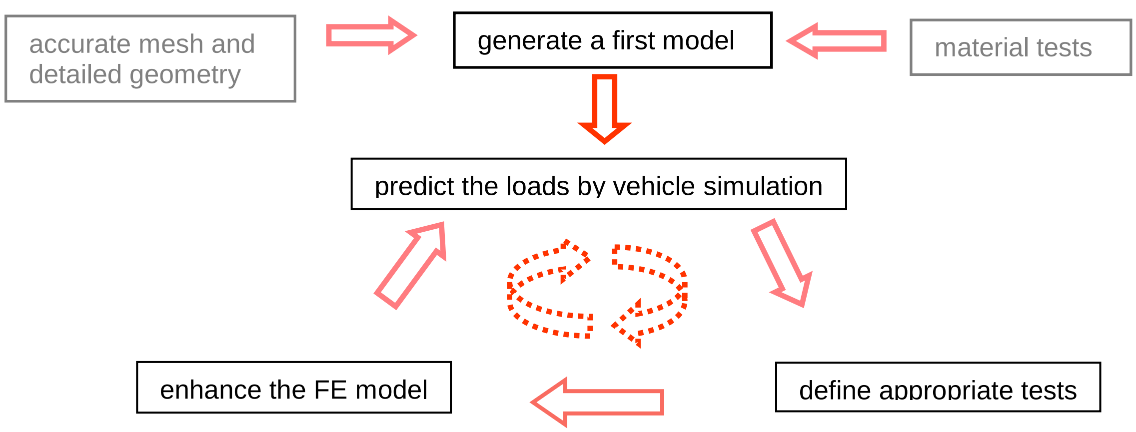

Figure 16: Validation process of FAT and PDB dummy models.

As example for a test in a later loop the lumbar spine tests of the ES-2 are showcased. To enhance the lumbar spine of the ES-2 which was mentioned in the previous chapter with loads closer to a vehicle three new component test were defined. The tests are depicted in Figure 17; they are defined to have separate bending, shear and torsional loads.

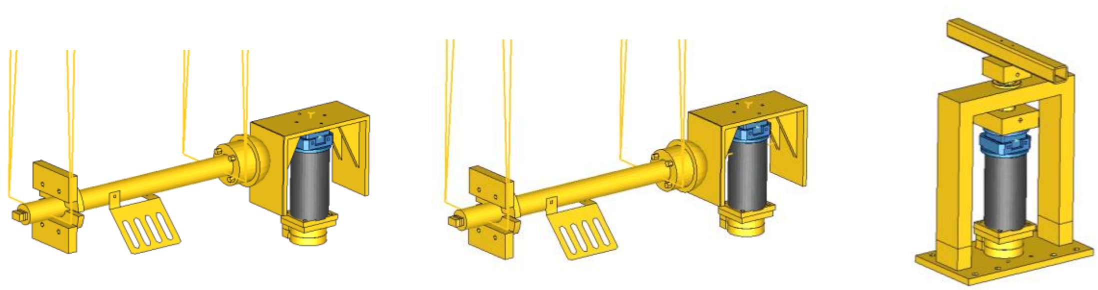

Figure 17: New component tests for ES-2 lumbar spine (left: bending; middle: shear; right: torsion).

The results of the ES-2 v4.5 and the ES-2 v5.0 for the medium velocity are depicted in the Figures 18-20.

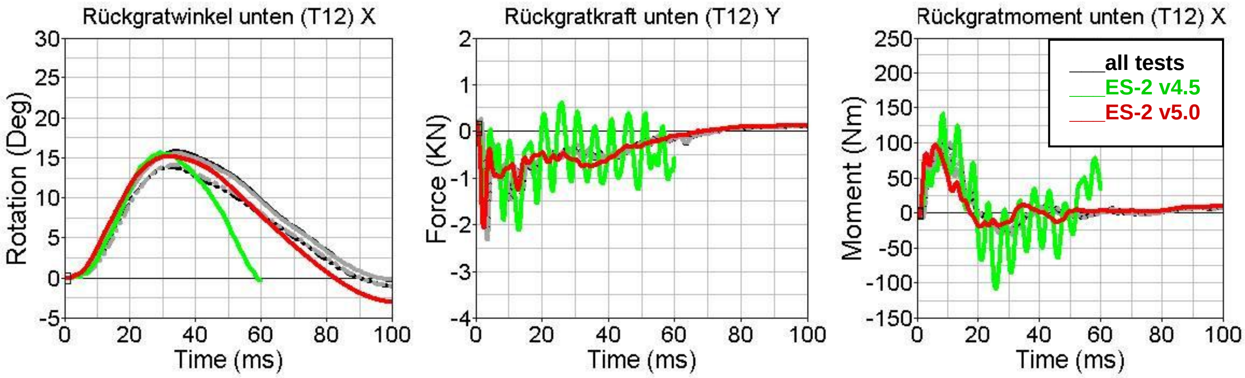

Figure 18: Lumbar spine bending test (left: T12 rotation; middle: T12 y-force; right: T12 x-moment).

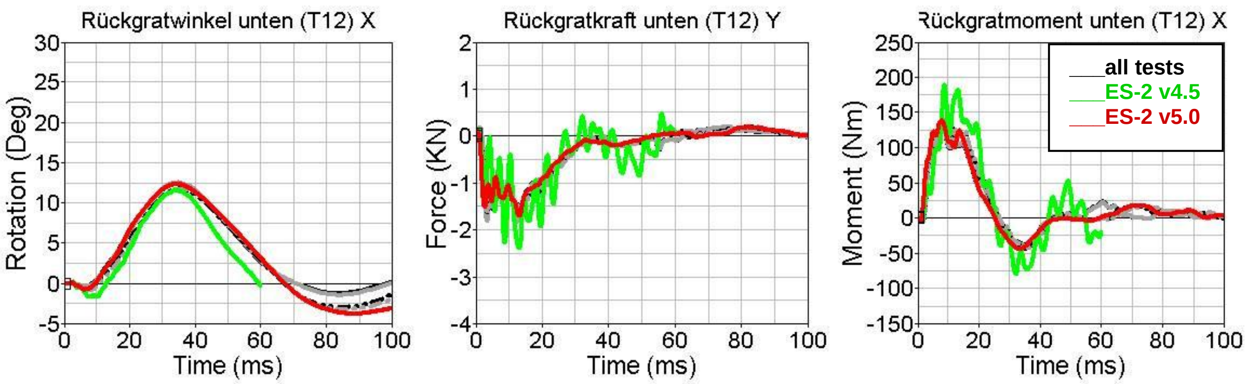

Figure 19: Lumbar spine shear test (left: T12 rotation; middle: T12 y-force; right: T12 x-moment).

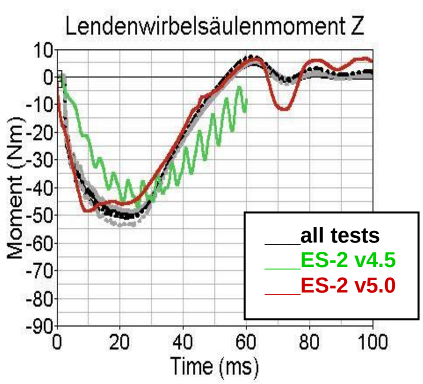

Figure 20: Lumbar spine torsion test (T12 Z-moment).

With the new tests it was possible to further enhance ES-2 model version 4.5. In the bending and shear load case especially the unloading performance is much better in the new model releases. For the torsional load case the loading and unloading characteristic is in the new models closer to the test. Furthermore, all signals of the ES-2 model version 4.5 are oscillating. This has been also improved for the ES-2 model version 5.0. These changes enhanced also the model performance in the sled tests.

Assessment of Model Validation Quality

Due to the huge number of test configurations it is difficult to judge if a modification in the model increases or decreases the model quality. Therefore, a tool that allows detecting changes in the results automatically is very helpful. As example for the vast test databases the tests for the WorldSID validation are shown in the tables below.

Component	Neck	Arm		Ribs		Lumbar Spine	Iliac wings	
Configuration		Notch 1	Notch 2	Inner band	Complete assembly		half	full
Type	Sled	Pendulum	Pendulum	Pendulum	Pendulum	Sled	Pendulum	Pendulum
Loads (velo x mass)	2	2x1	2x1	3x2	3x2	2	2x2	2x2
Load directions	2	1	1	3	5	2	1	1
Impact points	1	3	2	1	1	1	2	1
Specimen	2	1	1	3+2	4	2	1	1
Individual tests	8	6	4	90	120	6	8	4
Reruns	2	2	2	2	2	2	2	2
Total tests	16	12	8	180	240	12	16	8

Table 2: Test matrix of component tests for WorldSID 50% model development.

Full Dummy Tests	Pendulum	Sled		
Configuration	Full dummy	Full dummy	Full dummy without arm	Full dummy without jacket
Target point / sled shape	5	3	1	1
velocities	1	2	1	1
Individual tests	5	5	2	2
Reruns	4	2	2	2
Total tests	20	10	4	4

Table 3: Test matrix of pendulum and sled tests for WorldSID 50% model development.

Including the material tests approximately 400 different tests were performed for the WorldSID 50% model development. 260 of the tests have to be simulated and validated. The majority of tests are on the component level.

If one part is modified, all load cases where this part is included must be checked regarding the new model performance. As example we outline how a design change of the World-SID 50% impacted the development. During the project the geometry of the damping material that is bonded to the ribs was changed. Moreover, the material data for the damping material was enhanced. This change had an influence on 12 fully assembled dummy tests and also on 210 different rib component tests.

Obviously, an automated process to evaluate the influence of such a change facilitates the work significantly. The automation requires a modular model set-up, an automated assembly and assessment of the quality.

For the assessment of the quality the tool CORA, which has been developed by the PDB, is used. CORA is using two different methods to evaluate simulation results. The first one is a corridor method, where the deviation is calculated between curves using an enveloping corridor. The second method is a cross correlation method where specific curve characteristics like a phase shift or a different shape of the signals are detected. The rating results range from 0 (no correlation) to 1 (perfect match). The method requires a certain set of parameters like corridor width and weighting factors to map the quality to the [0,1] interval. More information about CORA can be found in [1] and [3].

In the following CORA is used to assess the above explained change of the rib damping material. The first version of the WorldSID 50% model was based on an early design, which was modified later. Additionally, the damping material was changed from a “gray” damping material to a “blue” one. In the model the geometry was adapted to the new design and the material properties were changed according to a new set of material tests. Figure 21 depicts the different designs.

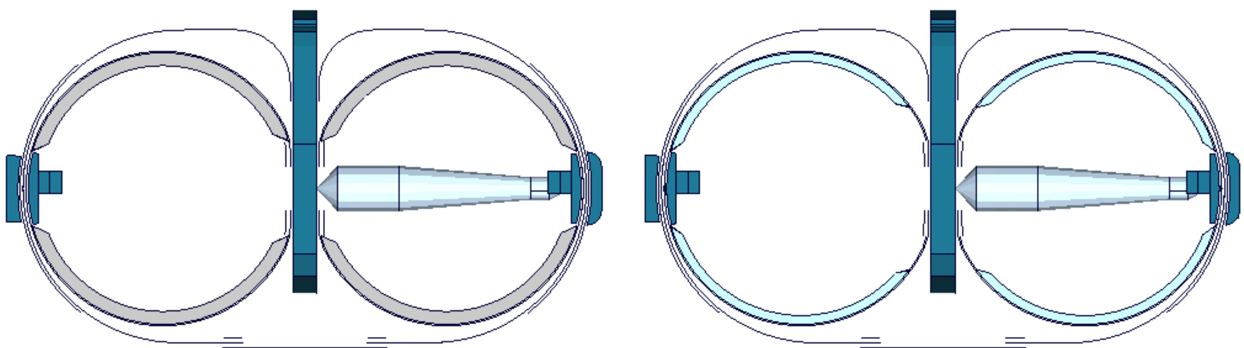

Figure 21: WorldSID 50% shoulder rib; comparison of old “gray” damping material (left) and new “blue” damping material (right).

The first release was based on a first set of selected tests. All rib component tests where done with the new “blue” damping material, but the first validations were done using the old “gray” damping material geometry and material data. After the change of the geometry and material, it must be assessed that the correlation of the new model (included in v2.0 of WorldSID 50%) is not getting worse than the old one. For the comparison the CORA tool was used.

Figure 22 depicts the different ribs tested in the pendulum tests. The different angles used for the impact are depicted in Figure 8.

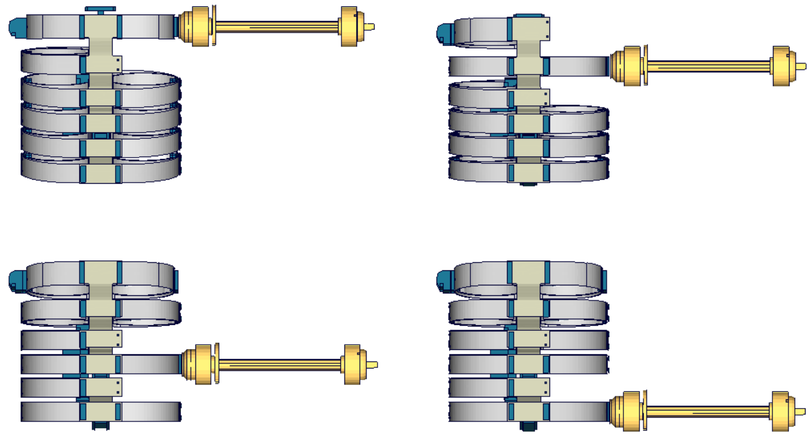

Figure 22: Different lateral impact locations of WorldSID 50% ribs. Top left: shoulder rib, top right1st thorax rib, bottom left: 3rd thorax rib, bottom right: 2nd abdomen rib.

In the following tables CORA is used to compare the simulation results for the models with the different rib damping materials. In the right column the difference of the ratings is calculated. If the difference is larger than 4 percentage points, the number is printed in green if the new model correlates better and in red if the old model correlates better. In case the difference is lower than 4 percentage points the results are considered to be of the same quality and the figure is printed in black.

Load Case	old gray damping material	new blue damping material	difference
90 deg shoulder rib inner band	0.912	0.958	**0.046**
90 deg third thorax rib inner band	0.910	0.914	0.004
90 deg second abdomen rib inner band	0.881	0.946	**0.065**
75 deg shoulder rib inner band	0.723	0.710	-0.013
75 deg third thorax rib inner band	0.669	0.706	0.037
75 deg second abdomen rib inner band	0.756	0.708	**-0.048**
60 deg shoulder rib inner band	0.790	0.810	0.020
60 deg third thorax rib inner band	0.859	0.798	**-0.061**
60 deg second abdomen rib inner band	0.777	0.826	**0.049**
TOTAL RATING inner band	**0.809**	**0.820**	**0.011**

Table 4: CORA results WorldSID 50% component tests on inner rib bands.

Load Case	old gray damping material	new blue damping material	difference
90 deg shoulder rib complete	0.857	0.910	**0.053**
90 deg fist thorax rib complete	0.861	0.863	0.002
90 deg third thorax rib complete	0.874	0.842	-0.032
90 deg second abdomen rib complete	0.903	0.935	0.032
60 deg shoulder rib complete	0.756	0.651	**-0.105**
60 deg fist thorax rib complete	0.751	0.749	-0.002
60 deg third thorax rib complete	0.741	0.736	-0.005
60 deg second abdomen rib complete	0.784	0.758	-0.026
75 deg shoulder rib complete	0.701	0.654	**-0.047**
75 deg fist thorax rib complete	0.757	0.754	-0.003
75 deg third thorax rib complete	0.678	0.692	0.014
75 deg second abdomen rib complete	0.709	0.697	-0.012
115 deg shoulder rib complete	0.788	0.714	**-0.074**
115 deg fist thorax rib complete	0.797	0.770	-0.027
115 deg third thorax rib complete	0.698	0.756	**0.058**
115 deg second abdomen rib complete	0.710	0.835	**0.125**
120 deg shoulder rib complete	0.602	0.572	-0.030
120 deg fist thorax rib complete	0.743	0.747	0.004
120 deg third thorax rib complete	0.723	0.735	0.012
120 deg second abdomen rib complete	0.741	0.757	0.016
TOTAL RATING complete ribs	**0.759**	**0.756**	**-0.003**
TOTAL RATING	**0.774**	**0.776**	**0.002**

Table 5: CORA results WorldSID 50% component tests on completely assembled rib.

The first impression from the rating is that the two models behave similarly in the rib component tests. The new model (included in WorldSID 50% v2.0) provides the right damping material geometry and more accurate material properties, with the same quality as the old one.

Nevertheless, the table shows some differences of the models. In all 90 degree pendulum tests the new model performs better. For some oblique pendulum tests it is the other way around. This could be explained by the fact that results of the oblique tests are very sensitive on the impact angle and impact location. Such observations could lead for instance to a new set of tests with an even more accurate measurement of the pendulum movement.

The rating tool is also used to compare official model releases. For this purpose a large test database should be available to generate meaningful results. In the following different versions of the ES-2 model are compared. The releases are v2.0, v4.5 and the latest version of the ES-2 v5.0.

ES-2 v2.0:
This version was released in spring 2004. The model was derived from the FAT EuroSID-1 model. For validation material tests for foam and vinyl materials are used and mainly full assembled tests like pendulum and sled tests. The focus was on a good overall performance.

ES-2 v4.5:
This version was released in summer 2009. The test database was not increased significantly compared to v2.0. Most work was on model refining by using the available test database and customer feedback. Some small component tests are used to improve the model. Also the robustness was increased a lot.

ES-v5.0:
The version was released in spring 2011. The version was initiated by the PDB in 2009. The model was re-meshed in nearly all body regions and validated for the new test related to the new FMVSS 214 regulation. The geometry is updated and more detailed material tests are used for foams, rubbers and plastics.

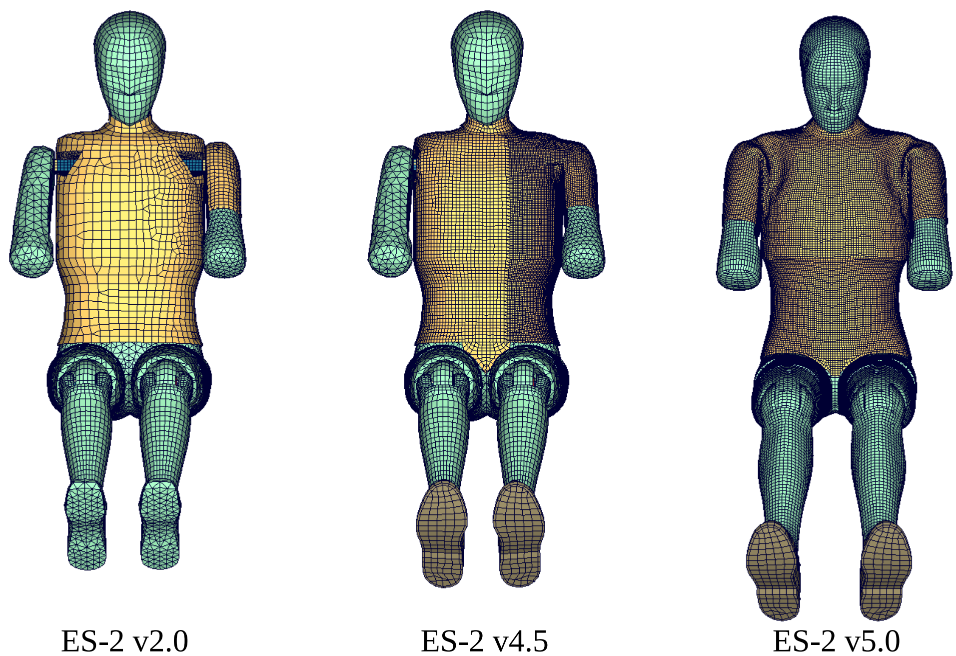

Figure 23: Different ES-2 releases for CORA evaluation.

The CORA study was done using a sub-set of component, certification and sled tests. Each of the component and sled tests with different velocities. A more detailed description of the load cases is presented in [5]. The results of the study are summarized in the following tables. The release with the best rating number is marked green, and the worst release is marked red.

	R2.0	R4.5	R5.0
Clavicle	0.551	0.594	0.776
Abdomen	0.690	0.714	0.750
Lumbar spine	0.675	0.562	0.731

Table 6: CORA results of various ES-2 component tests.

	R2.0	R4.5	R5.0
Shoulder certification	0.562	0.645	0.825
Thorax certification	0.841	0.919	0.911
Abdomen certification	0.532	0.576	0.774
Lumbar spine certifi.	0.394	0.397	0.568
Pelvis certification	0.748	0.625	0.785

Table 7: CORA results of ES-2 certification tests.

	R2.0	R4.5	R5.0
PDB sled tests	0.390	0.579	0.666
FAT sled tests	0.552	0.592	0.668

Table 8: CORA results of various ES-2 sled tests.

The Tables 6, 7, and 8 depict the results of CORA for a huge number of tests. It easily allows comparing between different model versions. It shows that the model was improved constantly. There is only one load case where a later model version is less predictive than an earlier one, but for this set of tests the assessment is very good, also for the new release.

Such an evaluation can also help users to assess in which body regions the correlation is improved. However, comparing the rating figures between different tests is not recommended since the magnitude of each figure depends strongly on the corridor width and the weighting factors. Thus, the rating tool does not entirely substitute the comparison of the time history plots. If a rating tool is used to compare models from different developers it requires that the tests and assessment parameters are exactly the same. Otherwise, the comparison is meaningless.

Conclusion

The FAT and PDB dummy models are detailed and accurate FE-Models for LS-DYNA. Their validation is based on a vast test database. The tests enclose material, component, pendulum, and sled tests. All tests are defined such that the load level is close to different car crashes occurring in small and large vehicles.

The validation process is a step-wise refinement of the tests and the model. These steps are performed in loops where the currently available model is used to define the next set of tests. Subsequently, the new tests are used to update the model.

The huge number of tests requires a certain level of automation for the model set-up and the assessment of the simulations. The usage of a rating tool increases the effectiveness and reliability of the development process significantly.

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