# DEVELOPMENT OF A COMPUTATIONAL MODEL OF THE WORLDSID 50$^{TH}$ MALE

**Christian Gehre**
PDB – Partnership for Dummy Technology and Biomechanics
Germany

**Ebru Taylak**
**Victor Oancea**
Dassault Systèmes Simulia Corp.
United States

**Sebastian Stahlschmidt**
**Alexander Gromer**
DYNAmore GmbH
Germany

**André Berger**
**Charles Thibaud**
ESI Group
Germany

Paper Number 09-0411

## ABSTRACT

Today the numerical simulation is an inherent process of the development of the passive safety of vehicles. So it is understood that every state of the art dummy has a virtual counterpart. Based on the positive experiences of the development of high quality dummy models within FAT working groups, German automobile manufacturers, represented by PDB, and the software vendors Dassault Systèmes SIMULIA, DYNAmore and ESI Group decided to develop a high quality WorldSID 50$^{th}$ FE model. It will be available for Abaqus, LS-DYNA and PAM-CRASH.

The WorldSID programme was initiated to develop an advanced worldwide accepted dummy of improved biofidelity to access the injury risk to occupants in side impacts.

The finite element model of the WorldSID is based on the latest production version of the physical dummy. Its FE mesh was developed by using the technical drawings of the dummy and additional scans of dummy parts.

At first, it was necessary to identify the material properties of the dummy parts. An extensive test programme was started to obtain the required data. All materials were tested quasi-statically and dynamically. The material samples were taken from dummy parts and custom-built material plates.

The first release of the model includes the geometry and the material properties. It is used to design set-up and boundary conditions of component and sled tests to validate the components as well as the complete model. A large number of tests of different types of loading for neck, thorax, lumbar spine, pelvis and arm were conducted to obtain data for the validation process. The overall response and kinematics of the dummy is validated by using sled tests with different rigid barriers.

The final release of the model will be published in 2010. Pre-releases of the model will be available till then.

## INTRODUCTION

In November 1997 the WorldSID Task Group was formed under the led management of the ISO (International Organization for Standardization). The Task Group's aim was to develop a harmonised, technologically advanced side impact dummy with improved biofidelity to replace the variety of side impact dummies used in regulation and in consumer testing. The development of the WorldSID 50$^{th}$ under direction of ISO/TC22/SC12/WG5 was completed in March 2004 when the first production version was released [1].

After the completion of the WorldSID and due to the activities of the WorldSID Task Group to introduce the dummy in legislation, it is clear that there will be a need of a high quality finite element model of the WorldSID 50$^{th}$ in the future. Therefore, PDB, an association of five German car manufacturers, and the software vendors Dassault Systèmes SIMULIA, DYNAmore and ESI Group started the development of this model in autumn 2006. The methodology of the project is very similar to that of the German FAT dummy projects. FAT working groups developed the US-SID, EuroSID 1, ES-2/ES-2re and BioRID II dummy models. These models are

frequently used worldwide and proved their suitability in enhancing vehicle safety since many years.

## APPROACH

The development of the WorldSID FE model is primarily based on the requirements of future customers, represented by PDB.

All validation tests cover a wide range of expected loading conditions in vehicle environments. The validation based on the certification tests is only a very small part of the validation programme.

### Development plan

A four step development plan was introduced to the project. The dummy release 0 is the first result of the project. This model contains the FE mesh, correct masses and inertia, all joints and sensors. The materials are generic or derived from other dummy models. Release 0 is used for pre-studies to define component tests for the validation work.

The second step, dummy release 1, comprises all data of the material tests as well as roughly validated components.

The development of the model is almost completed after the third step, the release of version 2. All parts are validated on component and sled test level.

Finally, Version 3 is released after a period of 12 months of use and user feedback of version 2.

Interim versions of the model are also released. So a pre-version 1 was mainly used to define the validation tests of the components. This preliminary version used almost all results of the material tests and was roughly validated by using the certification tests.

Release 1 of the dummy model was completed in the 1st quarter of 2009 and the release of version 2 is expected by end of 2009.

### Definition of validation tests

The validation of the model by using tests with loading conditions close to vehicle environments requires a new approach of defining these tests. The idea is to identify the loading type of a component in vehicle environment, to isolate this loading and finally, to transfer it into a simple test set-up.

Figure 1 shows this process in principle. At first, the estimated load to a component in a vehicle crash and its load path is identified. Different set-ups of component tests that cover these loading conditions are discussed. The focus is not only on these needs, the simplicity of the set-up is also an important requirement. The repeatability of simple tests is typically higher than of more complex configurations. Simple and highly repeatable tests are usually more helpful to validate a component because the uncertainties in the tests are clearly limited.

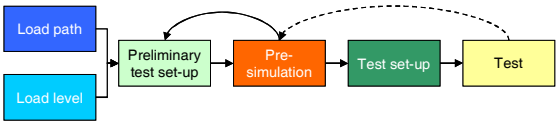


**Figure 1. Definition of component tests.**

Different proposals of set-ups are verified by using pre-simulations. Finally, the results of the first tests are compared with pre-simulation and estimations regarding load level and load path. The configuration and the boundary conditions are modified, if there is any problem or uncertainty.

This method is also applicable for material investigations and sled tests with the whole dummy.

In general, it is difficult to use a model that is under development to run pre-simulations to design validation tests for the same model. However, the requirements to the predictability of such models can be less restricting because simplifications and restrictions of the pre-simulation are considered. Iteration loops as shown in Figure 1 are common. Additionally, pre-simulations can also be conducted with other dummy models of a similar design.

## STRUCTURE OF THE MODEL

In a first step the mesh was generated based on CAD data, generated from the technical drawings of the WorldSID [2] and 3D scans of several parts.

**Figure 2. WorldSID FE model (LS-DYNA).**

The rubber and foam parts are mainly made of hexahedron elements. Solely the pelvic flesh is made of tetrahedron elements because of the very complex geometry. The WorldSID finite element model is shown in Figure 2.

The size of the finite elements of the dummy is set to ensure a time step of one microsecond. The current models are made of approximately 135,000 nodes and 200,000 elements. They are equipped with the same measurement devices as the physical dummy.

## VALIDATION TESTS

A significant effort was made to generate a comprehensive database on the static and dynamic material behaviour, and the dummy performance in component and whole dummy tests.

The validation starts on the material level with detailed analysis of the material properties. Component tests of the most important body segments are improving the level of validation. Finally, sled tests with the complete dummy are used to investigate the interactions of the components and to improve the quality of the model globally.

### Material Data

In total 26 materials were tested to obtain the required data to define the materials. The material samples (Figure 3) were directly cut from dummy parts, if possible. All rubber- and vinyl-like samples were taken from custom-built plates. Their characteristic was verified with samples taken from dummy parts.

**Figure 3. Material samples of the WorldSID.**

Depending on the type of material and the load they experience in a crash, static and dynamic tension and compression tests were conducted. The measured response curves can be directly implemented into typical foam and rubber material models.

Compression tests with constrained lateral expansion and free expansion were performed for the rubber-like materials. Lateral strains were not constrained and not considered.

All tests were conducted quasi-statically and dynamically. The strain rates range from 20/s up to 400/s. Cyclic compression and tension tests were additionally performed for rubber-like materials.

### Component Level

The implementation of valid material models ensures a certain level of validation. However, it is necessary to assure the validation with additional component tests of the most important dummy parts.

**Head** – The skin of the head was validated by using data of the head drop tests that are required for the certification of the WorldSID. The set-up of the frontal and lateral test is shown in Figure 4.

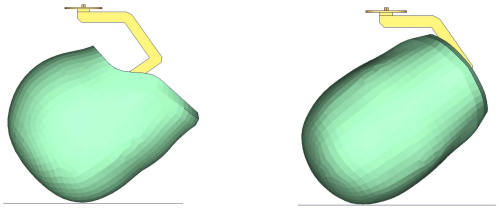

**Figure 4. Set-up of the frontal and lateral head drop test.**

**Neck** – At first, the neck was roughly validated by using results of the certification tests. As shown in Figure 5 the head has been replaced by a substitute. The pendulum is decelerated by a piece of honeycomb. As this test has to be conducted with every WorldSID periodically, the available data represents different specimen. So the scatter due to variances of the hardware is covered.

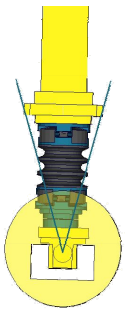

**Figure 5. Neck pendulum tests.**

The certification test does not cover the expected loading conditions of the neck in a vehicle environment. Therefore, a second test set-up was chosen to obtain data of lateral and oblique neck

bending modes. Two different necks were tested to consider the variance of the hardware.

As shown in Figure 6 head and neck were mounted on an accelerated sled. Two different crash pulses were used. The head hit the contact plate in the severe pulse only. A load cell measured head impact force.

The head was equipped with triaxial angular rate sensors.

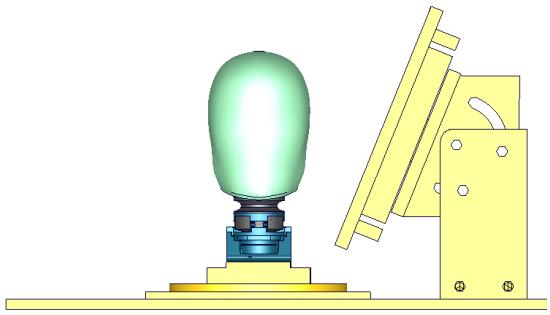

**Figure 6. Set-up of the neck sled tests.**

**Thorax** – The thorax is one of the most important body segments of a side impact dummy. Therefore, a special the focus of the validation was on the ribcage of the WorldSID. More than 400 pendulum tests at different impact velocities, impact angles and with different pendulum masses were conducted. Figure 7 shows the set-up of the test of the third inner thorax rib exemplarily.

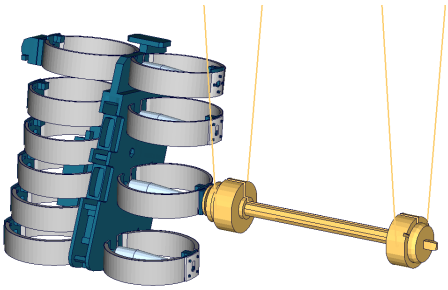

**Figure 7. Set-up of the pendulum test with the 3rd inner thorax rib.**

At first, the inner ribs were tested to get data for the validation of the rib steel (Nitinol). The blue damping material was scraped from the ribs to obtain the pure response of the steel.

Afterwards, the inner ribs were tested with damping material. The properties of the damping material were adjusted to get the right rib responses. The properties of Nitinol remained unchanged because the material was already adjusted in the first step of the validation.

After the validation of the inner ribs, the ribcage had to be validated for both, inner and outer rib. Pendulum tests (Figure 8) with different boundary conditions were used to obtain the required data. As all material parameters of the ribs are defined and validated in the tests with the inner ribs, the parameters to tune the model to these tests are limited. However, if the material models of Nitinol and blue rib damping material are defined correctly, the responses of the simulations with the whole ribs should correlate well with the tests.

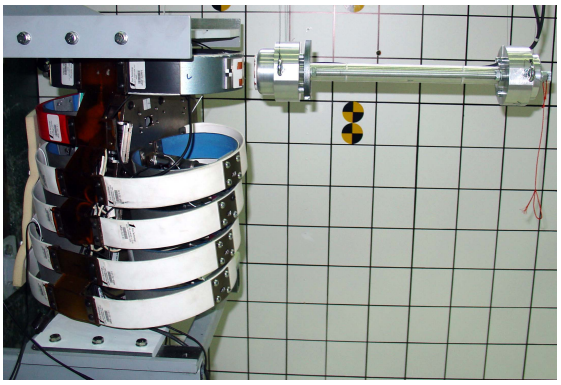

**Figure 8. Set-up of pendulum tests with the complete shoulder rib.**

The variance of the ribs was not analysed explicitly because most of the ribs had to be replaced during the extensive tests. Hence, the scatter of the hardware is included indirectly in the data set.

The data of the certification tests with the assembled dummy were also used to support the validation process. However, there was no focus on these kinds of data.

**Lumbar Spine** – The set-up of the lumbar spine tests is very similar to that of the neck sled tests. Two lumbar spines were mounted on an accelerated sled. The crash pulse as well as the mounting angle of the dummy parts was varied.

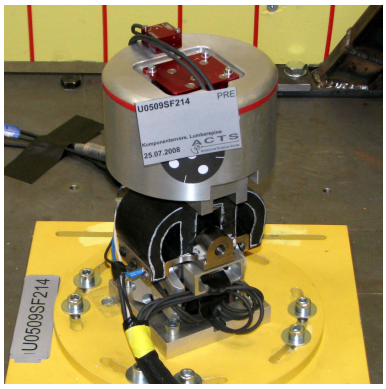


**Figure 9. Set-up of the lumbar spine tests.**

A replacement of the upper torso is mounted on top of the lumbar spine rubber. Accelerometers and angular rate sensors are directly embedded into this part. The geometry of the mass replacement was defined by using pre-simulations.

The focus was on realistic kinematics and on the right ratio of bending and shear of the spine rubber. High-speed videos of WorldSID crashes were taken as benchmark.

After the run of the pre-tests, the test set-up had to be modified. Mass and centre of gravity of the thorax replacement was tuned to improve the test results.

The lumbar spine is indirectly tested in the certification tests. Figure 10 show exemplarily one of the pendulum tests with the dummy. Due to the long load path and the large number of involved dummy parts, the relevance of these certification tests on the validation of the lumbar spine rubber is limited. However, some of the certification tests were also used to improve the performance of the lumbar spine.

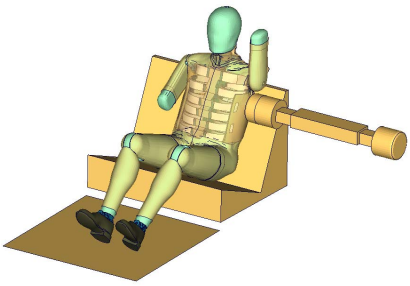

**Figure 10. Certification test of the WorldSID.**

**Iliac Wings** – Pendulum tests were used to obtain data for the validation of the bony pelvis. Main design parameter of the tests was the pubic force. It should be very close to the expectations in vehicle crashes. Two different set-ups with different impact locations and velocities were defined.

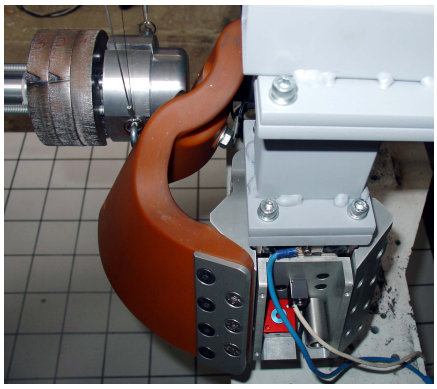

**Figure 11. Set-up of the iliac wing pendulum tests.**

At first, the half pelvis was tested. This set-up helped to validate the pubic buffer and the iliac wing. The complete pelvis was tested afterwards. These tests were conducted to investigate the interaction between left and right iliac wing and the influence of the soft pubic buffer on the pelvis kinematics.

All test configurations and its boundary conditions were defined by using pre-simulations.

**Arm** – Pendulum tests were used to validate the stiffness of the arm joint and to improve the material models of the foam and the plastic bone of the arm. Impact location and impact velocity were varied in the tests. Figure 12 shows one of the test configurations exemplarily.

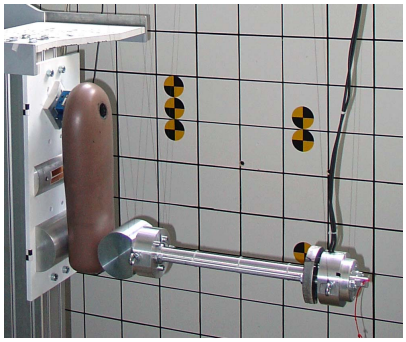

**Figure 12. Set-up of the arm pendulum tests.**

**Sled Tests**

The defined sled tests imparts loads on the dummy, which are similar to loads in the vehicle. The boundary conditions of these tests are well known and precisely described. That ensures a clearly higher level of repeatability of test results than tests with vehicles.

In general, sled tests are very important for the validation of a dummy model. Firstly, they are required to check the interactions of the validated sub-components and secondly, they cover typical loading conditions including similar kinematics of the dummy in vehicle tests.

Two different kinds of sled tests are defined. The first series with flat barrier faces can be compared to the barrier tests conducted within the EuroSID 1 and ES-2/ES-2re test programme [3].

The second test programme uses more sophisticated barriers. The curved front is derived from typical deformation patterns of vehicles in oblique pole tests.

The posture of the dummy was measured with a 3D measurement system prior every tests. So it is possible to reproduce it in the simulations exactly.

**Flat Barrier** – The test with the flat barriers were conducted at two different impact velocities. They represent severe and mid severe loading conditions. Target parameter for the definition of the velocity was the maximum deflection of the ribs and pubic force.

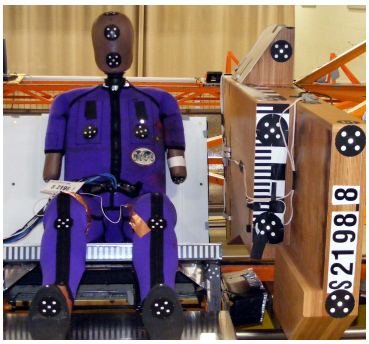


**Figure 13. Set-up of the sled test with flat barrier.**

Figure 13 shows the set-up of the test with the flat barrier. The main load is applied to the dummy through the shoulder. The lateral head excursion is limited by a contact plate to avoid damages of the neck or the sensors mounted in the head.

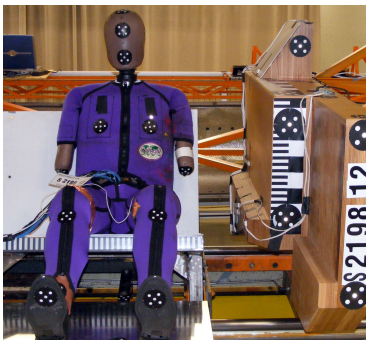

**Figure 14. Set-up of the sled test with pelvis pusher.**

The second set-up with the flat barrier is shown in Figure 14. Compared to the first configuration, the load is mainly applied through pelvis and shoulder to the dummy.

**Curved Barrier** – The tests with the flat barriers represents purely lateral crashes. There is almost no rotation of the upper torso. So it was decided to create a new kind of rigid barrier that induces upper torso rotation. The 75° degree pole test was taken as starting point of the development of this barrier face.

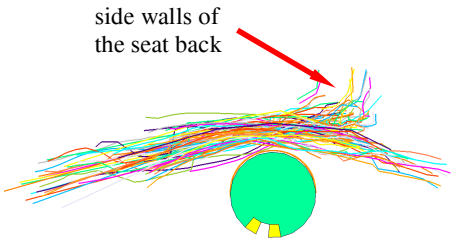


**Figure 15. Intrusion profiles of different cars.**

At first, the intrusion of several cars was analysed. Figure 15 shows feature lines of the door trim and the back of the seat at a certain time of a pole crash. Based on this information a new barrier face was defined. Pre-simulations were run with the ES-2 dummy model finalise the geometry. A draft of the new barrier is shown in Figure 16. The final version will be equipped with an arm rest. The impact velocities are not defined yet but will be similar to those of the tests with the flat barriers.

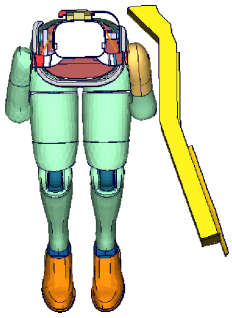

**Figure 16. Draft of the curved barrier face.**

## RESULTS

The validation of the dummy is not completed. Results of validation tests of some materials and body segments are shown exemplarily.

### Material Level

For some of the materials, the experimental data could be incorporated directly as input into the material models, for some others the data needed further calibration.

First step in the calibration process was to evaluate various material models to fit the quasi-static compression, tension and volumetric test data. Second step was to run material tests and come up with material parameters to predict the strain rate sensitive material behaviour. Figure 17 shows a simulation of a compression test exemplarily.

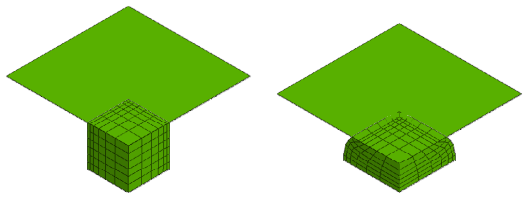

**Figure 17. Abaqus component model for compression testing.**

**Rubber Materials** – The results of the definition and validation of the WorldSID materials are exemplarily described for rubber materials of PAM-CRASH.

Rubber is usually modelled as incompressible visco-elastic material with viscous response. Material models of the Ogden family [4] do have these characteristics and are used for the World-SID model. All Ogden parameters are derived from the measured material properties such as uniaxial tension, compression and shear.

The accuracy of the generated material parameter was validated by simulating the material tests.

As mentioned above the material tests were conducted at different velocities. Parameters of the so-called Prony series have to be defined to cover viscous strain rate effects of the rubber.

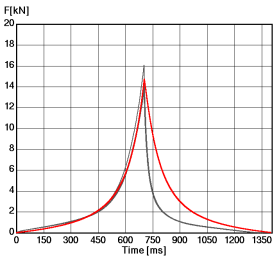


**Figure 18. Quasi-static loading of rubber in test (black) and simulation (red).**

Figure 18 shows a comparison of the test and simulation results of quasi-static compression. The deviances between both curves during the unloading phase have to be improved in a next step, if this behaviour is considered essential for the accuracy of the results of the global dummy model. Compared to that, the correlation of the signals in a dynamical load case is clearly better (Figure 19).

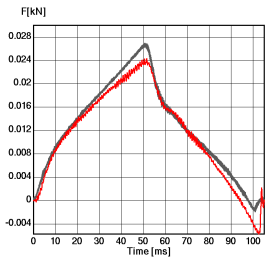


**Figure 19. Dynamical loading of rubber in test (black) and simulation (red).**

**Component Level**

The shown results of the validation are preliminary because the model is not completed yet. Beside the tuning of the material parameters the validation of the components includes also improvements of the modelling.

**Neck** – The neck component consists of moulded rubber neck, head, lower and upper neck brackets, neck buffers and neck interface plates. As shown in the previous section the neck assembly is attached on a sled and accelerated. The focus of the validation was on the right kinematics of head and neck and on the good correlation of lateral neck shear force $F_y$ and neck bending moment $M_x$.

The behaviour of the moulded rubber neck relative to the head on the top and the neck brackets at the bottom is determined by the half spherical screws and the neck buffers. The moulded neck and the buffer material models have been calibrated based on the quasi-static and dynamic material tests. The behaviour of the half spherical screws has been validated using the neck certification tests. Similarly, the head skin material was validated using the material tests and the head drop certification tests.

Comparisons between the experimental results (black) and the preliminary results from Abaqus simulations (red) of the oblique tests using the low severity pulse are shown below.

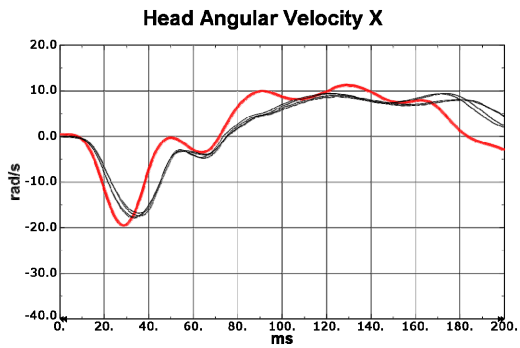


**Figure 20. Angular velocity of the head.**

The angular velocity of the head is a good indicator to evaluate the kinematics of the head by using responses curves. As the curves of Figure 20 indicate, the head of the model starts lightly earlier to rotate than the physical head. The upper neck torque confirms (Figure 21) these findings. However, the correlation between model and hardware is already acceptable.

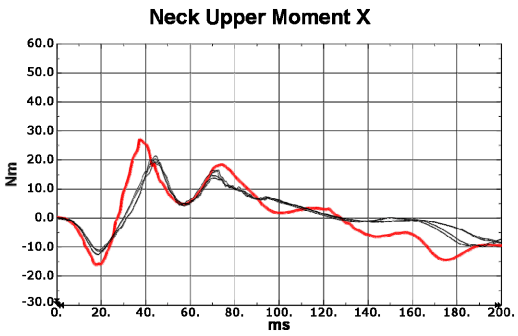


**Figure 21. Upper neck bending moment $M_x$.**

The performance of the neck is very similar in the other load cases. Nevertheless, the neck component validation is not completed yet. Studies to improve the neck kinematics are still ongoing.

**Thorax** –The WorldSID has one shoulder rib, three thorax ribs and two abdomen ribs which are designed in a similar way. The ribs consist of an inner and outer band made of Nitinol. This material is a memory shape alloy which undergoes a crystal transformation during deformation including high influence on the material stiffness. On the inner band of the ribs a damping material is used. The damping properties are similar to the rib damping material of the SID-IIs.

All curves shown in this section are taken from the LS-DYNA model.

In the first step, material tests are used to generate baseline material parameter sets for ribs and damping material. The responses curves of the tests with the material sample were directly implemented in the material models.

All ribs are modelled in the same way and use the same material models. The mesh fineness permits the modelling of different connection methods.

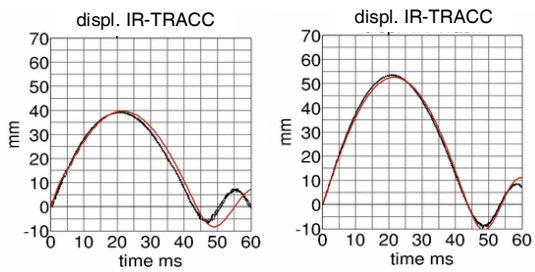


**Figure 22. Displacement of the 3rd thorax rib w/o damping material (different impact velocities).**

The Nitinol material was calibrated by using pendulum tests of the inner ribs without damping material. The connectors of rib and rib clamping bracket were validated in these tests too. Figure 22 shows the deflection of the 3rd thorax rib under different loading conditions. The responses of the LS-DYNA model (red) are shown exemplarily.

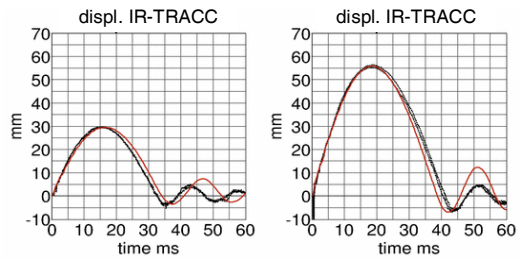


**Figure 23. Displacement of the 3rd thorax rib w/ damping material (different impact velocities).**

Afterwards, the blue damping material was validated by using pendulum tests of the complete inner ribs. Results of the third thorax rib with damping material at two different load levels are shown in Figure 23.

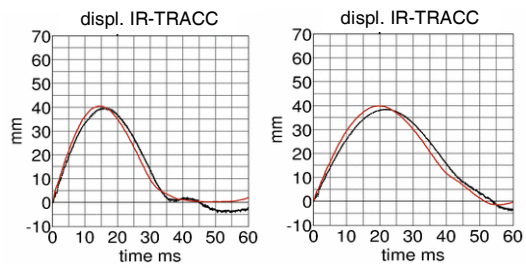


**Figure 24. Displacement of the complete 3rd thorax rib (different pendulum masses).**

Finally, the assembly of inner and outer ribs is validated by using pendulum tests of the almost fully assembled thorax. Solely the rib above and below the tested rib was disassembled to avoid contacts of the pendulum with those ribs. These tests are used to validate the whole rib assembly, including the sternum material and the connection method of the outer rib clamps. The tests are carried out using different velocities and different pendulum masses. Some results are shown in Figure 24.

The simulation results show good correlation to the test data. The level of validation, exemplarily shown for some responses of the 3rd thorax rib, is similar for all the other rib tests. Thus, the thorax validation is completed for the first releases of the WorldSID. The performance of the ribs might be improved after the simulation of the sled tests.

**Lumbar Spine** – The lumbar spine is a very important part of the WorldSID. Only its right implementation in the model ensures correct kinematics of the upper torso. Therefore, the lumbar spine sled tests have to cover a wide range of loading conditions.

The sled tests are mainly used to improve the Ogden and Prony parameters of the lumbar spine rubber. Especially the parameters for triaxial loading can only be defined with these tests because material tests with triaxial loading were not conducted. The interactions between the different parts involved in those tests needs to be considered in the validation process too.

Figure 25 shows the lateral shear force $F_y$ and the torque $M_x$ about the longitudinal axis of the dummy. Two different lumbar spines were tested (black curves) at the same time and their performance is clearly different. The PAM-CRASH model (red) correlates fairly well with one the specimen. The rubber of the other specimen seems to be different to that used in the material tests. However, in a next step the computational model will be tuned to correlate to the second lumbar spine. The final model will either match the first or the second lumbar spine. Averaging of the responses of the two specimens does not make sense in this special application.

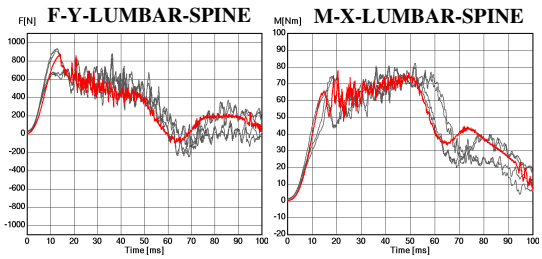


**Figure 25. Shear force and bending moment measured in the sacro-iliac load cell.**

Detailed analysis of tests and simulation indicates that pre-stress, which results from gravity loading, has to be considered in the model.

**Pelvis** – In order to validate the behaviour of the pelvic bones and the pubic buffer, tests were performed on the half pelvis and the full pelvis.

Two configurations were used to test the half pelvis. In the first configuration, the iliac wing was hit at a position in alignment with the pubic load cell. The accelerations measured on the impactor and the pubic load cell forces are used to calibrate the pubic buffer material. In the latter configuration, the iliac wing was hit at its outmost position. This test is used to validate the pelvic bone material. The iliac wing material will influence forces and moments measured at the sacro-iliac load cell, which is the interface between pelvis bone and the sacrum block.

The full pelvis was impacted only at its outmost position on one side. This is an ideal case to validate the interaction and the load path between the left and right iliac wing, as well as the influence of the pubic buffers on the overall pelvis kinematics.

Each component test was repeated for two different velocities, to help calibrate the rate sensitive behaviour of the iliac wing and the pubic buffer materials.

Preliminary results from the Abaqus simulations are shown in the plots below.

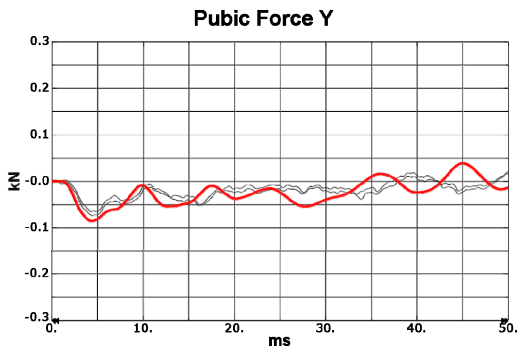


**Figure 26. Pubic force in the full pelvis test.**

The correlation of the pubic force $F_y$ in one of the tests using the full pelvis set-up is shown in Figure 26. The achieved level of correlation is acceptable.

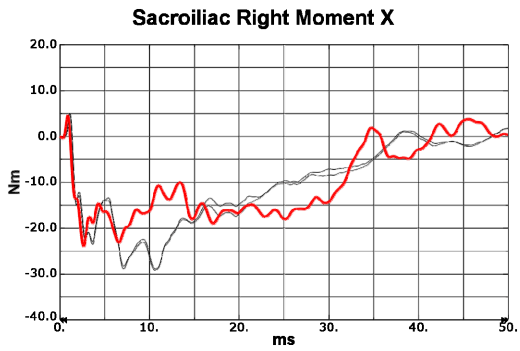


**Figure 27. Iliac wing torque at the sacro-iliac load cell (full pelvis test).**

Compared to that, the torque $M_x$ at the sacro-iliac load cell does not correlate well with the experiment in the same test (Figure 27). Peak and unloading phase of the signal deviate too much from the tests. More investigation is needed to identify the problem.

### Sled Tests

The validation of the model using the barrier tests is not completed yet. However, the first simulation runs with the flat barriers are very promising. So the amount of work to improve the level of validation of the sub-components is acceptable. New components tests are obviously not needed.

Figure 28 shows exemplarily one of the models used to define the boundary conditions of the sled tests. Initially, the arm position was defined as shown in Figure 28 (2nd notch). After the first pre-test the position was changed (Figure 14, 1st notch) because of the unrealistic rib deflection. While the shoulder rib was deformed up to the design maximum, there was almost no deflection at the thorax and abdomen ribs. This deformation pattern is not helpful for the validation of the model and does not correlate with the experiences with the WorldSID in vehicle environments. The arm covers the rib cage in the revised set-up. So the deformation of the ribs is more balanced now.

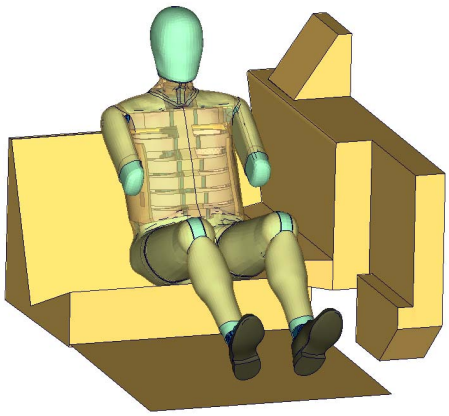

**Figure 28. Computational model of a sled test with the WorldSID.**

## LIMITATIONS

The current releases of the WorldSID are only validated by using material, component and dummy certification tests. So the individual components have a very good validation level for all codes. The validation of the interactions of all of these components is still in progress. It will be done by using the sled tests with the dummy as well as with dummy without jacket. So the performance of the model will be increased after completion of the validation using sled test data.

In general, the WorldSID is an unique and very new dummy. The experiences with this dummy is much lower than for others like ES-2 or ES-2re. Thus, it is possible that some behaviour appears in the future, that is not covered by the extensive validation databases of the WorldSID model.

## FURTHER DEVELOPMENT

The validation of the model will be completed by integration of the results of the sled tests with the flat barriers. Afterwards, the design of the curved barriers will be discussed and modified, if necessary. These tests should help to improve the models again.

## CONCLUSION

A group of car makers and software vendors developed high quality FE models of the WorldSID 50th dummy for the crash solvers Abaqus, LS-DYNA and PAM-CRASH. The models are based on the requirements of the automotive industry. All validation tests on material, component and sled test level are consequently based on experiences with the WorldSID and other side impact dummies in vehicle crashes.

The current models are validated on material and component level. The achieved quality is remarkable, especially as the results of the sled are not implemented yet.

The models of all three crash codes are at a very similar level. First releases are ready to use after implementation of the component and certification test data.

## REFERENCES


[1] Internet www.worldsid.org/news_and_releases_home_page.htm, WorldSID Production Design Completed, 2008-03-13.

[2] International Organization for Standardization; International Standard 15830; Road Vehicles; Design and performance specifications for the WorldSID 50th percentile male side-impact dummy; Geneva; 2005.

[3] Franz U., Schuster P., Schmid W.; FAT Side Impact Dummy models – Remarks on Usage and potential Pitfalls; 4th European LS-DYNA User Conference; Ulm; Germany; 2003.

[4] Virtual Performance Solution 2008; Explicit Solver Notes Manual; 2008.