Accurate and Detailed LS-DYNA FE Models of the US- and EUROSID: A Review of the German FAT Project

Ulrich Franz, Oliver Graf
CAD-FEM GmbH, Grafing/ Munich, Germany

Ulrich Franz
CAD-FEM GmbH, Hannover office
LS-DYNA Group
Schmiedestr. 31
31303 Burgdorf
Germany

Tel: +49-(0)5136/88092-0
Tel: +49-(0)5136/88092-11 (direct)
Fax: +49-(0)5136/693289
E-mail: ufranz @cadfem.de

Abbreviations:
FAT: German Association for Automotive Research
SID: Side Impact Dummy
FE: finite element

Keywords:
FE-Dummy simulation, Side Impact, USSID, EUROSID, FAT, Validation

ABSTRACT

Finite element side impact dummy models of the USSID and EUROSID are of major interest for industry, as more detailed models are required for better prediction capabilities, but still efficiency has to be maintained to some degree. Both type of models, the so-called FAT-USSID and FAT-EUROSID have been developed by CAD-FEM in cooperation with the German Association for Automotive Research (FAT). The main objective was to achieve highly validated finite element models. During the development process the models are validated at three levels: material, component and assembly and tested finally by sled test applications. Additional input was provided by other type of simulations from the LS-DYNA users within the FAT.

This paper summarizes the experience gained during the validation and optimization process which may be used as a guideline for an efficient methodology to generate reliable finite element dummy models. Finally, the good performance of the current USSID and EUROSID models is presented for some selected tests.

INTRODUCTION

Nearly all German automotive companies join parts of their research activities within the FAT, the German Association for Automotive Research (FAT, 1997). In the recent years projects on spot welds, ODB-Barriers, and soft foams led to extensions in the code of LS-DYNA. Since 1992 a working group within the FAT drives the development of improved finite element dummy models. The models follow the European and the US-American regulations of the EUROSID 2 and the USSID, respectively.

Initially, two types of finite element models were developed, one more detailed fine model and for efficiency reasons another coarse model with largely rigid parts. Within the course of the project it turned out that an approach with 'rigid' models was rather limited for the simulation of side impact crashes. In particular, the highly nonlinear behavior of the foam materials and the complex contact situations affected the desired results significantly. The coarse approach of the nearly rigid body dummies could not satisfy the required reliability criteria. This conclusion was drawn after simulating barrier tests with different codes. Hence, the development focused on more complex finite element models. The major goal for the development was a high degree of accuracy of the models, followed by 'stability' criteria in order to avoid numerical instabilities. The demand on computational efficiency of the models were lowered considerably setting the priority on the quality of the results.

All members of the FAT participating in the project met regularly to define new experiments, and to discuss further general proceedings for the project.

The project was divided in two major phases. In the first phase of the project the FAT finite element dummies were modeled with the intention to use only features that are available in all three major crash codes (Erbelding C., Kurz A., Schelkle A.,1996) in order to achieve a general model. This proved to be a severe limitation of the quality of the models and was dropped in the second phase in January 1997. Since then the software companies resp. their representatives were included in the development of the dummy models. Each vendor was responsible for the enhancements of the models with respect to the specific features of their explicit codes. CAD-FEM took responsibility for the LS-DYNA models, and cooperated with the FAT to specify the experiments required to improve the model for LS-DYNA.

The schedule and the focus of the development for the LS-DYNA models were mainly determined by the LS-DYNA user group within the FAT. Representatives of Autoliv, Daimler-

Chrysler, Johnson Controls, Opel, Porsche, Volkswagen contributed with their specific experience.

Since the hardware dummies are standardized, the results of the project are of interest for the worldwide community of LS-DYNA users who are involved in dummy simulations of side impact crashes. The models are commercially available from CAD-FEM and the local responsible distributors. The models will be updated on a regular basis according to further regulations and knowledge.

EXPERIMENTAL DATA

The major experiments performed within the last 3.5 years of the project are described below. One essential goal was to obtain experimental data close to the loading expected in real crash scenarios. The test procedures are presented in a logical order, which differs significantly from the actual schedule of the experiments. The difficulties in the definition of the experiments and the resulting schedule are outlined in Section 'Successive re- and de-refinement'. More details on specific tests are presented in (Franz. U., Walz M., Graf O., 1999). The tests were performed at different test facilities and locations.

Material Tests
Almost all specimen were taken from new parts delivered by TNO or ENDEVCO (FTSS). In order to get more generally applicable data the specimen were chosen from areas where the materials appeared to be homogeneous. The following types of 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 addition, the densities of the tested materials were determined.

Component Tests
The experiments on component level for USSID and EUROSID were the following: 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. Specifically for the EUROSID: Impact tests for the arm and the pelvis plug, static tests for the iliac wing and the force transducers. Simple experiments were performed to estimate the frictional coefficients. The dynamic impact tests were all performed with different impactor speeds, angles and masses. If possible, common tests racks as for the dummy calibration were used.

Barrier Tests
The majority of experiments were performed with rigid (rather stiff) barriers. The speed varied from 4 to 8 m/s with barrier masses usually above 1 t. The experimental data recorded are: Accelerations, force and intrusion. Furthermore, the dummies were equipped with contact foils to determine the moment of contact. Much of the new instrumentation for the EUROSID proposed in (Janssen A., Verschut R., Saladin A., 1995) was installed. The following sled shapes were used: Plane barrier, barrier with diagonal arm impactor, barrier with airbags, barrier with an impactor for the arm, barrier with an impactor for the abdomen, barrier with an impactor for the pelvis, barrier with an impactor avoiding direct loads to the upper legs, barrier with an impactor with limited extension in z-direction (comparable to the height of usual door panels). For both models the main focus during the calibration phase was a) on the accelerations of the upper and lower spine, of the ribs and the pelvis and b) on the intrusion of the ribs, as well as c) on the forces measured in the pubic symphysis and d) on the peak force of the abdomen of the EUROSID.

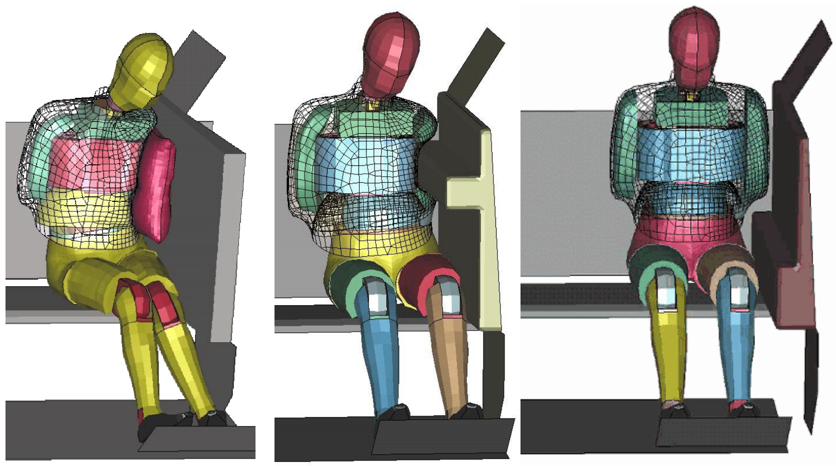

Figure 1: Simulation of the USSID in sled tests with varying barrier shape.

METHODOLOGY OF DEVELOPMENT

Like in all finite element simulations the question of de-featuring and gaining appropriate material data was addressed to the model developers. In many parts of both dummy models complex geometric details and highly nonlinear behavior can be found. Many nonlinearities of the models are captured in the LS-DYNA models, but as a timestep size limit of one micro second was agreed on as a model rule some details in the FE models had to be simplified. For the development of the simplified models the experimental data from the component test had to be taken as a basis. Since the simplified models are not capable to represent the exact behavior of the complex part the selection of the appropriate loading to achieve a rather close response becomes a crucial point for the simplified models and the resulting general performance of the dummies.

In addition, the sled tests raised further questions which were not addressed in the simulation of the component or material test. These were mainly determined by the influence of different components interacting with each other, which can hardly be obtained from component testing. Unfortunately, such effects can be found in many areas of the dummy models (i.e. the arm motion of the EUROSID or the behavior of the lower spines). Hence, the development of a well performing dummy model also has to take into account the large experimental data base of sled tests. Aspects regarding observations during the simulation of the sled tests are outlined in Section 'Aspects of the Sled Test Simulations'. Furthermore, the information from the sled test simulation were indispensable to accentuate the results of the component and material tests.

This experience, the observation from experiments and the restriction concerning efficiency, altogether lead to the applied methodology outlined in Section 'Successive re- and de-refinement'.

Implementation of Experimental Material Data

During the project a large basis of experimental data was gained. Many material data could be used directly with the appropriate material model from LS-DYNA. Due to the large variety of material models in LS-DYNA only a few concessions concerning material modeling had to be made. For instance material model 83, Fu-Chang-Foam allows to consider the static as well as the dynamic behavior of rate dependent foams. Another advantage of material model 83 is that almost no effort is necessary to generate some material data required for the input in LS-DYNA, as e.g. the curves from the experimental data can be directly used.

The generation of material properties for pre-stressed materials as well as for parts consisting of different material layers was more difficult. One example is the jacket of the USSID. It consists of a rubber like material with a fabric on the inner side of the jacket, see Figure 3. The fabric provides the high resistance in tension, while in compression the behavior is mainly influenced by the rubber. In bending, the fabric determines the neutral fiber. In addition, the material properties vary depending on the manufacturer. Another even more complex part is the hinge of the USSID rib-cage, see Figure 2. It consists of several layers of fabric embedded in an elastic rubber material. The hinge connects the ends of the steel ribs with the spine. Hence, it significantly contributes to the overall stiffness of the rib cage. Therefore the parameters of the material cards for the finite element model of the hinge had to be purely determined by component tests and then adjusted by corresponding component simulations.

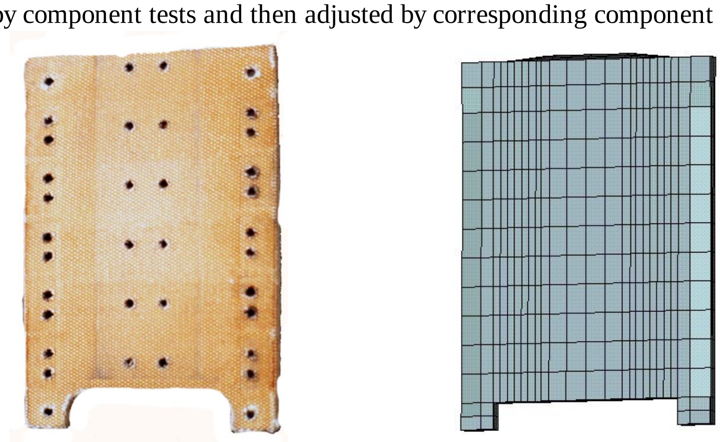

Figure 2: Rib hinge of the USSID, original part and FE model.

An example for pre-stressed structures is the lumbar spine of the USSID. The spine consists of a thick rubber cylinder which is compressed by a steel cable. Again, material data for the rubber and the steel cable are found by simulating component test. Even for the simple cable it is not trivial to model the non-linear bending behavior and the different stiffness in tension and compression.

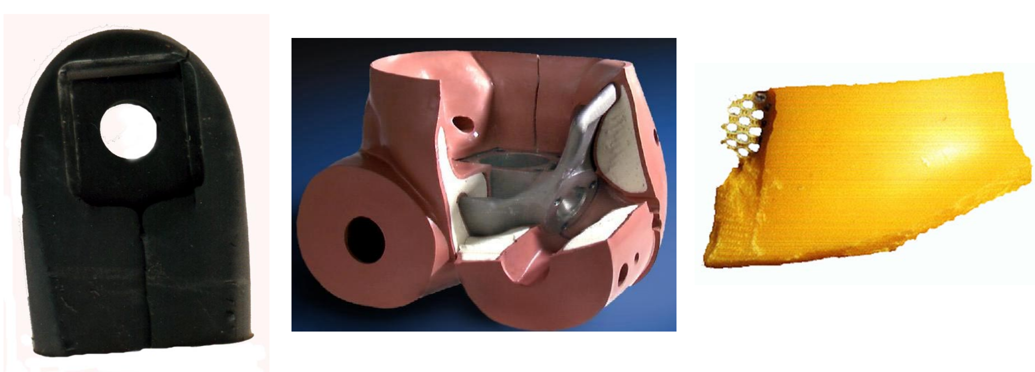

Figure 3: Upper arm foam EUROSID (left), part of the USSID pelvis and jacket (right).

Implementation of Experimental Data on Component Level

Obviously, component testing for the spring damper units, for the thorax or drop tests for the head are reasonable. Furthermore component tests were performed to optimize material definitions, if the material tests were not possible, as described above. In addition, some component tests were defined to consider blocking and sticking effects. For instance non-lateral impacts on the thorax were performed. The crucial question for all experiments was to define a load scenario close to the loading expected in an side impact crash. Trivially, the strain rate effects in foams are visible, if a structure is loaded with the corresponding strain rates. Unfortunately, the majority of experimental data available for the calibration of the hardware dummy is obtained at considerably low loading velocities. Furthermore, the geometry of components is extremely important for their behavior, however, it is often neglected. As examples the complex geometry of the a pelvis and the upper arm foam of the EUROSID are depicted in Figure 3.

Even for foam materials small adaptations had to be made, since the behavior of the open cell foams depends on the outflow of the air. Hence, the size of the specimen, the open surface and the venyl coverings influence the properties of the part, unless this effect is considered within a further model.

The difficulties to define appropriate component tests can be demonstrated on the already mentioned simple example of the lumbar spine. Depending on the impact we observe a superposition of shear, bending, torsion and tension. Often the loads result in small deflections only. A pure pendulum test (see Figure 4) is considered in the following, where the spine is clamped between a long pendulum and a defined mass at the bottom. Initially, all parts have the same rotational velocity around the joint of the pendulum. In the experiment the pendulum is decelerated by a block out of honeycomb material. For this simple test the initial and the boundary conditions are clearly defined. In the test we have to work with high angular velocities to have the same initial conditions as in a crash. This results in rather high deflections which usually do not appear in the dummy. However, the test gives important information on the bending behavior, despite the effect of the combination with other observed loading is neglected. Test procedures combining the different types of loading are very difficult to perform. In addition, it must be mentioned that the test racks have complex designs which often results in uncertainties in the boundary conditions, particularly for high speed tests.

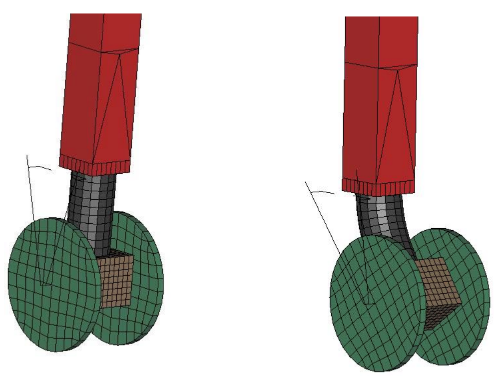

Figure 4: FE model of the lower spine in the pendulum test.

Since the deflections of the spine of the dummies are usually small, already the beginning of the bending of the spine must be carefully considered. In order to achieve this, the material properties must be optimized for a good correlation in this phase. The correlation in the later bending phase, however, is secondary for the dummy development. Such a selective accentuation of test data seems to be one of the key issues during the development of the finite element models.

Implementation of Experimental Data from the Sled Tests

The considerations about appropriate loading as presented above is also a major argument to use test data of sled tests to further enhance the finite element models. In the majority of the sled tests rather rigid barriers, some even with mounted airbags, are used. Since the dummies show considerably good correlation in integrated simulations, it seems sufficient to use mainly rigid barriers during the development also in the simulation models. The simulation of the sled tests, however, showed new phenomena manly affected by the interaction of different parts in contact. Hence, the proper modeling of the complex contact situations becomes a high priority. For some soft foams the correct modeling of the contact, allowing almost no penetration, caused difficulties for the stability. The latter is a result of the high deformation, as these soft foams get frequently extremely squeezed between different parts. Particularly the abdominal inserts and the arm foam of the USSID needed additional consideration concerning contact and contact stiffness. Interestingly the real hardware dummies show often damage in exactly these foam parts. The stability of the created FE models is tested with the simulation at very high loads. Even for these extreme loads a good correlation with test data is often achieved. Different stages of deformation of the arm foam are depicted in Figure 5.

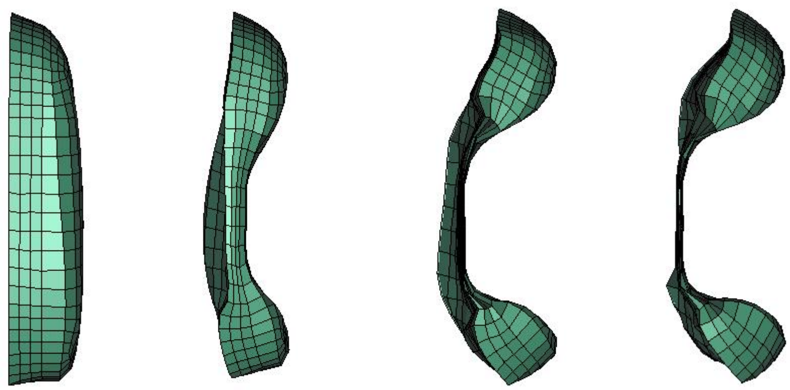

Figure 5: Deformation of the soft arm foam of the USSSID in a sled test.

The significant advantage of getting more appropriate loading from sled tests yields to the question if the material tests and the component test would be dispensable. However, the simulations with the fully assembled models have the clear disadvantage that it is very difficult to locate the corresponding entities to modify the models correctly, as the results are determined by many factors affecting each other. Thus it is very difficult to assign a signal to a single specific event in the model. Roughly speaking: There are far too many unknowns in the equations for a good inverse analysis. Basically, the work with the experimental data from the sled test is comparable with a common nonlinear optimization problem. From optimization theory it is known how important a good starting point is. The goal of the material and component test is to reduce this figure of unknowns and to provide a good staring point by sticking to the original idea of FE modeling with continuum theory and corresponding material models and material data. For the dummy development this implies that the finite element models must already have a certain quality, until the model can be enhanced with sled test data. Then an optimum between efficient modeling and necessary detailing can be achieved.

Additional Aspects

During the development experiments of the EUROSID were performed with the jacket and without the jacket. The jacket is made of Neoprene material with approximately 5 mm thickness. Even for the plane barrier the rib intrusion varies significantly for both cases as shown in Figure 6. Due to the lack of the jacket a higher rib intrusion should be expected, however, the opposite is measured. The difference is mainly a result of the different motion of the arm. It is generally observed that the model is highly sensitive against the motion of the arm on the impacted side. For this experiment the major dependence is on the difference in friction a) between arm and barrier as well as b) between arm and ribs. Hence, in a simulation great caution has to be taken to use sufficiently accurate models also for the parts interacting with the dummies thus the car interior and the airbag.

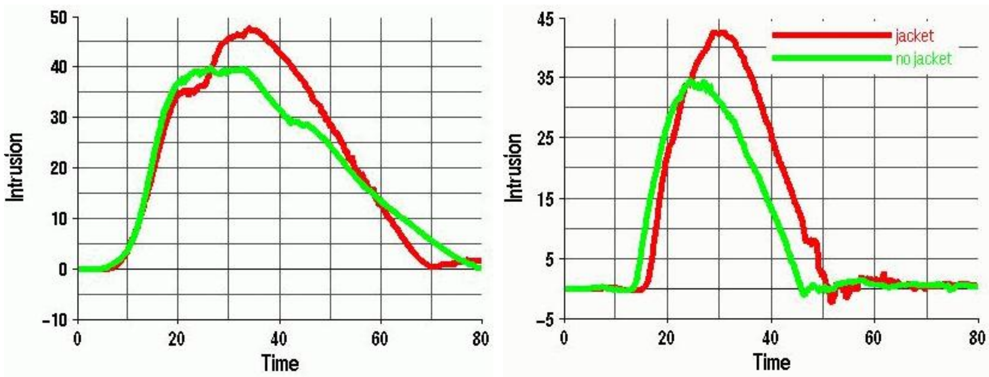

Figure 6: EUROSID, upper (left) and lower (right) rib intrusion vs. time, plane barrier; rib cage with and without jacket

Successive re- and de-refinement
Above we have seen, that for the definition of test procedures on material and component basis specific knowledge on the loading during the side impact crash is vital. In many cases, however, it is not possible to get this information from the hardware dummies, since it can not be measured. Hence, finite element models appear to be a good instrument to obtain the desired information. This kind of inverse problem lead to the methodology applied in the project which we named 'successive re- and de-refinement'. First data from simulations with course models were used to predict the loads. Based on this information the material and component tests were defined. The results of the tests were again used to correct the dummy models. This procedure was repeated a couple of times. Within these development loops the models were mostly refined; less often a de-refinement was possible. Different stages of discretization for the pelvis of the USSID are depicted in Figure 7 representing different states in the loop. For each stage the geometry is modeled with more details. New element technologies are used. The element size of the deformable parts were first refined significantly and later de-refined slightly. Furthermore, the geometry of the outer hull of the pelvis is modified from version 2.5 to 3.0. As material model initially Viscous_Foam (Type 62) was used, then material type Low_Density_Foam (Type 57), and finally, Fu_Chang_Foam (Type 83) was taken.

The original models for the EUROSID and the USSID were first enhanced based on barrier tests (Erbelding C., Kurz A., Schelkle A., 1996). These models were then used by the members of the FAT in full car crashes. Furthermore, the FAT used the models to analyze the loading in some detail. The result was the specification of tests procedures on material, component and fully assembled level. Often further ideas for appropriate tests were proposed during the enhancements of the models. Thus performing tests was an ongoing process during the development. For instance, more than 4 series of materials tests were performed for the EUROSID parallel to the model development.

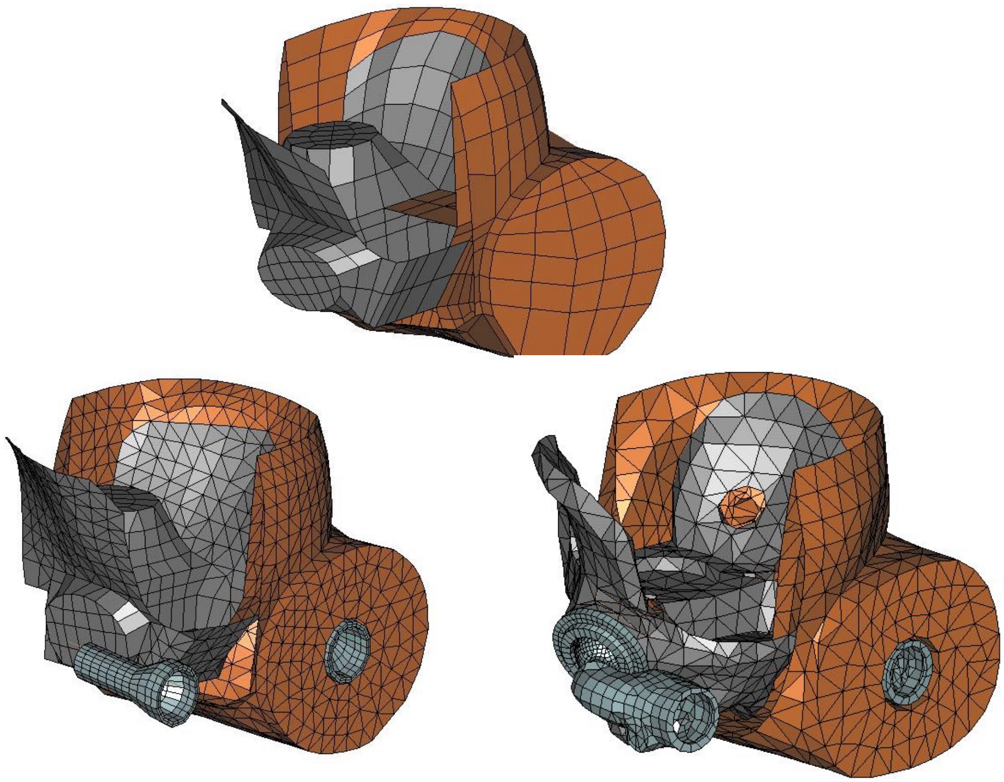

Figure 7: Development stages of the pelvis of the USSID
(top: Version 1.00; left: Version 2.5; right: Version 3.0).

MODEL DESCRIPTION

Commercially available are currently version 2.0 for the EUROSID and version 2.5 of the USSID. Version 2.5 for the EUROSID will be available soon. Both consist of approximately 30,000 nodes, 20,000 brick elements (mainly tetrahedrons; element type 10 in LS-DYNA) and 20,000 shell elements (mainly Belytschko-Tsay elements) and a couple of discrete and beam elements and more than 100 part/material definitions. For modeling the foam materials usually material type 83 (Fu_Chang_Foam) is employed. In some cases the extensions of material law 83 (Hirth A., Du Bois P., Weimar K.,1998) are applied. Only a few foam parts are modeled with material model 62 (Viscous_Foam). For modeling the venyl skins different models are used: Depending on the importance, material type 61 (Maxwell/Kelvin Viscoelastic with Maximum Strain) or material type 1 (Elastic) are chosen. Material law 76 (General Viscoelastic) is used to describe the jacket of the USSID. Rubber parts are modeled with material type 6 (Viscoelastic) or type 61 (Maxwell/Kelvin Viscoelastic with Maximum Strain). The majority of the iron or aluminum parts are modeled with material type 20 (Rigid). In some soft foam parts material Type 9 (Null), usually combined with shells are used to avoid element collapse. One major single surface contact (Type 13) with the soft constraint option is used to model the contacts in the dummy. The contact takes the real thickness into account. All contact parameters are default settings. In addition, contact type Automatic General (Type26) is applied in specific areas. The recent models use the stiffness based joint definition in combination with the generalized stiffness option. Global damping is not applied. The models run with LS-DYNA version 950a upwards.

BARRIER TEST CORRELATION

In the following the correlation of the simulation with barrier sled tests is presented. The following graphs depict the experimental results in thin dashed lines, the simulated signals are printed with thick lines. Since the performance of the FAT USSID model Version 2.5 was already presented in (Franz U., Graf O., 2000), (Graf O., Walz M., Franz U., 1999) and (Franz U., Graf O., Walz M., 1999) only a short excerption is given in the following. More results are presented for the EUROSID. Since Version 2.5 for the EUROSID is upcoming soon results are presented for version 2.0 and the beta-release of version 2.5.

Barrier with Arm Impactor, FAT USSID Version 2.5

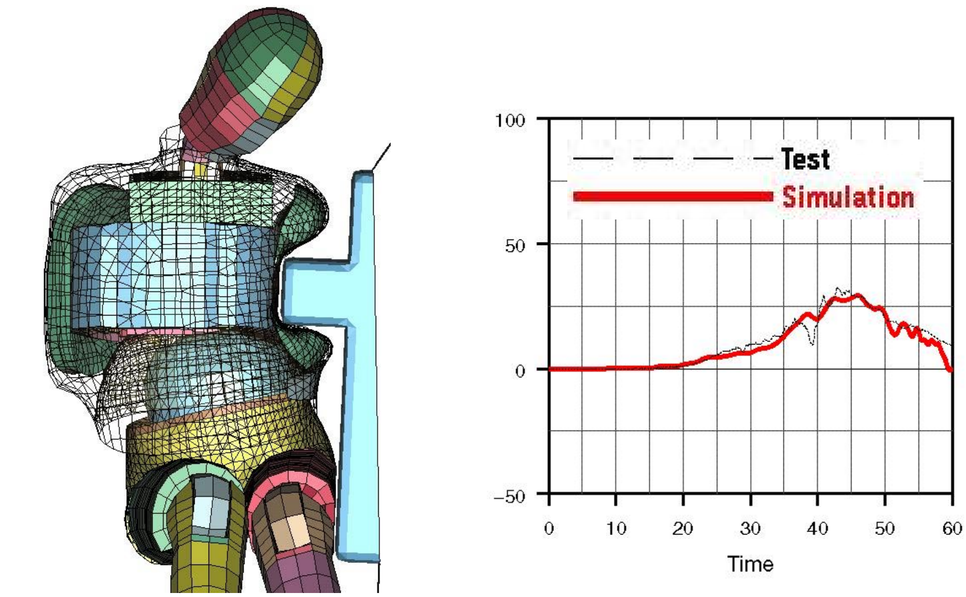

Figure 8: Model during sled test, acceleration [g] in pelvis vs. time [ms].

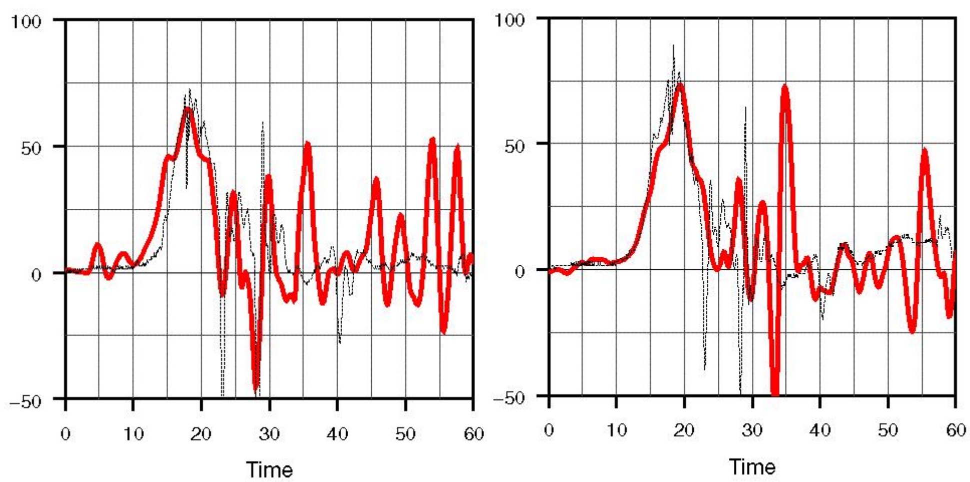

Figure 9: Acceleration [g] upper and lower rib vs. time [ms].

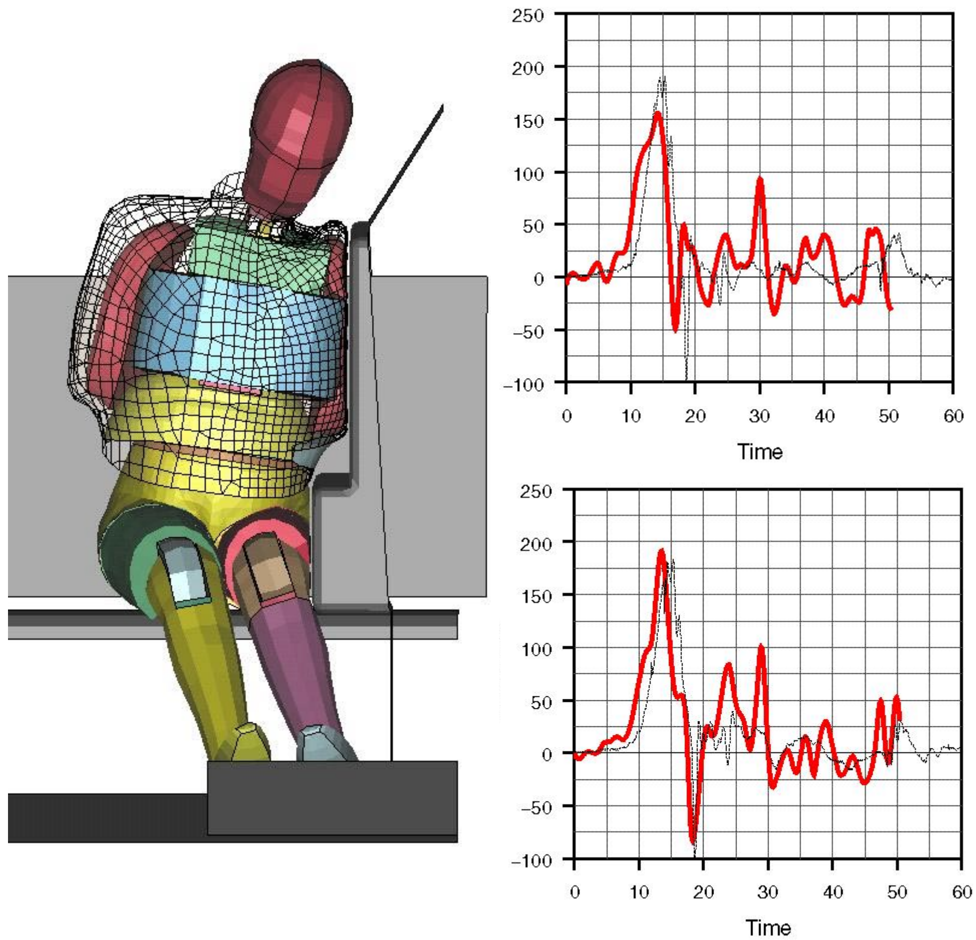

Figure 10: Accel. [g] upper (right top) and lower rib vs. time [ms], barrier velocity 8 m/s.

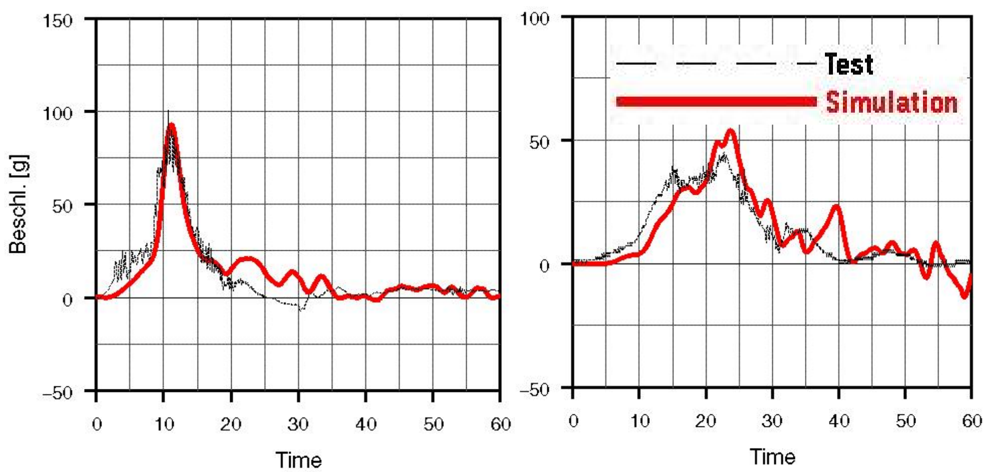

Figure 11: Accel. [g] pelvis (left) and lower spine vs. time [ms], barrier velocity 6 m/s.

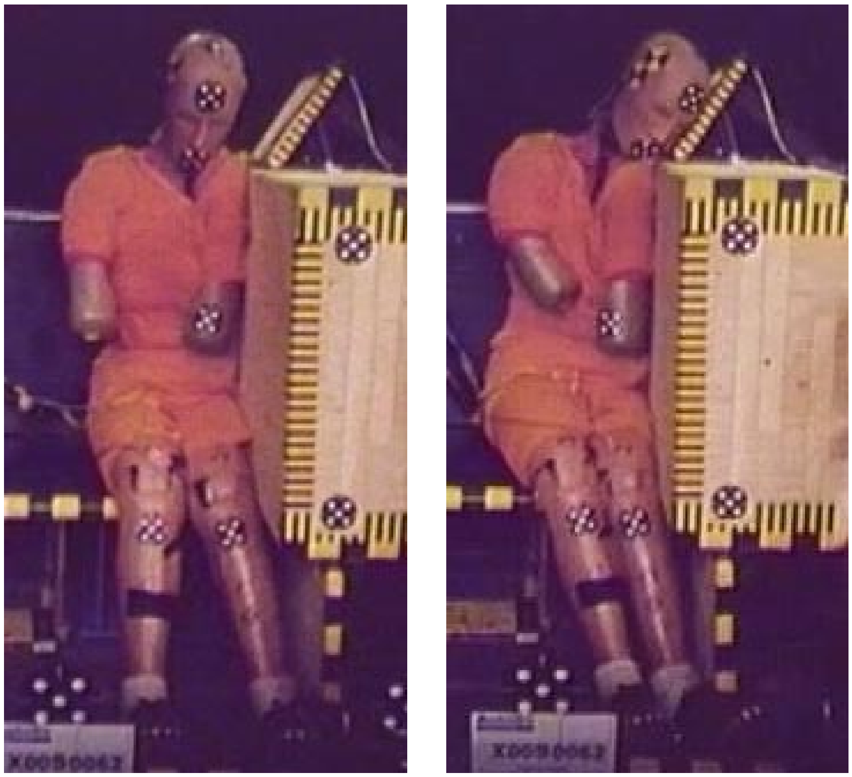

Figure 12: EUROSID during impact.

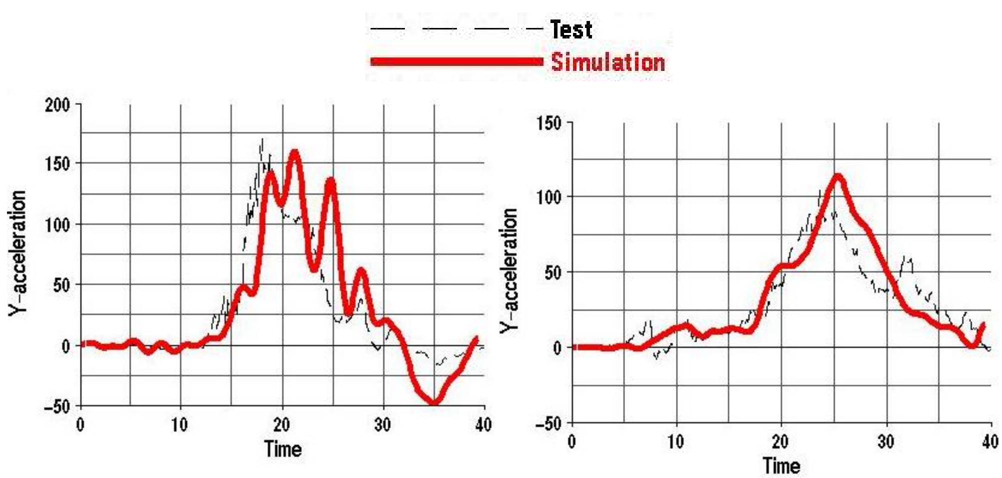

Figure 13: Acceleration [g] for pelvis and upper spine vs. time [ms].

Plane Barrier, FAT EUROSID Version 2.0

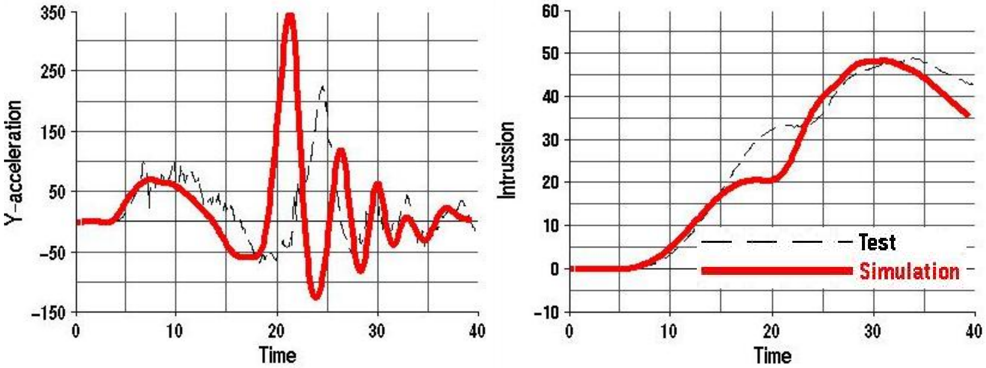

Figure 14: Acceleration [g] and intrusion [mm] upper rib vs. time [ms].

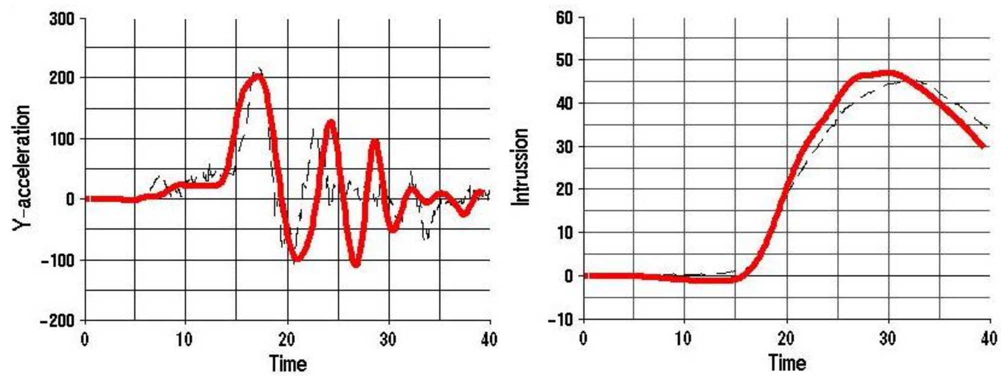

Figure 15: Acceleration [g] and intrusion [mm] middle rib vs. time [ms].

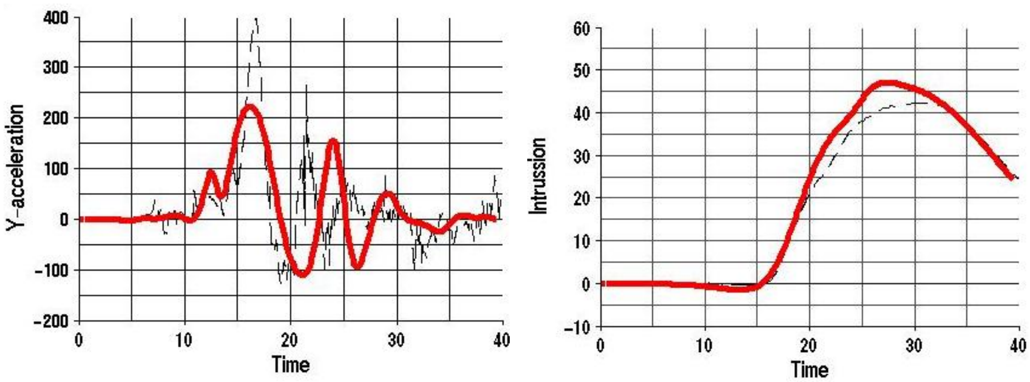

Figure 16: Acceleration [g] and intrusion [mm] lower rib vs. time [ms].

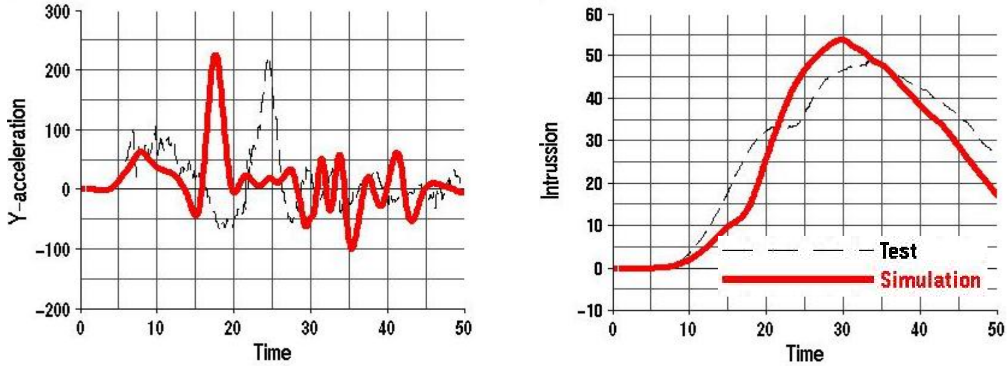

Figure 17: Acceleration [g] and intrusion [mm] upper rib vs. time [ms].

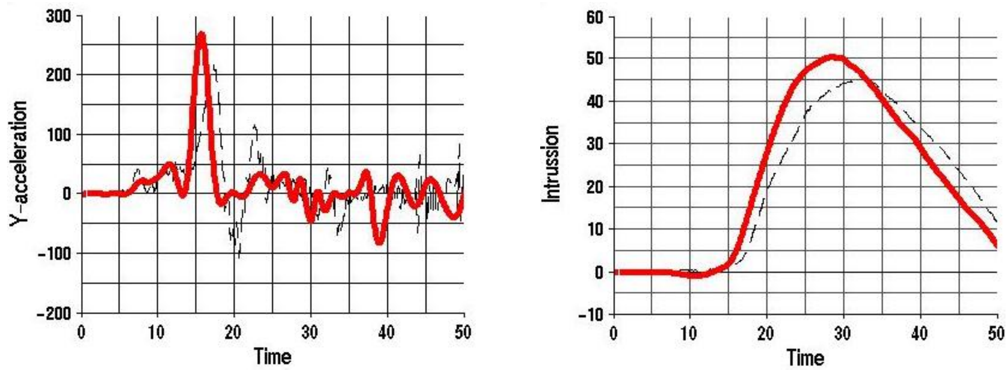

Figure 18: Acceleration [g] and intrusion [mm] middle rib vs. time [ms].

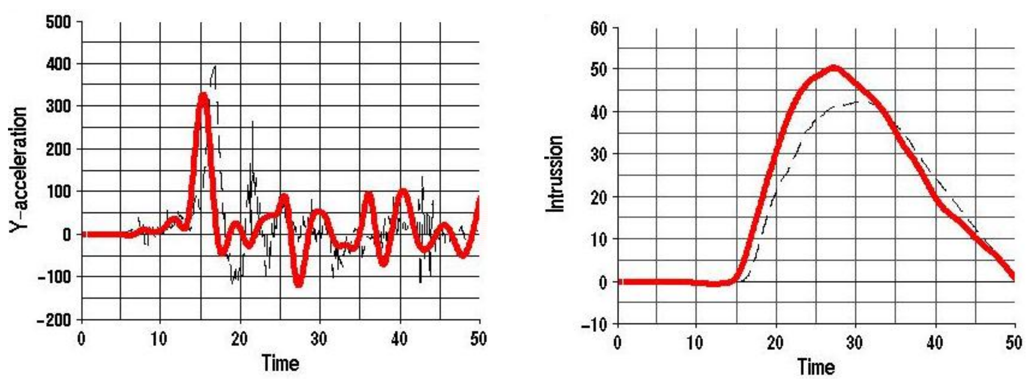

Figure 19: Acceleration [g] and intrusion [mm] lower rib vs. time [ms].

Barrier with Pelvis Impactor, FAT EUROSID Version 2.5 (beta)

Figure 20: EUROSID during impact.

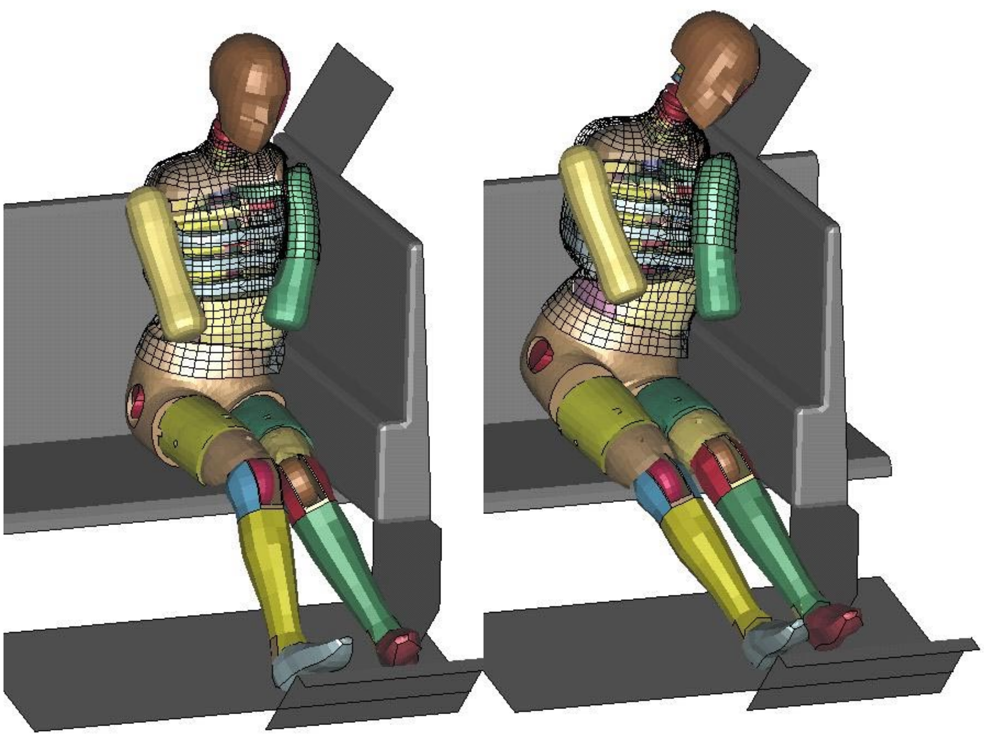

Figure 21: FAT EUROSID model in the simulation.

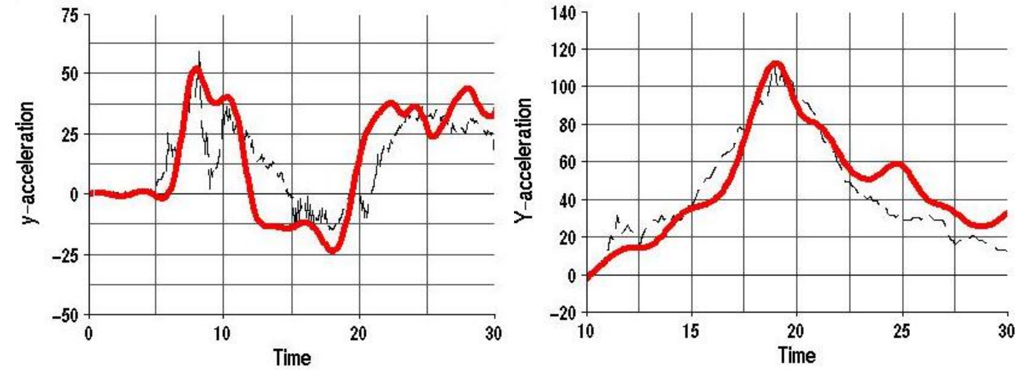

Figure 22: Acceleration [g] upper and lower spine vs. time [ms].

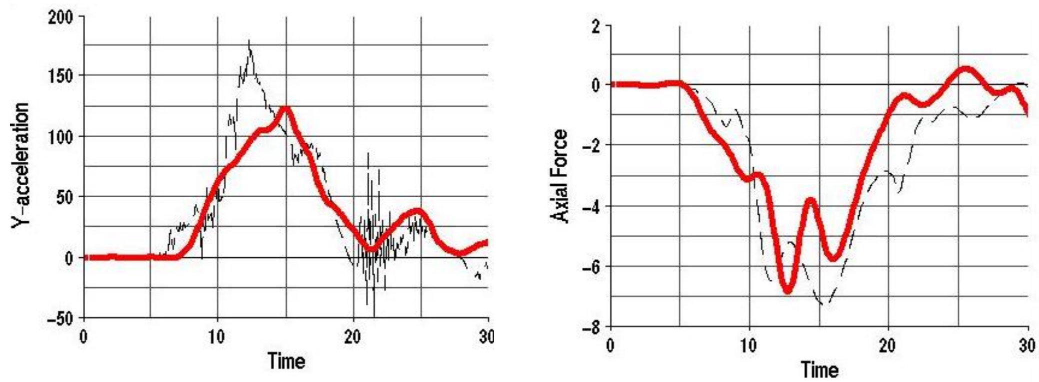

Figure 23: Acceleration [g] and force [kN] pelvis vs. time [ms].

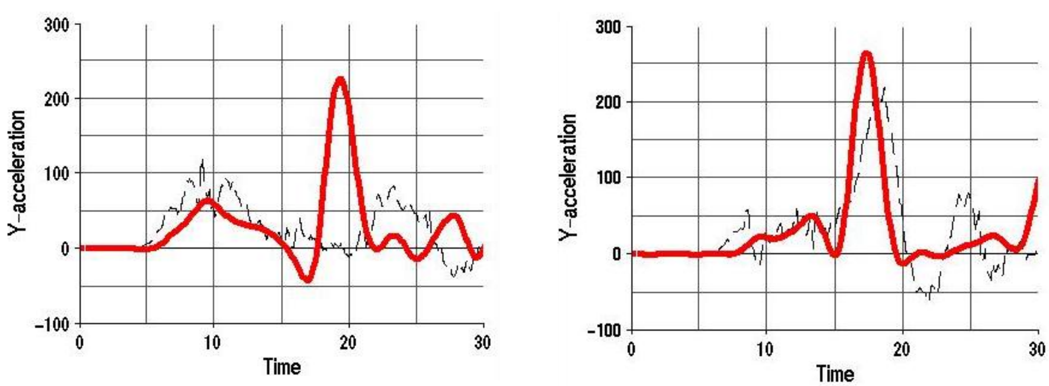

Figure 24: Acceleration [g] upper and middle rib vs. time [ms].

CONCLUSIONS

The methodology applied in the development of the FAT dummy models was outlined. The indispensable need of both, component and sled tests is explained using simple examples.

The LS-DYNA FAT USSID and EUROSID models are validated using a wide range of experimental data. The models rely on many new features of LS-DYNA to describe the occurring effects. The features available in LS-DYNA allow the direct use of a wide range of experimental data. Regarding other finite element dummy models, the FAT models are capable to capture many details with very high complexity with relative high efficiency. The major goal of the cooperation of CAD-FEM with the FAT to generate accurate and stable finite element models has succeeded up to now.

The models are commercially available in version 2.0 for the EUROSID and 2.5 for the USSID. The results of the simulation presented in the paper show the good performance of the models compared to experiments.

ACKNOWLEDGMENTS

The authors would like to thank the LS-DYNA users of the FAT project for the encouraging support. In particular we express our thanks to Mr. Andreas Hirth from DaimlerChrysler AG for his substantial contribution during the development of the USSID. In addition, we thank Mr. Matthias Walz from Daimler Chrysler AG for his strong engagement.

REFERENCES

ERBELDING C., KURZ A., SCHELKLE A., (1996), "Development of Finite Element Side-Impact Dummies: A contribution to efficient occupant simulation". Berechnung und Simulation im Fahrzeugbau. Tagung Würzburg. VDI-Gesellschaft Fahrzeug- und Verkehrstechnik. VDI-Berichte: 1283. ISBN 318 091283 9,Page: 263 to 282

FRANZ U., WALZ M., RUST W., (1998), "CAD-FEM development of finite element side impact dummy models in cooperation with the German automotive industry", 5th International LS-DYNA Conference, Detroit, USA.

FRANZ U., GRAF O., WALZ M., (1999), "ENHANCEMENTS TO THE FAT FE DUMMIES USING SPECIFIC FEATURES OF LS-DYNA", 2nd European LS-DYNA Conference, Gothenburg, Sweden.

FRANZ U., GRAF O., (2000), "Development of the FAT Dummies", CAE 2000 Conference, Fujitsu, Nagoya, Japan.

FAT, (1997), "FAT im Überblick". Forschungsvereinigung Automobiltechnik e. V. (FAT). Westendstrasse 61, 60325 Frankfurt, Germany.

GIBSON L., ASHBY M., (1998), "Cellular Solids Structure & Properties", Pergamon Press Oxford, New York.

GRAF O., WALZ M., FRANZ U.,(1999), "Erfolgreiche Anwendung neuer LS-DYNA Features bei der Entwicklung des FAT-USSID", 17th CAD-FEM Users'Meeting, Sonthofen, Germany

HIRTH A., DU BOIS P., WEIMAR K., (1998), “Erweiterungen des LS-DYNA Materialgesetzes 83 (Fu Chang) für die industrielle Simulation von energieabsorbierenden reversiblen Schäumen“, 16th CAD-FEM Users’ Meeting, Bad Neuenahr-Ahrweiler, Germany.

HIRTH A., DU BOIS P., (1999), “From complex 3D-foam parts to ready input data in less than one hour”, 2nd European LS-DYNA Conference, Gothenburg, Sweden.

JANSSEN A., VERSCHUT R., SALADIN A., (1995), “ New Instrumentation for EUROSID 1”, TNO, Information Document, Netherlands.