15 Years of Finite Element Dummy Model Development within the German Association for Research on Automobile Technology (FAT)

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Abbreviations:

FAT: German Association for Research on Automobile Technology
PDB: Partnership for Dummy Technology and Biomechanics
SID: Side Impact Dummy

Keywords:
USSID, EUROSID, ES-2 ES-2re, FAT, FE Dummy Models

ABSTRACT

This paper describes a series of projects launched during the last 15 years to develop finite element dummy models. The activities are initiated and guided by a working group of the German Association for Research on Automobile Technology (FAT). The projects result in various finite element dummy models, which are frequently used world wide in the development of restraint systems. The products developed are side impact models of EUROSID-1, ES-2, ES-2re, USSID, and SIDHIII and a model of the rear impact dummy BioRID II. Currently, a model of the upcoming WorldSID 50% is under development. The paper focuses on models generated for LS-DYNA. During the time of development the methodology has been refined several times to achieve efficiently models fulfilling the high demands regarding predictability. The paper summarizes the adopted methods and gives an overview on the models and its continuous enhancements.

INTRODUCTION

The FAT is part of the German Association of the Automotive Industry (VDA). The VDA has members of automobile manufacturers and their development partners, the suppliers, and manufacturers of trailers, body superstructures and containers - in total more than 580 companies. The predecessor organization of the VDA was founded in January 1901. The FAT itself was founded in 1971 with the aim of joining topics of scientific research of the automotive industry. The FAT does not conduct this research itself but places orders with selected partners within the framework of joint industrial research.

Areas of research are safety, environment, materials/assembly procedures, transport efficiency, electronics and software and calculation methods.

Individual projects are defined, selected and backed up by the members of the specialist Working Groups (WGs). Currently, the following working groups exist:

- Automobiles and the environment
- Human drivers
- Accident research/biomechanics
- Dynamic axle loads and road stress
- Air-conditioning
- Aerodynamics
- Optimization of the road traffic system
- Torque conversion and transmission
- Driving dynamics of commercial vehicles
- Recycling
- Tire/road surface noise levels & adhesion coefficient
- Lightweight constructions
- Driving dynamics of passenger cars
- Passive safety in commercial vehicles
- Electro-magnetic compatibility
- Joint technology
- Vehicle interior emissions
- Finite element methods in vehicle design
- Simulation of mixed-signal systems using VHDL-AMS

- Electronics and simulations

The working group WG 27 'Finite element methods in vehicle design' is divided in 5 subgroups.
- Quality assurance using CAE
- CAE in planning/guidelines
- Optimization
- Networking technologies
- Crash and occupant simulation

The work presented in the paper is performed by members of the subgroup of (UA 5) 'Crash and occupant simulation' of the working group (WG 27) 'Finite element methods in vehicle design'. Representatives of the following companies participated in the initial project:

- Audi AG
- Autoliv GmbH
- BMW AG
- Ford AG
- Johnson Controls GmbH
- Keiper GmbH&Co.
- DaimlerChrysler AG
- Adam Opel GmbH
- Dr. Ing h.c. F. Porsche AG
- Volkswagen AG

With very few changes the participating companies stayed the same during the projects. This is almost the same for the representatives in the working group.

The authors of the paper contribute with different responsibilities to the success of the project. Prof. Erich Schelkle is leading the work group WG 27 since approximately 15 years, Thomas Frank is heading the subgroup UA 5, Ulrich Franz works since 11 years as developer for the models in LS-DYNA, and Sebastian Stahlschmidt is the lead developer of the models developed for LS-DYNA.

MILESTONES OF THE PROJECTS

The first project to develop numerical models at the FAT started in 1992, which is rather early if the computational capabilities at his time are taken into account. Even the requirements related to the dynamic testing were in an early stadium. For instance: In 1989, the International Standards Organization (ISO) first published ISO/TR 9790, which defined a bio-fidelity evaluation approach for side impact dummies. Another example: NHTSA adopted requirements for a special side impact dummy and a moveable barrier similar to a medium-sized car to be used in dynamic side impact compliance testing in 1990. The standard was phased in, with partial compliance necessary by 1994 and full compliance required by 1998.
Besides the testing procedures the testing devices were also under development. E.g the first production phase for the EUROSID-1 dummy was from 1986 to 1989.

The main dates of the FAT projects are:

June 1992:
- Definition phase for first project

January 1993
- Contracts with research partner LASSO GmbH
- Initial development of models based on finite elements
- Initial development of models based on rigid body dynamics
- Identical models for the 3 major crash codes was targeted
- First releases of EUROSId-1 and USSID.

January 1997till today
- Development by the software vendors/developers
- Development for the different codes is separated
- Termination of development of models based on rigid body dynamics
- First commercial release of EUROSID-1 and USSID in 1997
- Model of SIDHIII developed based on the model of USSID

2001 till today
- Project to develop ES-2 model launched
- Development by the software vendors/developers
- Development for the different codes is separated
- First commercial releases available in 2002.
- Model of ES-2 re developed based on the model of ES-2
- Constant enhancements of models

2004 till today
- Project to develop BioRID II model launched
- Development by software vendors/developers
- Development for the different codes is separated
- First commercial release available in 2005

2006 till today
- Project to develop WorldSID 50% model launched
- New host is Partnership for Dummy Technology and Biomechanics (PDB)
- Development by software vendors/developers
- Development for the different codes is separated
- First commercial release available in Q1/2008

2007
- Project to do further studies for ES-2re launched

Since the projects are no longer research related the FAT is not hosting the projects any more. The latest activities for new models are hosted by the Partnership for Dummy Technology and Biomechanics (PDB) - an organization of the German OEMs. The companies and representatives in the PDB working group contributed formerly to the dummy development projects in the FAT framework. The PDB adopts the exact the same proceedings as the FAT.

EXPERIMENTAL DATA

A wide range of experiments were performed during the projects in order to obtain parameters determining the behavior of materials, components, and the assembled dummy. The definition of experiments was an ongoing process which interacted with the numerical results of the finite element models. In many cases the available releases were used to determine an appropriate test specification. This strategy seems to be very suitable to determine simple test set-ups that impose loads comparable to loads in vehicle accidents.

Material Tests

The specimens were taken from new parts or specifically produced material blocks delivered by FTSS or Denton. Exceptions were some vinyl skins, which came from a repair kit for the dummy models, and the red confor foam which was provided by the manufacturer.

The following tests were performed: static tension tests, dynamic tension tests, static compression tests, dynamic compression tests, relaxation tests, hydrostatic triaxial compression tests, static shear tests and dynamic shear tests. In the later projects the goal of the tests was to obtain data which could be used directly as input for the LS-DYNA materials like Mat_Fu-Chang_Foam and Mat_Simplified_Rubber. Hence, the focus was on static and dynamic tension and compression tests. For generality reasons the tests cover a wider range of loads than expected in a vehicle load case.

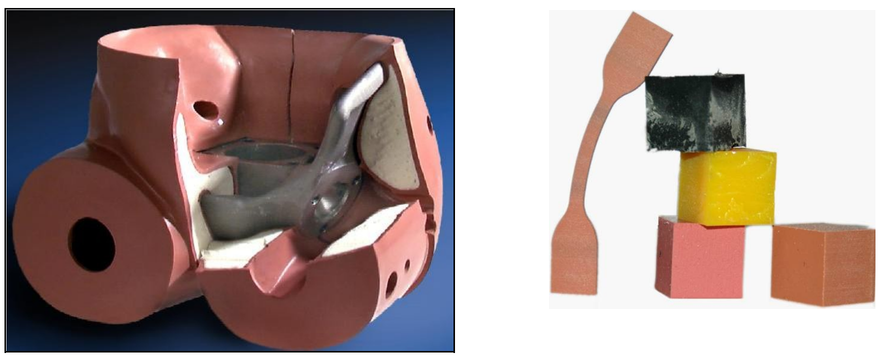

Figure 1: Pelvis foam separated to take samples (left), specimen (right).

As an example the experiments for rate dependent foams are described in more detail:

- Static compression test on an cubic specimen (30x30x30 mm**3)
- Dynamic compression on a cubic specimen with almost constant compression speed. This resulted in information of the material behavior for the strain rates 10 /s, 20/s, 50/s, 100/s and 200/s. Depending on the foam the considered maximum volumetric strain was 90% or 50%.
- Static tension tests
- Dynamic tension tests with strain rates of: 10 /s, 20/s, 100/s, 200/s.

Component Tests

Often material data is sufficient to predict the behavior of a part. For the dummy components this is not always the case since several connected and joined parts determine the behavior significantly and the meshes are not sufficiently fine to model the connections. Furthermore, the behavior of preloaded parts is difficult to examine in a simple material test. The experimental database contains head drop tests, dynamic shear tests for the lumbar spine, pendulum tests for the lumbar spine, neck pendulum tests, drop tests for the damper, partial and complete thorax impact tests, pendulum tests for the abdomen, impact tests for the pelvis and impact tests for pelvis/upper leg. Often the tests are specifically designed to be in a load range comparable to loads in a vehicle crash. Therefore, the first releases of the finite element models are used to design appropriate tests. The calibration tests of the dummies are also used for validation purposes, but often these tests have the disadvantage that they impose loads that are not in the load range of interest.

As example the experiments for the ES-2 rib cage (depicted in Figure 2) are described in more detail:
- Velocity of pendulum is determined to reach 10,20,30,40 and 50 mm rib intrusion.
- 4 different impact locations
- 2 different angles
- Pendulum with 2 different masses
- Tests with and without damper
- In total 25 different tests with the single rib

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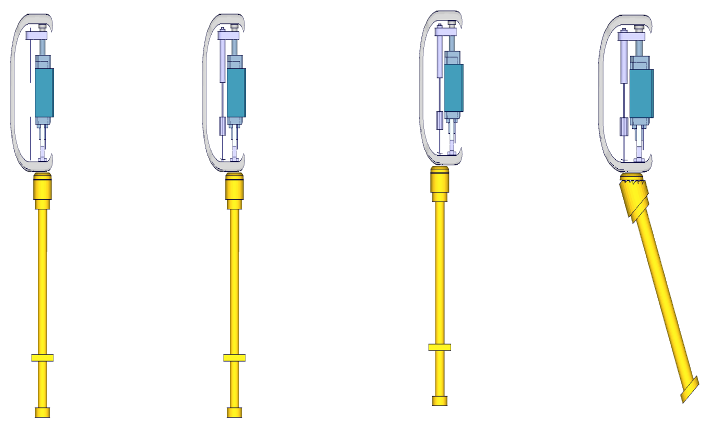


igure 2: Simulation of different impact tests on single rib of ES-2.

As second example the tests of the spine of the BioRID II (depicted in Figure 3) are described in more detail:
- Tests with different pulses
- Test with different support of the spine
- Tests with and without the damper and pre-loaded spring
- In total 10 different tests with 3 different dummies for the spine

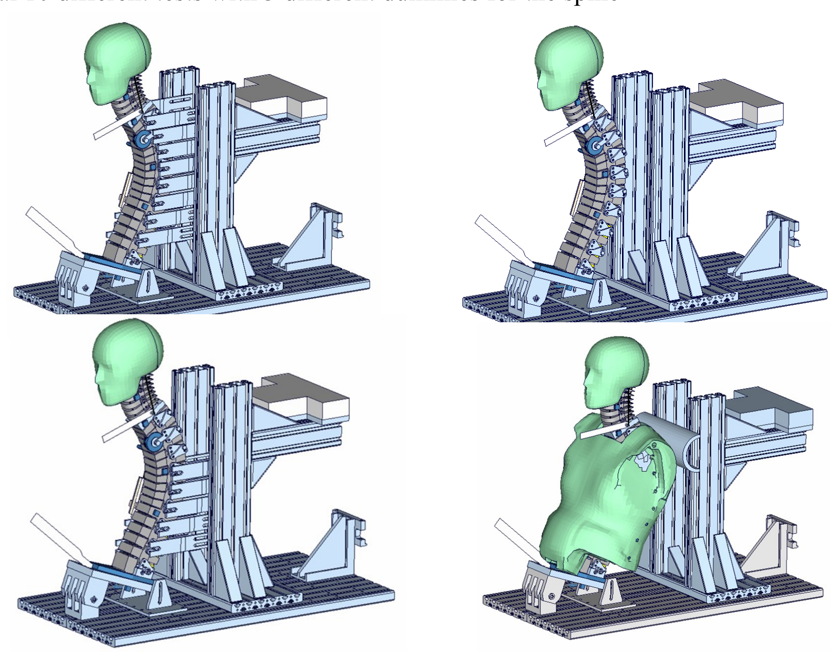


Figure 3: Simulation of component test of spine and thorax of BioRID II.

Tests with Fully Assembled Dummy

The information of the material tests and the component tests lead to models that still miss the information on the interaction of the different parts. Since the interaction has a significant influence on the injury values many tests are performed to study the completely assembled dummy.

Pendulum Tests

Since the tests performed on sleds have a load level closer to a vehicle crash than pendulum tests, the emphasis is on sled tests. The pendulums have the advantage that a certain body region can be loaded separately. Hence, for investigating the performance of a model in a certain region the pendulum test is very suitable. For instance the abdominal forces of ES-2 or EUROSID-1 can be validated against pendulum tests effectively. Like for the component tests, the standard calibration tests were used for modeling purposes as well. Figure 4 depicts the pendulum impact locations tested for ES-2 development and a test to load the fully assembled thorax. Figure 5 depicts tests performed to investigate the influence of the rib extension of the ES-2re. Figure 6 shows simulation of 2 calibration tests of USSID.

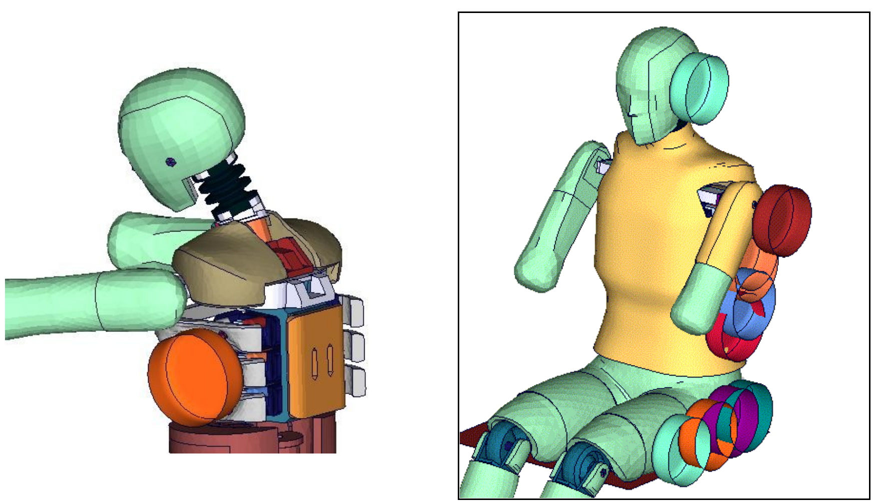


Figure 4: Pendulum impact on thorax of ES-2 (left); Tested impact locations of pendulum to validate ES-2 model (right).

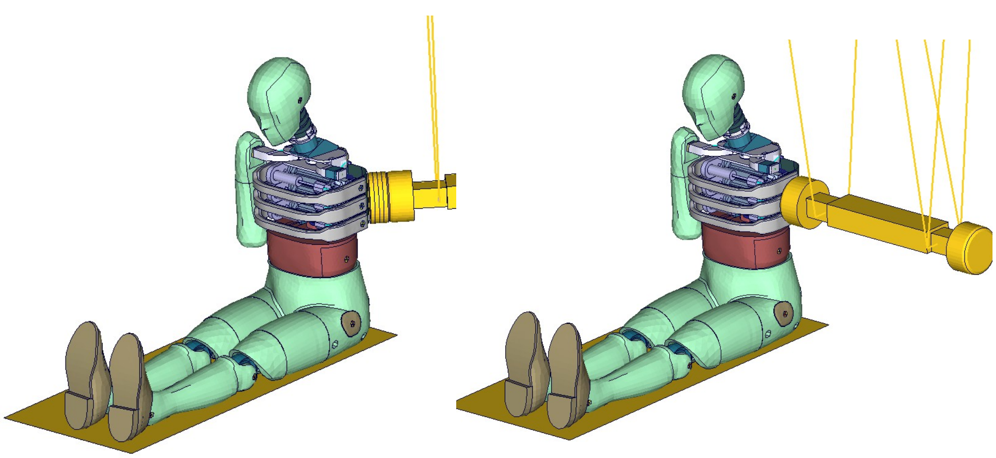


Figure 5: Tests to investigate influence of rib extension of ES-2re.

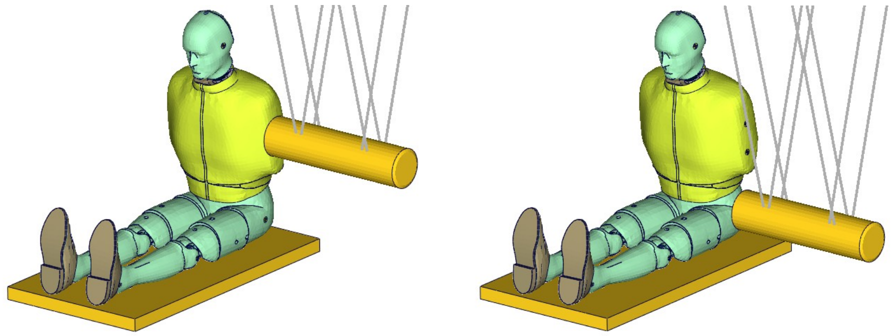


Figure 6: Calibration Pendulum tests to validate USSID.

Sled Tests

The experiments for the side impact models are performed with rigid wooden barriers. The speed varies from 4 to 8 m/s with barrier masses above 1 t. The recorded experimental data are: Accelerations, forces, moments, and intrusions. Usually, the dummies are equipped with maximum available instrumentations. Furthermore, contact foils are used to determine times of contact. In the early projects a plane barrier and barriers are equipped with a shaped contour to load specific body regions. Figure 7 depicts the barrier shapes used for USSID validation. In the later projects plane barriers with different oblique angles and only mild contour shapes are used to load specific parts of the dummy. Figure 8 depicts the barrier model used for development of the ES-2 model. For the BioRID-II model development the sled test uses a test device that imposes resistance comparable to a vehicle seat. The device is a slightly modified version of the seat that Chalmers University used to develop the hardware dummy. It is depicted in Figure 9.

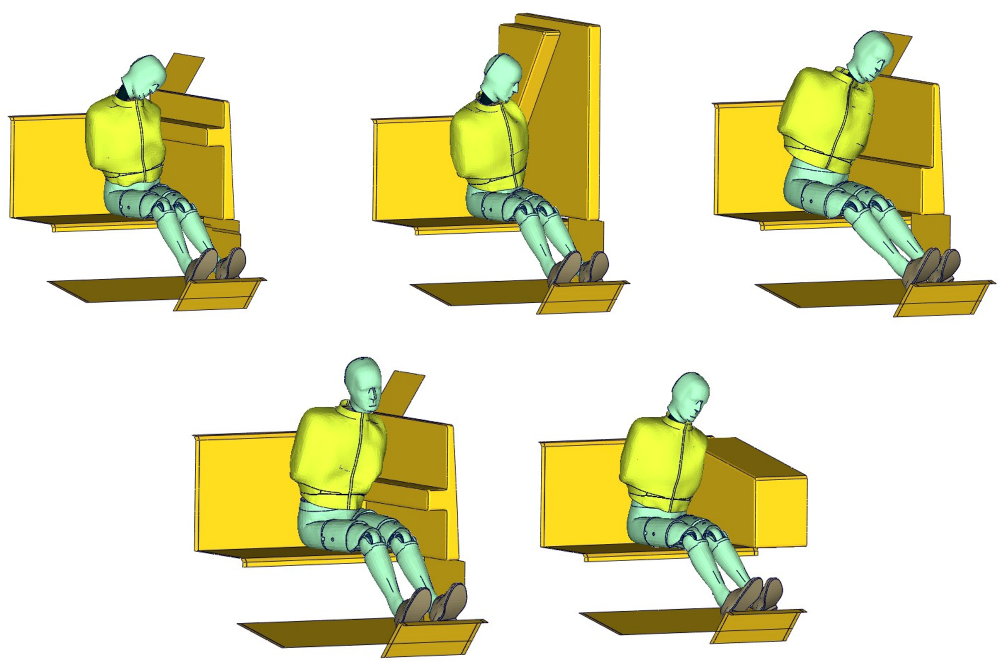


Figure 7: USSID model in sled tests with varying barrier shapes.

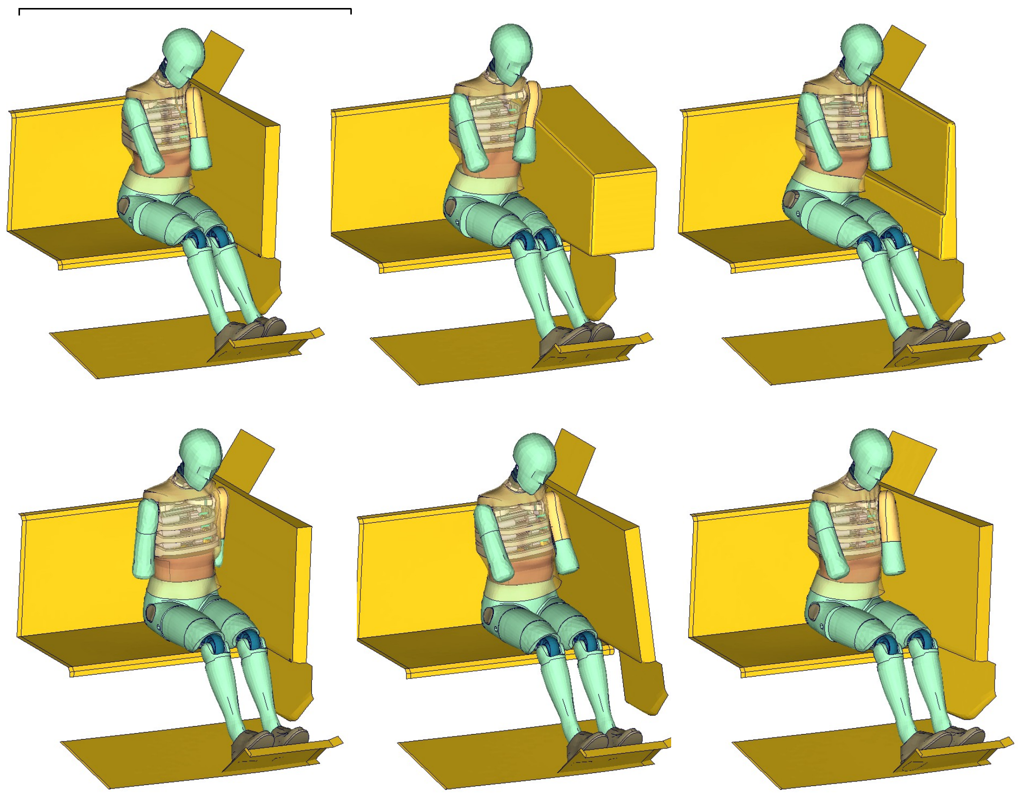


Figure 8: ES-2 model in sled tests with varying barrier shapes, oblique barriers and initial arm positions.

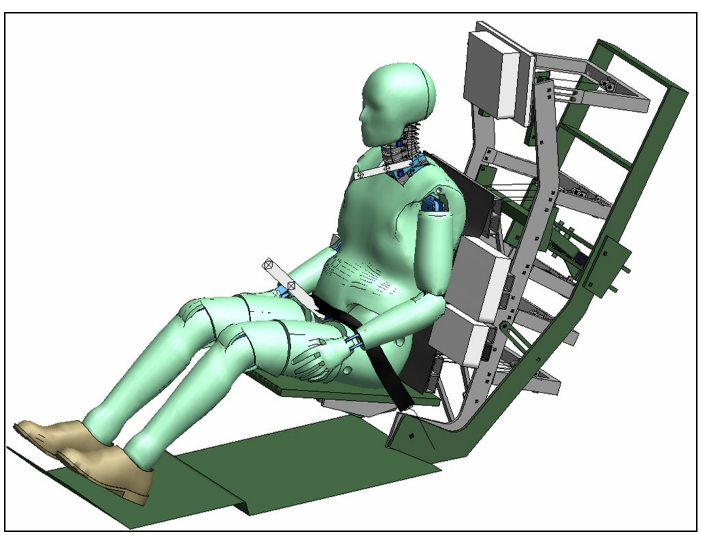


Figure 9: Simplified seat model to develop model of BioRID II.

Full Crash Tests

The question rises if sled tests are sufficient to generate predictive finite element dummy models in a full car crash simulation. Differences to the performed tests may occur because of the seat, the belt, the deforming door trim, the airbag, the restricted leg space or the specific velocity profile of intruding parts. Fortunately, it seems that the occurring effects can be captured by the FE models. This statement is based on the simulations performed by the LS-DYNA users in the FAT which gave often very satisfactory results. Hence, tests including 'real' seats, 'real' doors, etc. have not been included in the test database. In general, the validation of a dummy model in a vehicle environment would involve a huge effort. For dummy model enhancements the accuracy of the vehicle model and its restraint system must be significantly higher than the dummy model itself. If this is not the case the simulation in the vehicle can be used to identify weak points, but for enhancing the dummy model it is usually not sufficient. Many conclusions from results of car simulations were drawn and used to enhance the model, by defining a much simpler component or fully assembled test that shows similar effects.

METHODOLOGY OF DEVELOPMENT

In the first years of development the question of de-featuring and adapting appropriate material data was an important part of the work. Since computational power increased significantly the later updates show almost all geometric details and the importance of simplifying has decreased significantly. In the current models each part is modeled accurately with a reasonable fine mesh. Combined with the correct material data each model of a part should behave reasonably well. The current effort is to model the connection of the parts properly, the current meshes are still too coarse to model the connections in detail. Common questions that have to be addressed are:

- How much does the joint modeling of the ES-2 arm influences the arm movement?
- How much the thick bolts and washers stiffens the plastic iliac wing of the ES-2?
- How much the arm adaptor of the WorldSID 50% stiffens the rib?

A cut through the pelvis of ES-2 with the iliac wing and one of the mentioned bolts are depicted in Figure 10 at the left hand side. Figure 10 depicts also the arm adaptor. It is connected with 4 bolts to the steel rib.

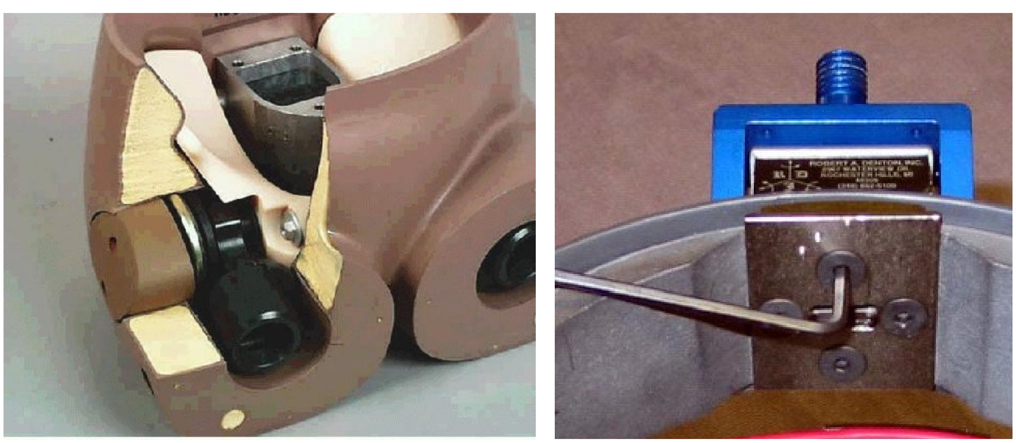


Figure 10: Assembly details. Pelvis of ES-2 (left), Shoulder of WorldSID (right).

A strong effort was made to define appropriate simple tests with properly defined boundary and initial conditions. Thus, with a first test sequence of material, sled and pendulum tests a first model is built. This model is then used to understand load paths and levels in the model and to define new tests. This leads to development cycles for each model which was guided by the FAT members. The development scheme is depicted in Figure 11. In addition to the new test data new features of LS-DYNA are implemented. So new material laws, new element types, new ways of handling easily pre-stress were adapted in the updated models. In some cases the FAT also initiates new features in LS-DYNA. The ongoing testing and development together with the strong involvement of the users group of the FAT is one of the main reasons for the reliability, predictability and usability of the models.

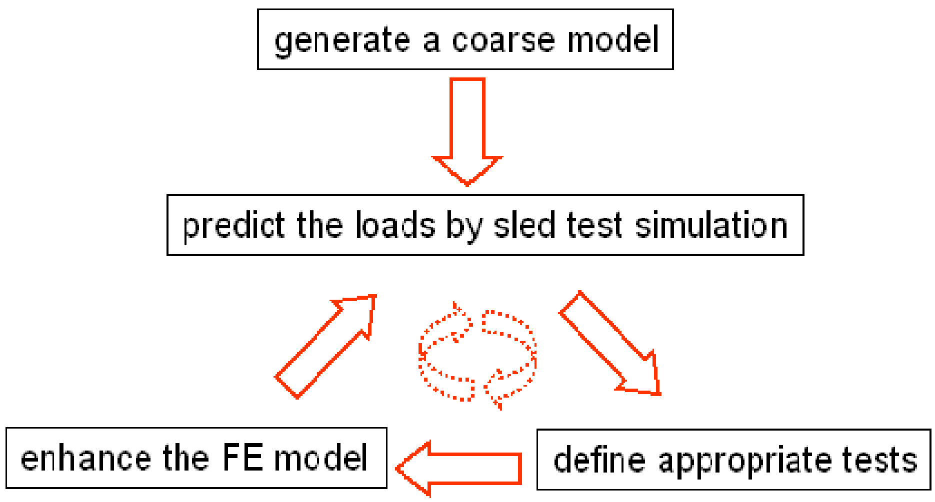


Figure 11: Show graph on development cycle.

An ostensive example for the difficulty of finding an appropriate test is the lumbar spine; a considerably simple part. In the USSID or ES-2 it is a rubber cylinder with steel disks at the top and bottom. The cylinder is pre-stressed between the 2 disks by a steel cable. In the assembled dummy the weight of the dummy leads to an additional bending of the lumbar spine. Due to the pre-stress the material properties from material tests have to be modified, if the pre-stress is not considered in the model. But an appropriate component test is difficult to define. Figure 12 depicts the deformation modes in a vehicle and Figure 13 depicts the deformation in a pendulum test used for the calibration of the lumbar spine. 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 have not 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.

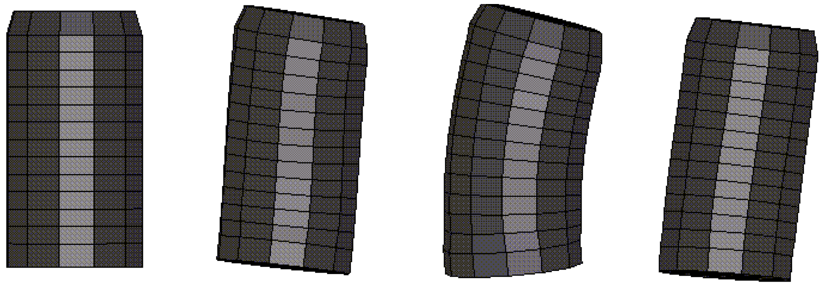


Figure 12: Deformation of lumbar spine in side impact simulation at different times.

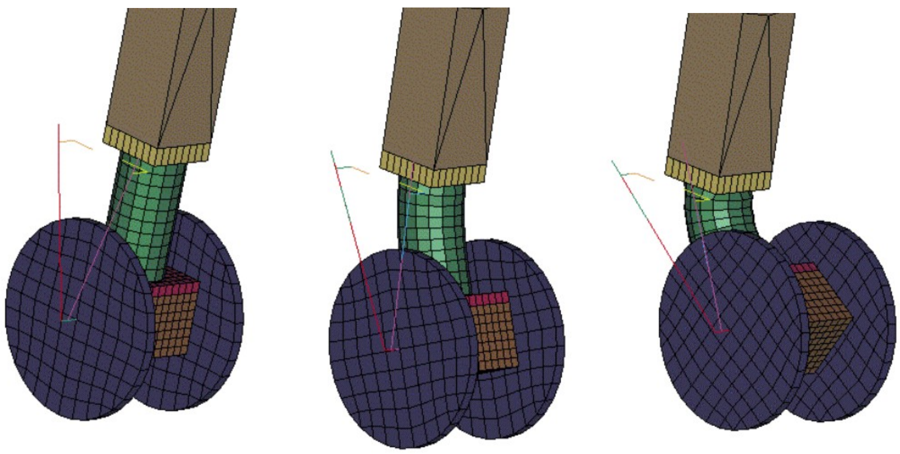


Figure 13: Deformation of lumbar spine (green) in calibration tests at different times.

In addition to the models released to the customers detailed models are built to understand phenomena and to choose the adequate modeling techniques. Figure 14 depicts as example a fine model of the neck of the ES-2 and a modeling of the abdominal insert. In the recent projects optimization techniques provided by LS-OPT are more and more used during dummy development. The emphasis is on studying sensitivities, correlations and to investigate robustness.

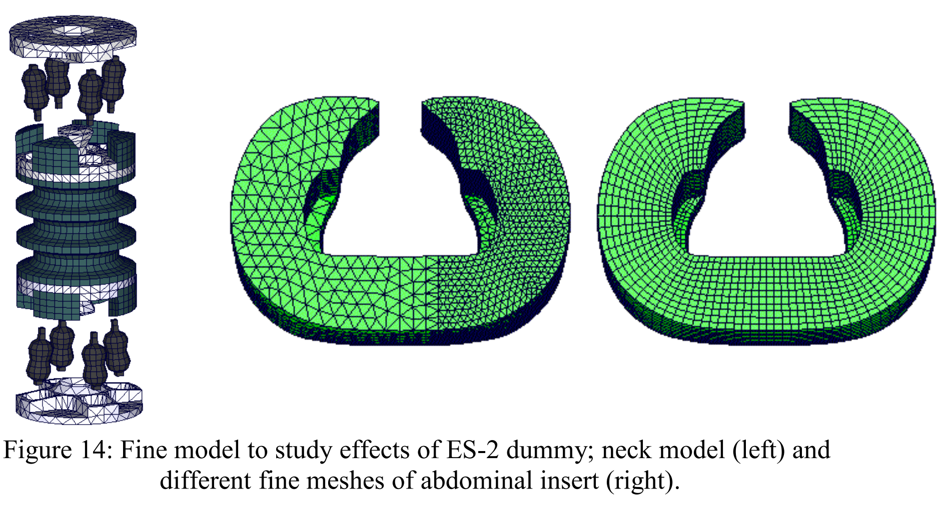


Figure 14: Fine model to study effects of ES-2 dummy; neck model (left) and different fine meshes of abdominal insert (right).

The following two figures depict components of models at different development stages. Besides the mesh the element types and material definitions and contact definition have changed. Figure 15 shows the pelvis assembly of the USSID model and Figure 16 depicts the thorax model of an early version of the EUROSID-1 and the current version of the ES-2.

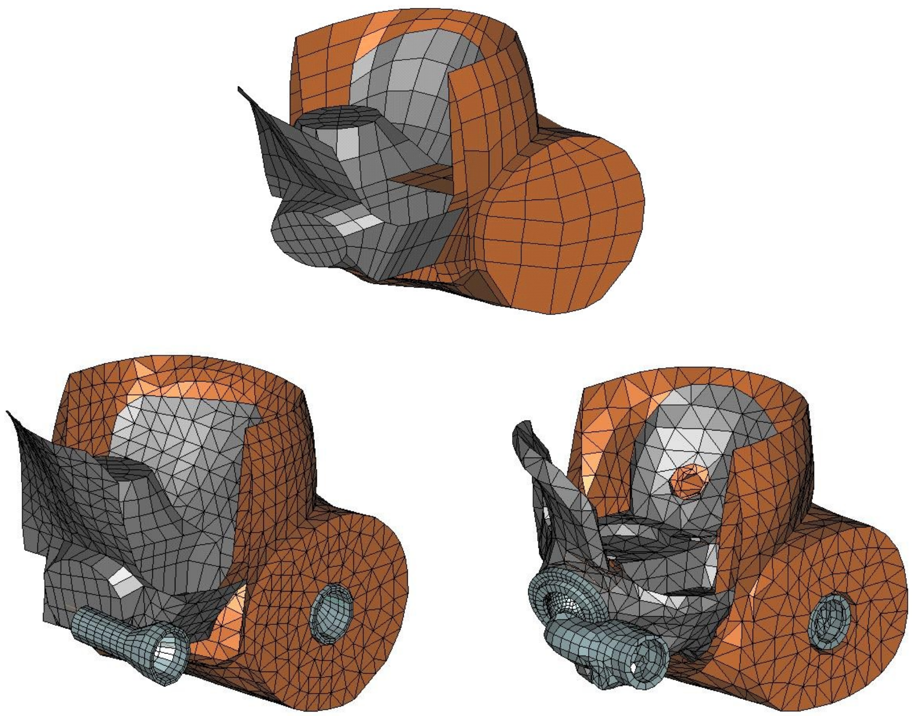


Figure 15: Development stages of the pelvis of the USSID model
(top: Version 1.00; left: Version 2.5; right: Version 3.0).

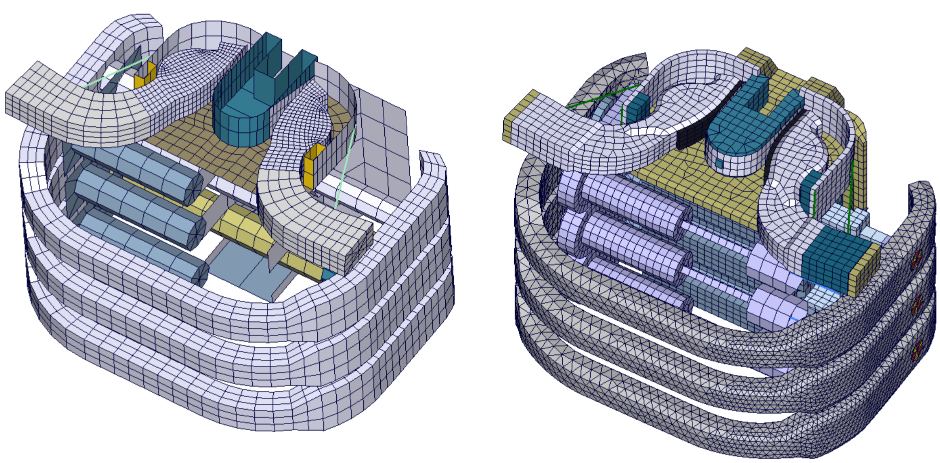


Figure 16: Development stages of EUROSID-1/ES-2 thorax model

(left: Version 1.00; right: Version 4.5).

THE FINITE ELEMENT MODELS

Geometry

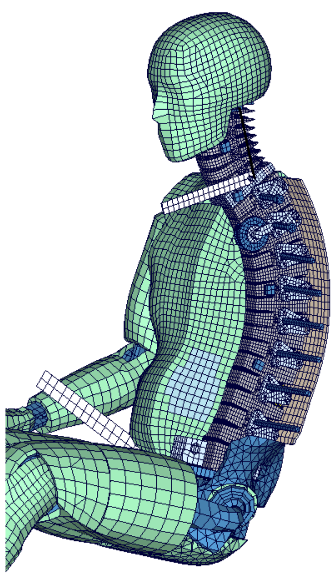
The ES-2, ES-2re, BioRID and WorldSID 50% are meshed based on CAD data purchased from the hardware manufacturers. In addition to the CAD data some parts are based on scanned data, in particular if a shape change is expected during manufacturing. The older models are based on simple measurements and scanned data. Since the assembly changes the shape of some parts the geometry is adapted according to a measurement on the fully assembled and upright sitting dummy. The adaptations are achieved by pre-processing or by a pre-simulation.

Constitutive Equations

Many material tests were performed to lead directly to an input to LS-DYNA Material definitions. For these material definitions usually curves or tables are required as input. The curves are smoothed and sometimes adapted according to energy assumptions and then used directly in the material cards. Thus, Mat_Fu-Chang_Foam or Mat_Simplified_Rubber are frequently used constitutive equations. The used formulations take strain rate effects into account. For some parts it is difficult to define reasonable material test procedures. An example is the lateral pad of the abdominal insert of the ES-2. The pad is built by small lead balls embedded in rubber. In such difficult cases an optimization process based on component tests is used to determine the material parameters.

Mesh Density and Quality

The dummies are modeled with many details. For instance the BIORID II model contains all cables, cable guides, dampers, bumpers, accelerometers. Figures 17 and 18 depict details of the BioRID II and WorldSID 50% model.



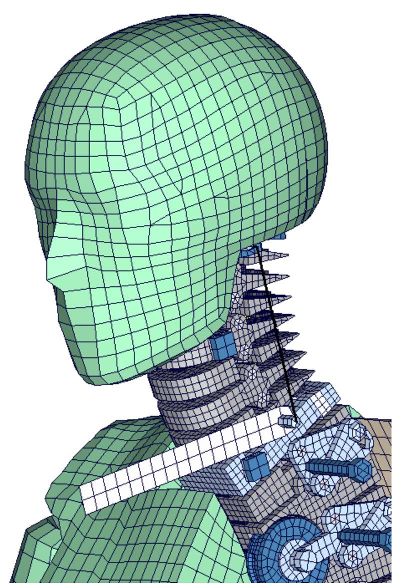


Figure 17: Details of BioRID II model.

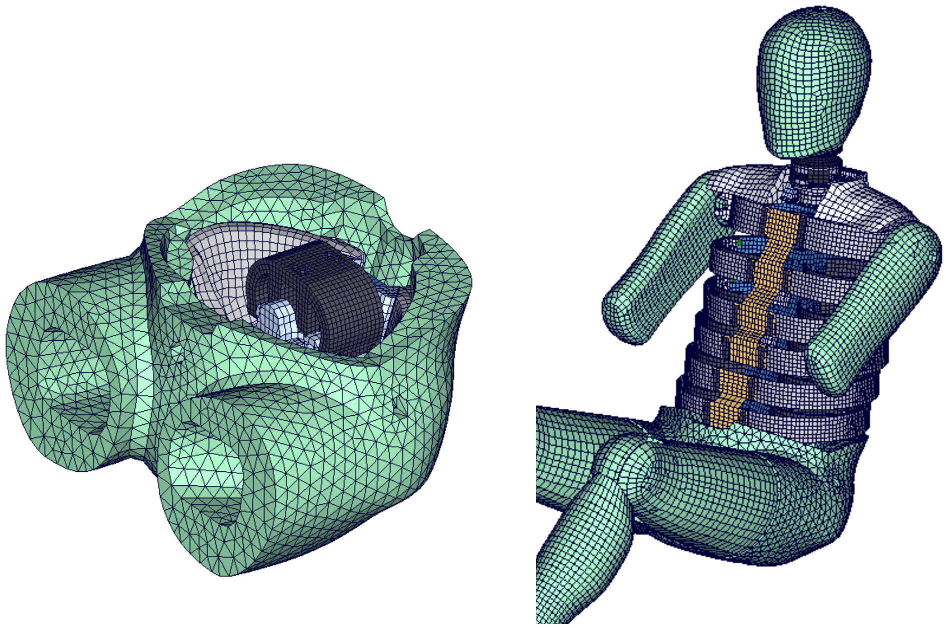


Figure 18: Details of WordSID 50% model.

Contact Definitions
In the early stages of the models many contact definitions with different penalty factors and a prescribed contact thickness were used. The recent models are working with one major contact definition (type 13, soft constraint), and a limited number of additional contact cards. If a contact force is desired the force transducers are used. The shell thickness is considered in the contact algorithms.

Discrete Elements, Joints
Discrete elements are used to model dampers and springs in the thorax. In particular, the BIORID II model has many seat belt elements connected via slip rings to model the 2 cables in the pre-stressed neck. Stop angles, friction properties and the generalized stiffness definitions are used.

Mass Distribution
The mass distribution follows an exact measurement of each part. The mass of parts that are not modeled in detail are added to the part they are connected with. E.g. the mass of a bolt is added to the part the bolt is tightened with.

Model Size
The latest models have approximately 150,000 -200,000 elements and nodes. They run with a time step of 0.7 microseconds. The models include a positioning file in the Primer tree file format.

Pre-stress
The BioRID II model contains pre-stressed parts, which can be easily handled since the information on the pre-stress is in ASCII format. They can be included in the model by simply adding the file with the INCLUDE command. The other models do not include pre-stress; the only exception is the elastic cord at the ES-2 clavicle box.

EXAMPLES OF PERFORMANCE

ES-2 Model

In the following the results of one selected sled test of the current ES2 dummy model (v4.0) is shown. The test is depicted in Figure 19 below. The ES2 is sitting on a bench with 10° pelvis angle. The barrier has a plane shape and a velocity which is comparable to an intrusion velocity in a vehicle side impact. The dummy is fully assembled and the arm adjusted to 40°. The friction is minimized by Teflon plates between dummy and bench. The results of this test are shown in Figure 20 to 25.

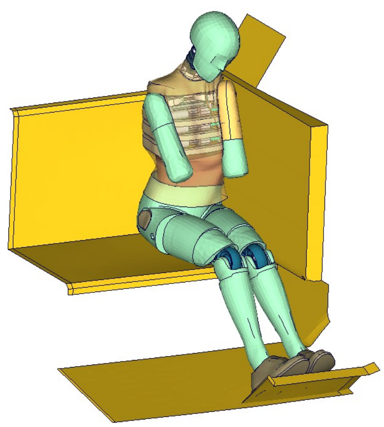


Figure 19: ES2 sled test with 40° arm and a plane barrier.

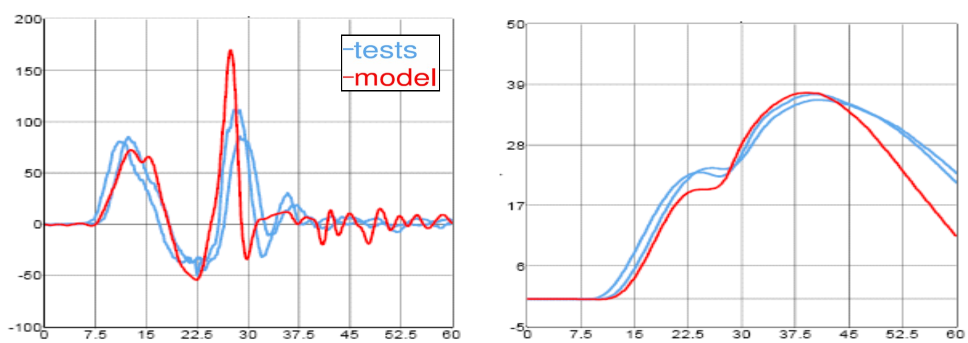


Figure 20: Upper rib results vs. time [ms]. Right: y-acceleration [g]. Left: intrusion [mm].

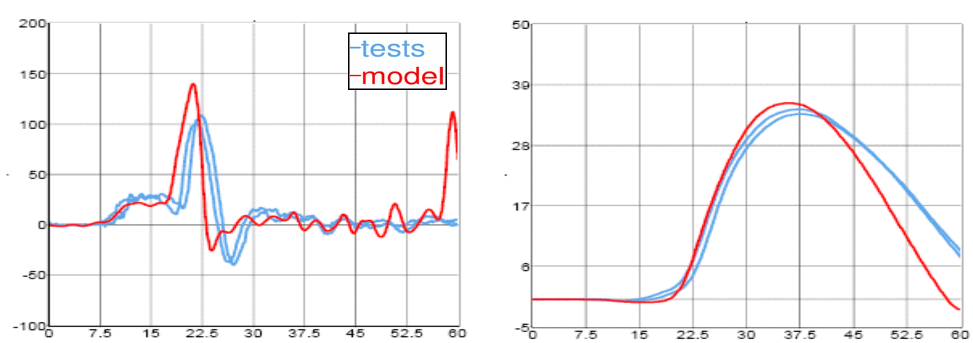


Figure 21: Middle rib results vs. time [ms]. Right: y-acceleration [g]. Left: intrusion [mm].

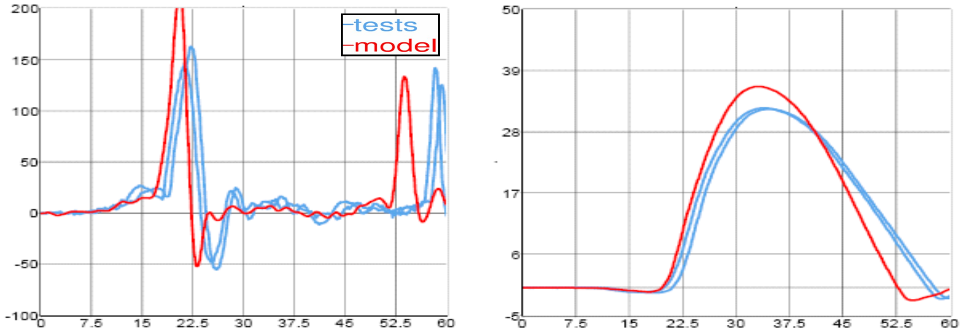


Figure 22: Lower rib results vs. time [ms]. Right: y-acceleration [g]. Left: intrusion [mm].

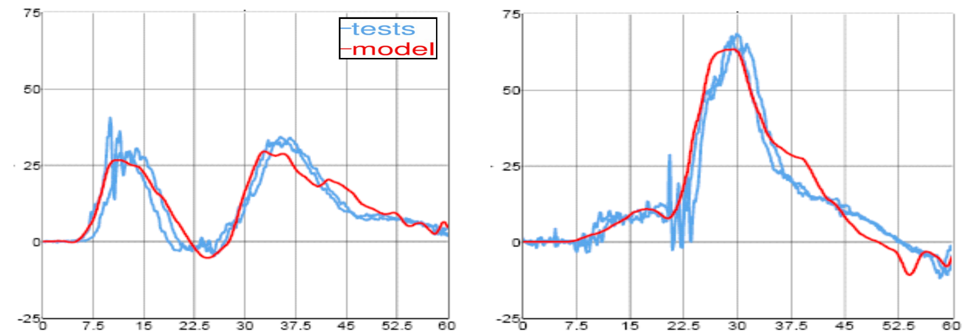


Figure 23: Spine y-acceleration [g] results vs. time [ms]. Right: upper spine. Left: lower spine.

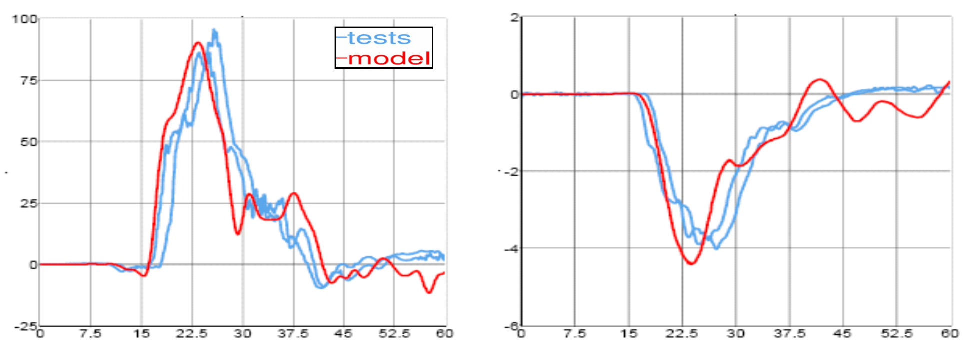


Figure 24: Results vs. time [ms]. Right: pelvis y-accel.[g]. Left: pubic symphysis force [kN].

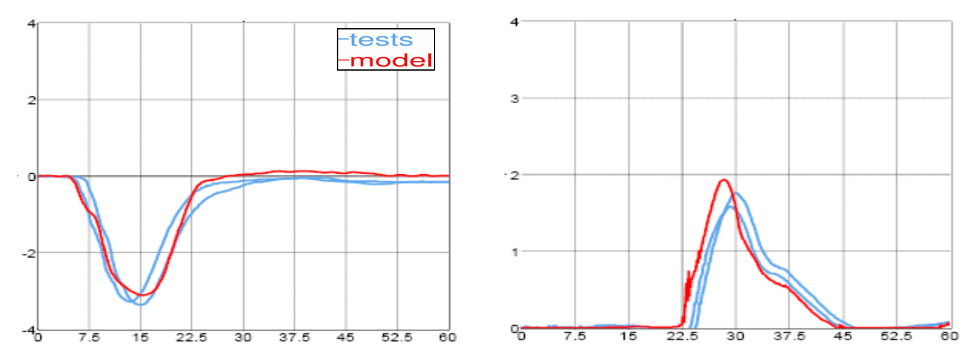


Figure 25: Results vs. time [ms]. Right: shoulder force [kN]. Left: abdomen result. force [kN].

BioRID II Model

In this section the results of one selected simplified seat test of the BioRID II v2.0 are shown. The seat is depicted in Figure 26 below. At the back of the dummy the simplified seat provides four pads, which can move separately with a specific resistance. The resistance of each panel was adapted to behave similarly to the local stiffness of a back rest. Additionally, the frame (grey color in Figure 26) of the four pads can rotate about a pivot center at the bottom. The rotation of the frame is resisted by a break system which represents the stiffness of the back frame against rotation. The seat and the head rest were equipped with foam pads to provide contact conditions for the head and the arms comparable to a seat.

In the tests the seat is accelerated with three different pulses. The pulses are used from the EuroNCAP proposal for whiplash tests. In the following the results of a 5g trapezoidal pulse are shown.

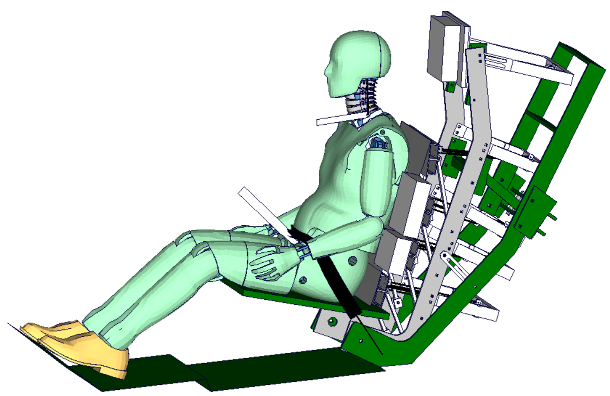


Figure 26: Results vs. time [ms]. Right: shoulder force

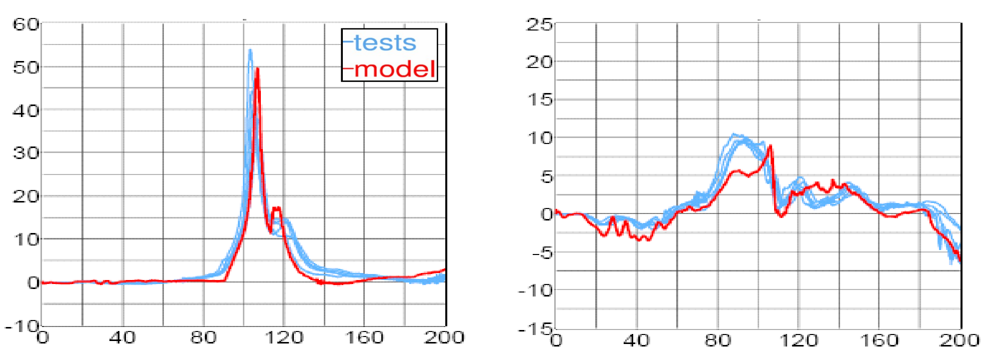


Figure 27: Head acceleration [g] vs. time [ms]. Left: x-acceleration. Right: z-acceleration.

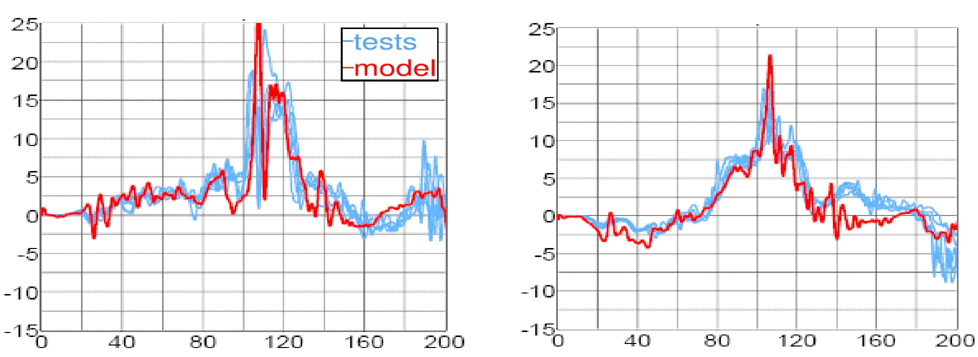


Figure 28: Neck acceleration [g] vs. time [ms] at C4. Left: x-acceleration.
Right: z-acceleration.

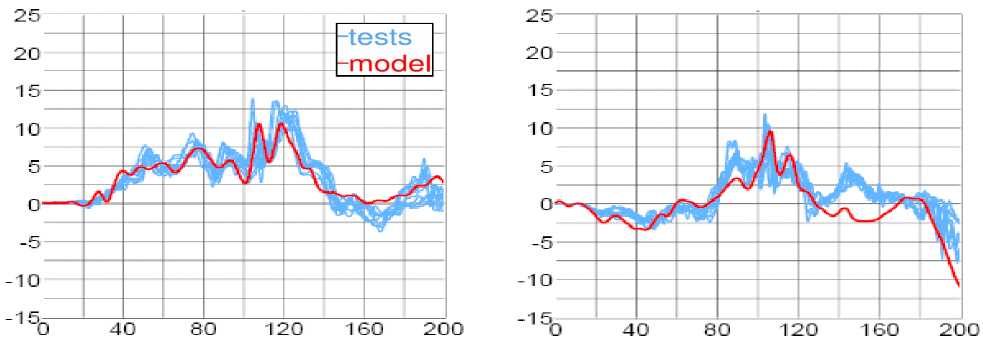


Figure 29: Upper spine acceleration [g] vs. time [ms] at T1. Left: x-acceleration.
Right: z-acceleration.

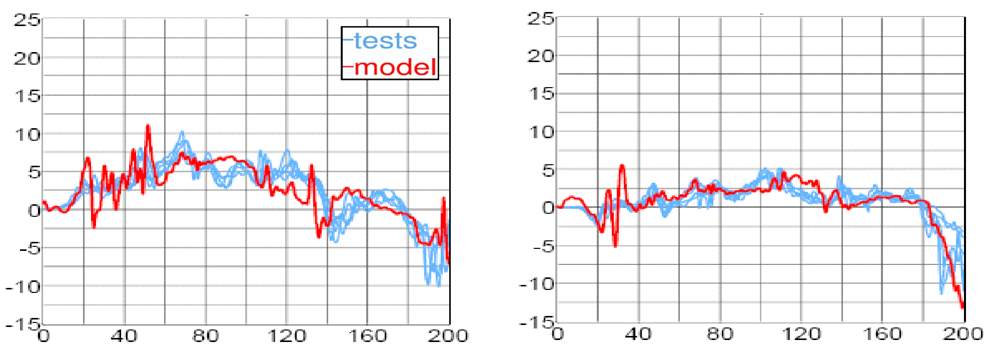


Figure 30: Spine acceleration [g] vs. time [ms] at T8. Left: x-acceleration.
Right: z-acceleration.

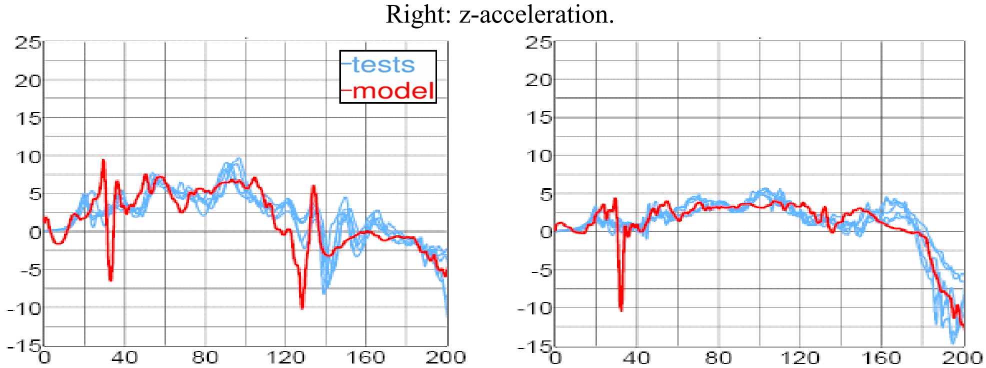


Figure 31: Spine acceleration [g] vs. time [ms] at L1. Left: x-acceleration.
acc

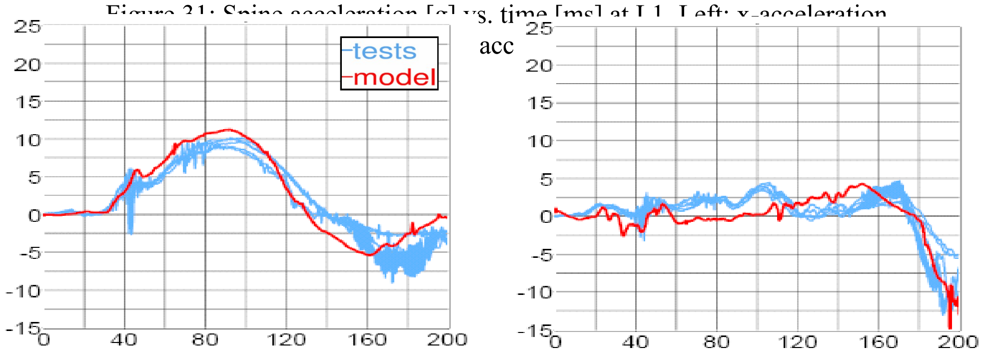


Figure 32: Pelvis acceleration [g] vs. time [ms]. Left: x-acceleration. Right: z-acceleration.

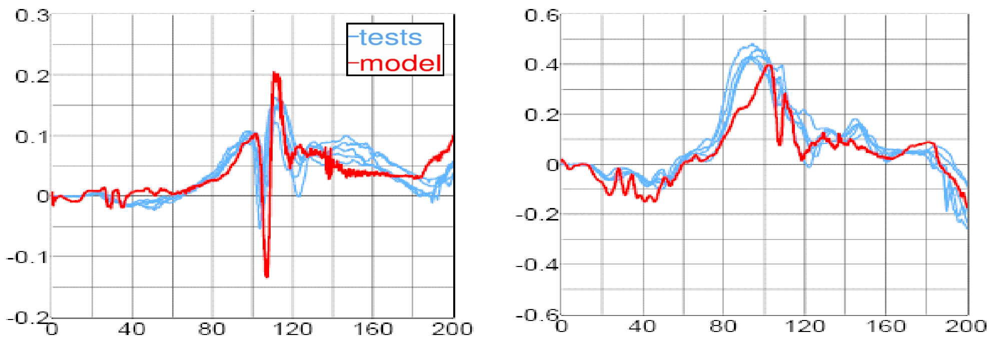


Figure 33: Upper neck force [kN] vs. time [ms]. Left: Force in x. Right: Force in z.

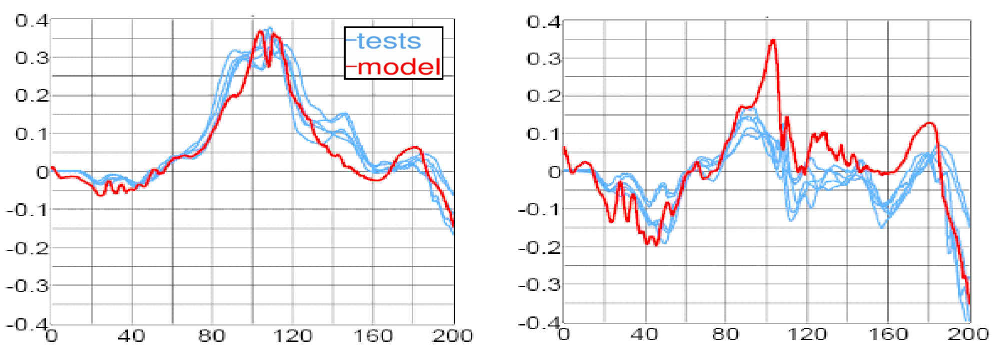


Figure 34: Lower neck force [kN] vs. time [ms]. Left: Force in x. Right: Force in z.

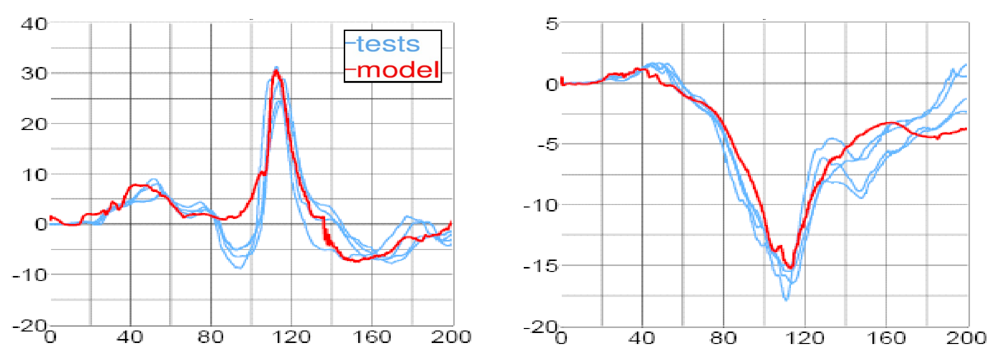


Figure 35: Neck moment [Nm] vs. time [ms].Left: Upper neck moment.

Right: Lower neck moment.

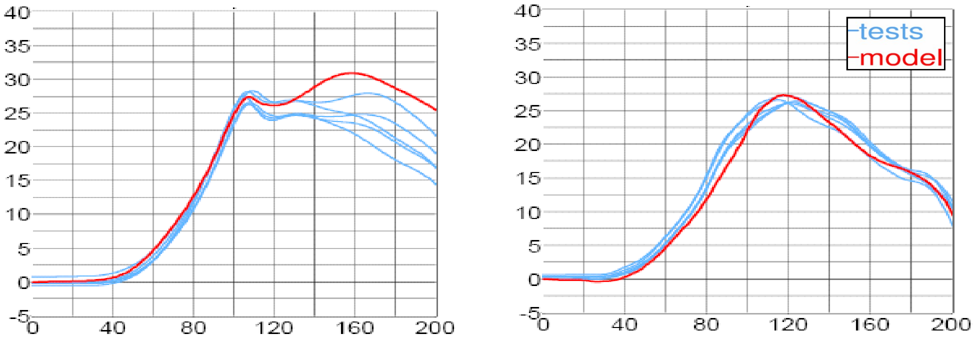


Figure 36: Rotation [degree] vs. time [ms]. Left: Global rotation of head.
Right: Global rotation of T1.

CONCLUSION

The development of finite element models of software suppliers with a group of automotive companies is very powerful and effective. It leads to predictive state of the art models. The process of continuous enhancements with updates often initiated by observations from users contributes significantly to generate models fulfilling current demands. The strong effort to generate a test database with loads comparable to loads in a vehicle crash, by designing simpler test set-ups is crucial for the success of the projects. During development many parts are remodeled based on new tests and observations. The models itself are often used to understand phenomena of the dummy, and to define tests to penetrate an effect in detail. The method applied at the FAT working group will be used for further developments of dummy models. Since the model development is not research related any more it will be hosted in the future by the PDB. The companies and representative in the working groups of the PDB are the same as in the FAT. The PDB implies exact the same proceedings as the FAT. With the FAT the models for the USSID, EuroSID-1, ES-2, ES-2re, SIDHIII, and BioRID have been developed. The WorldSID 50% model is the first one coordinated by the PDB.

Since the involvement of software companies in 1996, the staff from DYNAmore is responsible for the development of the LS-DYNA models. The continuity of participants in the FAT working group and the developers contributes also to the effective development. The models are commercially available and supported by local software suppliers. All models are frequently used world wide to enhance passive safety behavior of vehicles.