FAT SIDE IMPACT DUMMY MODLES
REMARKS ON USAGE AND POTENTIAL PITFALLS

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Abbreviations:

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

Keywords:

FE Dummy Simulation, Side Impact, ES-2, USSID, EUROSID, FAT, Validation

ABSTRACT

Detailed finite element side impact dummy models of the USSID, EUROSID, and ES-2 have been developed in cooperation with the German Association for Automotive Research (FAT) during the last 5 years. All models are validated using tests at material and component levels as well as fully assembled models. The models are used by nearly all car manufacturers worldwide who use LS-DYNA for occupant safety simulations. The paper describes modeling aspects of the dummies and gives an overview of their performance in sled tests. Furthermore emphasis is put on difficulties and potential pitfalls that might arise during the everyday work with the models in predicting occupant injury risks. In addition to the knowledge gained during the development process, experiences from the support for and the consulting with the FAT dummy models are presented.

INTRODUCTION

Nearly all German automotive companies join parts of their research activities within the FAT, the German Association for Automotive Research [1]. In 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-1 and the USSID, respectively. In 2001 a development for the ES-2 model was launched. The major goal for the development was to achieve a high degree of accuracy of the models, followed by 'stability' criteria in order to avoid numerical instabilities. The demands on computational efficiency of the models were lowered considerably setting the priority on the quality of the results. 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, DaimlerChrysler, Johnson Controls, Opel, Porsche, TRW, and Volkswagen contributed their experience and guided the development.

DYNAmore took responsibility in the projects to develop the 3 models in LS-DYNA. The models are commercially available from DYNAmore and the local responsible distributors. The models will be updated on a regular basis according to further regulations and knowledge.

EXPERIMENTAL DATA FOR MODEL DEVELOPMENT

An essential goal was to obtain experimental data close to the loading expected in real crash scenarios. The tests are described more detailed in [3]. After a series of tests simulations were used to define subsequent tests and the test results were used again to enhance the models and so on. The methodology of development is described in [4].

Material tests
Almost all specimen were taken from new parts delivered by FTSS. In order to get more general 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. Emphasis was directed towards strain

rate dependent foams used in many areas of the dummies. Details on specific material tests are presented in [1].

Component tests

To develop the EURSID-1 and USSID model a large variety of component tests were performed as: Head drop tests, dynamic shear tests for the lumbar spine, pendulum tests of the lumbar spine, neck pendulum tests, drop tests of the damper, partial and complete thorax impact tests, pendulum tests of the abdomen, impact tests on the pelvis and on pelvis/upper leg, and impact tests for the shoulder foam cap. If possible, standard test devices used in dummy calibration were used. The tests were performed usually for a large variety of speeds and masses. For the ES-2 model fewer component tests were performed. It was mainly the rib module that has been investigated by pendulum tests. Different masses, different speeds and impact locations and angles were considered. Along with the standard measurements the motion of the damper piston was measured. Furthermore, pendulum tests for the neck and lower spine were performed.

Pendulum tests on fully assembled dummy

For the validation of the EUROSID-1 and USSID no pendulum tests on the fully assembled dummies were performed. However, for the ES-2 model a considerably high number of tests were made to validate the model. Figure 1 depicts the ES-2 dummy in a pendulum test and the numerical model in the corresponding test. Usually the test is performed at two different impactor speeds. Pros and cons of the pendulum and sled tests are given in [7]. Figure 3 (right) depicts the different impacting positions.

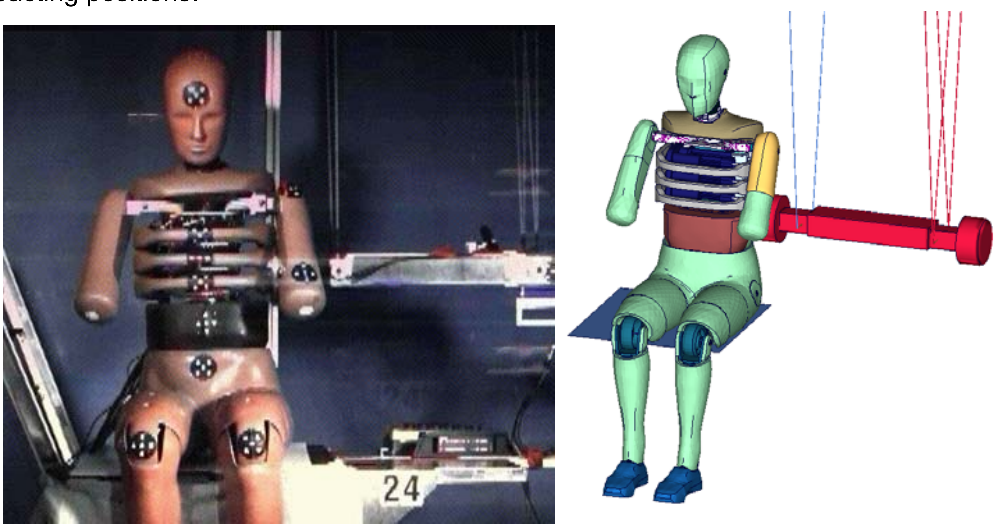


Figure 1 Dummy (left) and model (right) in pendulum test

Barrier tests with fully assembled dummies

Many experiments were performed with rigid (rather stiff) barriers. The speed varied from 4 to 7 m/s with barrier masses above 1 t. The dummies were fully instrumented and the recorded quantities were: Accelerations, forces, moments, and displacements. Furthermore, the dummies were equipped with contact foils to determine the time of contact between several parts. For the ES-2 model all shapes of the barriers were designed to have comparable loads to a vehicle test. For the EUROSID-1 and USSID model additional barrier shapes were used to validate specific parts of the dummy model. The different barrier shapes implied for the validation are depicted in Figure 2 and 3 (left). The impacting surfaces were inclined in some barrier tests for the ES-2 model. A discussion if a good correlation in the barrier tests is sufficient to achieve good dummy models for a full vehicle test is presented in [6].

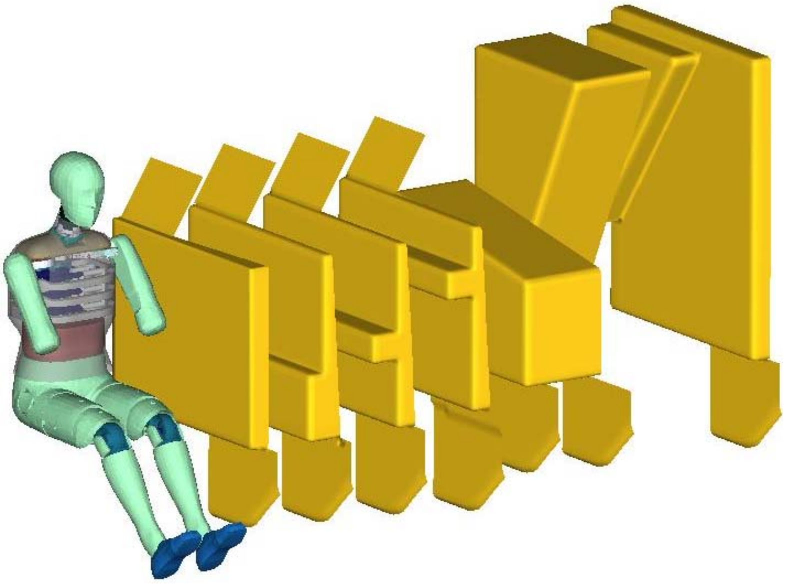


Figure 2 Barrier shapes used to validate FAT EUROSID-1 and USSID model

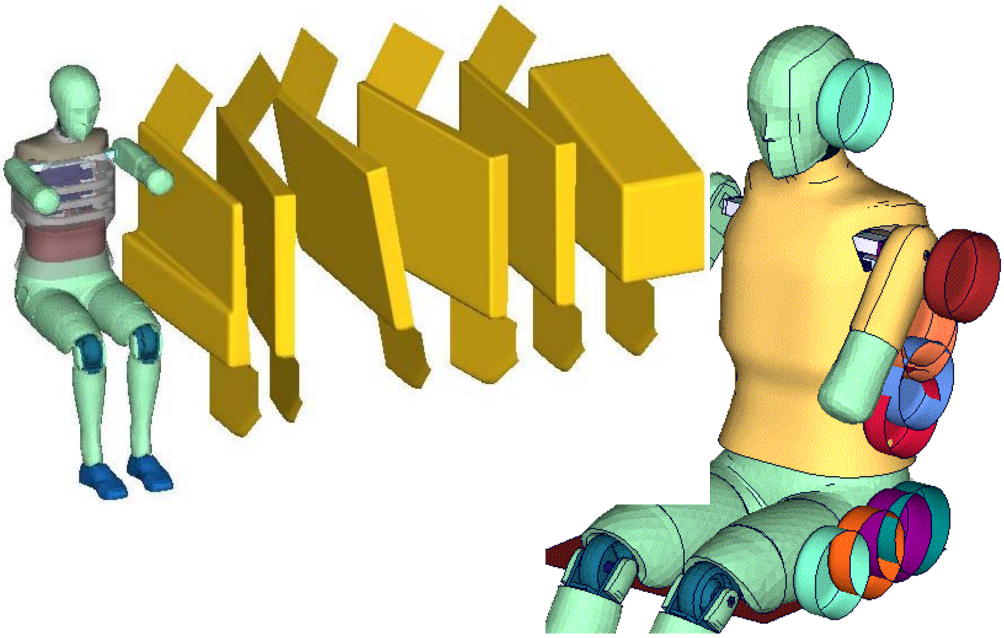


Figure 3 Barrier shapes (left) and pendulum impact locations (right) used to validate the FAT ES-2 model

REMARKS ON USAGE AND POTENTIAL PITFALLS

In the following we listed ideas assessed to be useful during the daily work with the models. It is a collection of information aiming to facilitate the usage of the models and to explain occurring effects.

Geometry of model

For the USSID and the EUROSID-1 no CAD-data is available and the geometry was obtained by 3D measurements and drawings. For ES-2 CAD data was purchased from the manufacturer. However, for all the models the used geometry is not unique. The inaccuracies and arbitrariness are described below. The CAD data of the foam parts describes the surface of the mold of the venyl hull. A model based on this data would have many penetrations, because the real parts shrink due to the manufacturing process, and during assembly many parts are pre-stressed and deformed by neighboring parts. Hence, non-unique assumptions have to be made to obtain a representative model. Furthermore, the geometry of the model is influenced by gravity loading and deformations during positioning. The gravity leads to shrinkage of the dummy as well. Figure 4 shows a comparison of the ES-2 dummy model based on the shrunk CAD data and the model under gravity loading. The shoulder is lower in the model under gravity, the sacrum block in the pelvis is slightly rotated and the lower spine is bent. The delivered model of the ES-2 is a model under gravity loading; it is meshed using the CAD data and then adapted based on a 3-D measurement of the fully assembled model with an upright seating position. For the USSID we have an influence of the pelvis angle due to the gravity loading. Therefore, an adaptation has to be made. For the USSID a 3D measurement of the fully assembled model is difficult to compare because the jacket has no significant point of reference. In addition, the dummy has to wear the jacket in order to have the correct upright position. For the Eurosid-1 model the geometry is achieved by pre-simulation.

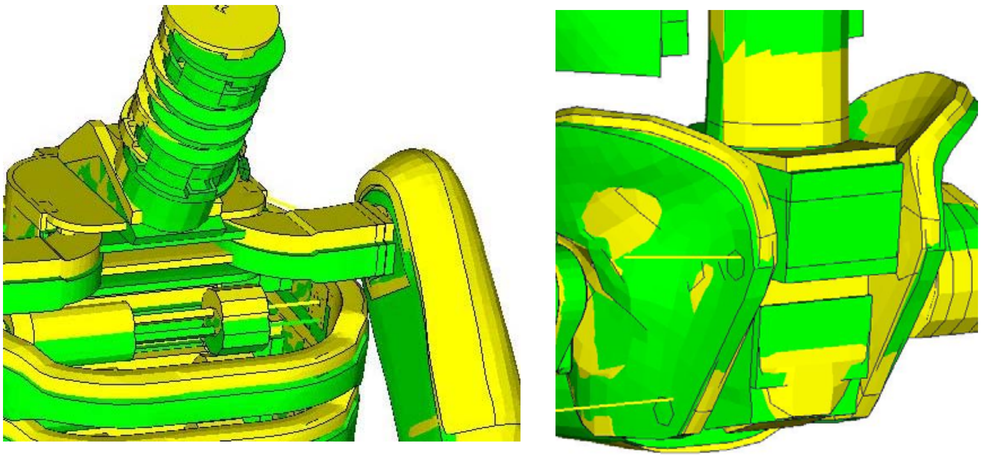


Figure 4 ES-2 dummy parts as obtained by meshing CAD data in yellow and model under gravity load in green; Upper thorax (left), sacrum block (right)

In case sharp edges e.g. an arm rest will hit the dummy model it is recommended to position the dummy carefully and to consider the inaccuracy sources in z direction (Axis in SAE notation). Sometimes the nose of the dummy is used to check the position of the dummy in the x-z-plane. Unfortunately, the neck of the dummy has a large slack and the position is determined by the seating procedure. The neck of the

ES-2 model is modeled such that the nose tip position fits to the 3d-measurement of the dummy, i.e. the head is nicked forward; no slack remained in the front parts of the neck model.

Positioning

For all models the lower legs and feet can be moved to adjust the model to the seating position. The movement of the upper legs in respect to the pelvis is very limited for all three dummies. If an upper leg is moved the foams in the pelvis and the upper leg will be deformed. To achieve the change in geometry a pre-simulation has to be performed otherwise the model will end up with large initial penetrations. Exactly the same effect can be observed regarding the deformation of the seating cushion, the pelvis and upper leg due to the contact of dummy with the seat. Additionally, the problem is also present at the back of the model if the seat is equipped with a narrow back rest. A pre-simulation is needed as well. In many applications it is sufficient to neglect the initial stresses and to avoid initial penetrations by re-meshing the adapted geometry of the involved parts. The back of the USSID has been changed already slightly to fit better to a standard seat. The modification is only in the soft foams and has no influence in all performed test. Another important influence has the arm position of the ES-2 and EUROSID-1 after positioning. A large tolerance of the angle between the arm and the thorax can be observed in the dummies. A variation of +/- 5 degrees seems reasonable. The position of the arm determines if the hard upper arm foam hits the middle rib or the much softer lower arm foam and result in differences in the rib intrusions. The movement of the arm towards the thorax is also influenced by the height of the impacting surface. Figure 5 shows the rib intrusions of the middle rib and the upper spine acceleration of the barrier depicted in Figure 19. For on curve the barrier height is 20 mm higher. A difference in the intrusions and almost no difference can be observed for different.

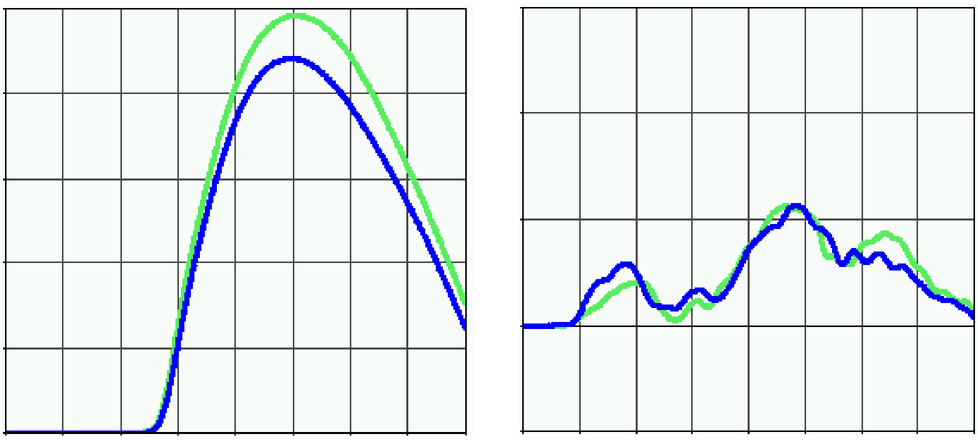


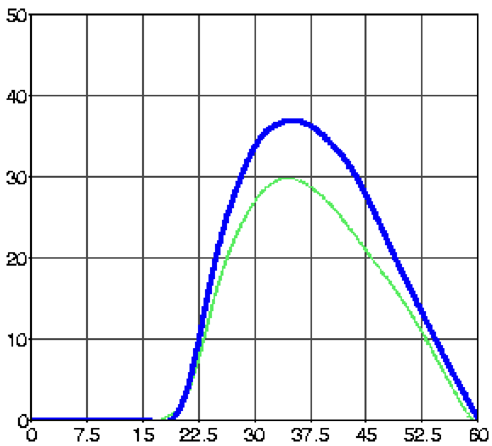
Figure 5 Rib intrusion and upper spine acceleration of ES-2 dummy barrier height of barrier depicted in Figure 19; barrier height for green curve 20 mm higher

H-Point

Often the question arises how the h-point measured in tests fits to the h-point of the EUROSID-1 or ES-2 model. In tests the h-point is measured by an h-point manikin. But the h-point of the manikin is not the h-point of the 2 models. The h-point (center of hip joints) of the dummy is more forward and above the h-point of the manikin. The difference is 21 mm in x direction and 5 mm in z direction, more details are given in [9]. In the models both, the real h-point and 'manikin h-point' are modeled as extra nodes.

Frictional dependencies

In the sled tests the friction has a significant influence for the rib intrusion of the ES-2 or EUROSID-1 model. The intrusion is influenced by the friction between the different dummy parts and the friction of the dummy with the barrier. It seems that the difference in rib intrusion is due to the different movement of the arm. Figure 6 depicts the rib intrusion of the middle rib and the pelvis acceleration in a sled test; the difference between the two models is solely due to different frictional parameters in the internal contact. The model with signals in green lines has static frictional coefficient of 0.3 and dynamic coefficient of 0.25, the curve in blue has 0.2 and 0.15 as coefficients. Moreover, we found it very difficult to define suitable methods to determine the frictional values in tests. In the barrier tests for the ES-2 the frictional influence was reduced by a coating of the barriers. But even with the coating the friction was not reduced to zero, depending on the different contact partners, for instance jacket with barrier, venyl with barrier or shirt with barrier. Many other signals e.g. accelerations do not show the high dependency on the frictional parameters as the rib intrusions. We assume that the influence is much less important for load cases with airbag involvement. The airbag encloses and prevents the movement of the arm significantly and thus will reduce the influence of the friction. If the airbag pushes the arm forward and the influence of friction will be limited as well. The investigations of this effect in a full car crash simulation with different airbags and varying seating positions have not been completed yet. For the USSID model the frictional dependency was not observed.



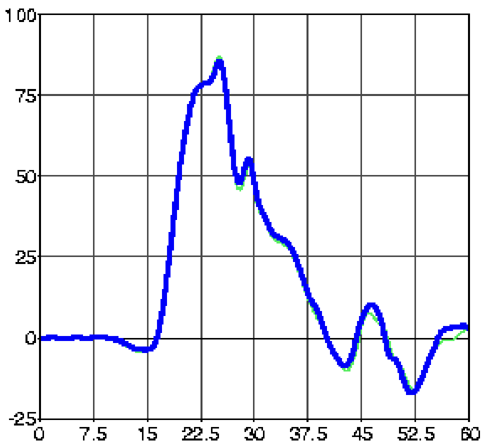


Figure 6 Rib intrusion of middle rib (left) and pelvis acceleration (right) of ES-2 in a sled test with different frictional parameters for the dummy to dummy contact; the graphs show [mm] and [g] vs. time [ms], respectively

2nd peak in USSID Rib acceleration

In some full vehicle test the rib acceleration of the USSID shows a second peak with a considerably high amplitude. This behavior can not be observed in the barrier tests, hence a reliability regarding this effect can not be shown in a sled test with a barrier hitting the dummy with an almost constant speed. However, the results achieved by several customers indicate that the behavior is predicted properly.

Contact definition of dummy with surroundings

The models use an automatic single surface contact with the option 'Soft Constraint equals one'. For the contact of dummy with surroundings we recommend a node to surface or an automatic node to surface contact. A second single surface contact containing parts of the dummy should be avoided, because the soft constraint option may lead to too high penalty forces and as a result to instabilities in the contact. To have a proper modeling of the contacts it is important to use on of the latest dummy model releases and recent LS-DYNA versions. The earlier models showed much more problems in handling the contact properly, in particular on the MPP platforms.

Correlation of results

It seems to be reasonable to group the measured quantities in three classes depending on their ease or difficulty to correlate them with numerical data. Accelerations belong into the first class. They are usually dependent on the direct impact (rib accelerations, pelvis accelerations). The second class contains length measurements like rib deflections. In addition to the impact these signals also depend on the movement of the dummy in particular for the EUROSID-1 and ES-2 models on the interaction of the dummy parts themselves. The third class are forces and moments which also show a strong dependency on the movement of the dummy and subsequently on the inertias, friction, pivoting parts and the car interior. Examples are T12 or back plate moments and forces. Achieving good correlation with tests was most difficult for class 3 signals, class 1 signals were the easiest quantities to correlate. The signals of class one showed a high stability in terms scattered signal due to variations of the material properties. Small changes in the material properties usually had a minor effect on the measures acceleration. Signals in Class 2 and 3 are much more sensitive on the material parameters. This classification might be trivial, for us it was surprising to apply this classification on the quantities used in the regulations and NCAP assets. For the USSID only signals of class 1 are used. Hence, they use only signals with the highest confidentiality in simulation. Only measurements not used in the regulations like the rib intrusion are of class 2. Considering the ES-2 model signals from all classes are present. But the quantities most difficult to predict (class 3) are not used in the direct assessment. These quantities are only used as modifier if the quantity exceeds a certain limit. Again, the quantities with the lowest predictability in simulation are not used in the direct assessment.

In summary we have a high confidentiality in the spine and pelvis accelerations. For the rib intrusion the user must take care to have proper modeling of the airbag and the door trims to achieve the real arm movement. Abdominal forces are determined by the intruding geometry and the movement of the dummy, in particular the movement of the spine with regard to the pelvis. If the spine acceleration does not correlate with the test, the abdominal forces are not predictive. To achieve a proper correlation for forces and moments of T1 and T12 or the pubic symphisis force the exact modeling of the surrounding is indispensable. Figure 10 to Figure 41 show the correlation of the dummies in different tests and illustrate the above described classification. Also Figure 6 illustrates the predictability of signals of class 1 and 2.

Oscillations

We found four main sources for oscillations in the model. Initial penetrations have a direct influence on oscillations that might occur during positioning of the dummy or other operations during pre-processing. It is recommended to review any initial penetrations in the dummy model and to avoid them entirely. A second source for oscillations is the problem of round-off errors of the computer that might appear if the dummy model has a large distance from the origin. Oscillations also appear if the user runs the model with a very small time step. This is due to the fact that the 'soft constraint option' determines the penalty for the contacts proportional to the time step. For the models the recommended time step is between 0.8 and 1.3 micro seconds. Sometimes contact problems in the dummy cause high oscillations. We tried to avoid any source for these problems but do recommend to check all signals unfiltered before using the filtered signal to assess the vehicle.

MODEL DESCRIPTIONS

Material definitions

For modeling the foam materials usually material type 83 (Mat_Fu_Chang_Foam) is used. Very few parts are modeled with material type 62 (Mat_Viscous_Foam). For modeling the venyl coverings mainly material type 6 (Mat_Viscoelastic) is used. Other rubber parts are modeled with material type 62 (Mat_Viscous_Foam). Steel or aluminum parts are modeled with material type 20 (Mat_Rigid).

Contact definitions

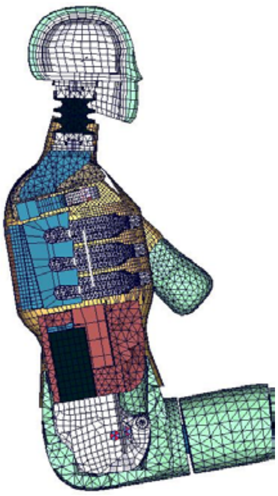
The models work with one major single surface contact (Type 13, Automatic_Single_Surface) with the 'Soft Constraint' option. An additional contact definition is implied, e.g. the rather fine mesh of the rib foam is 'glued' to the much coarser mesh of the steel inlet of the ribs with Contact_Tied_Shell_Edge_to_Surface (Type 7) for the EUROSID-1 and ES-2 model.

Others

The recent models use the stiffness based joint definition in combination with the generalized joint option. Global damping is not applied. The models run with LS-DYNA version 960 upwards on computers with SMP and MPP architecture.

Model size

The EUROSID-1 model release 3.51 consists of 53,302 nodes,15,949 hexahedron elements, 83,805 tetrahedron elements, 93 beam elements, 45,410 shell elements, and 21 discrete elements. The model is depicted in Figure 7.



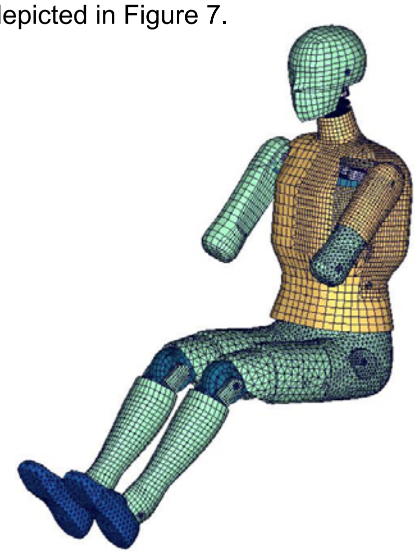


Figure 7 FAT Eurosid-1 model; cut (left), complete model (right)

The USSID model release 4.5.1 consists of 61,150 nodes, 24,008 hexahedron elements, 72,034 tetrahedron elements, 46 beam elements, 45,363 shell elements, and one discrete element. The complete model (right) and a cut through the pelvis (left) is depicted in Figure 8.

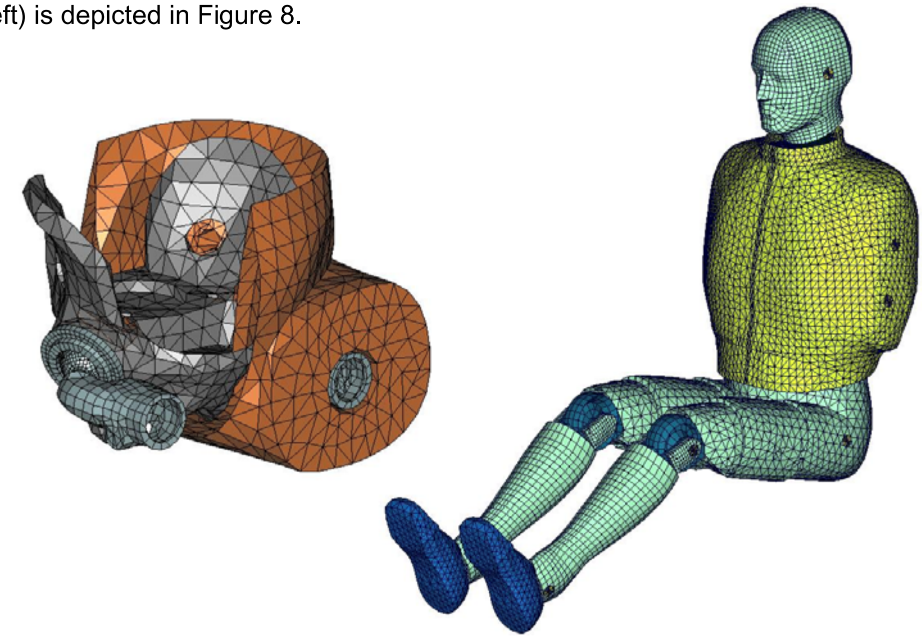


Figure 8 FAT USSID model; cut of pelvis model (left), complete model (right)

The ES-2 model release 2.0 consists of 68,985 nodes, 22,566 hexahedron elements, 87,953 tetrahedron elements, 188 beam elements, 57,486 shell elements, and 12 discrete elements. The model is depicted in Figure 9.

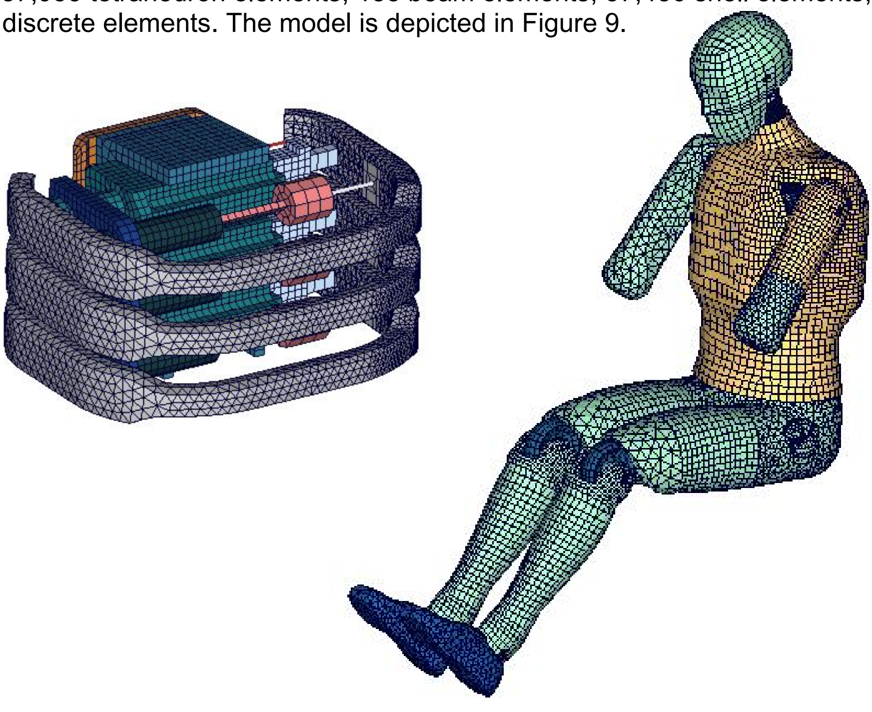


Figure 9 FAT ES-2 model; rib assembly (left), assembled model (right)

CORRELATION IN BARRIER TESTS ES-2 MODEL

The performance of the fully assembled ES-2 model impacted by a planar rigid barrier is presented in the following. Figure 10 depicts on the left the model before and during impact. Figures 11 to 18 depict the comparison between the dummy model and the test results.

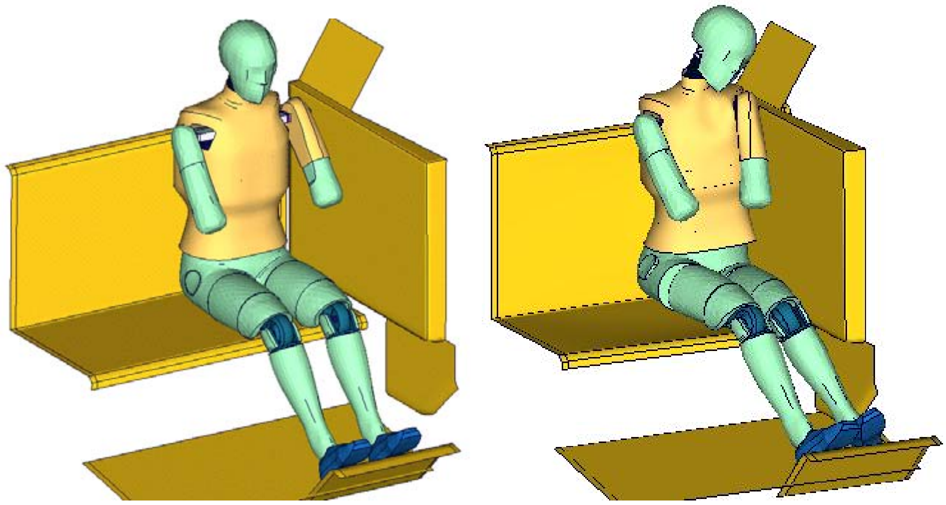


Figure 10 Dummy model before (right) and during impact (left)

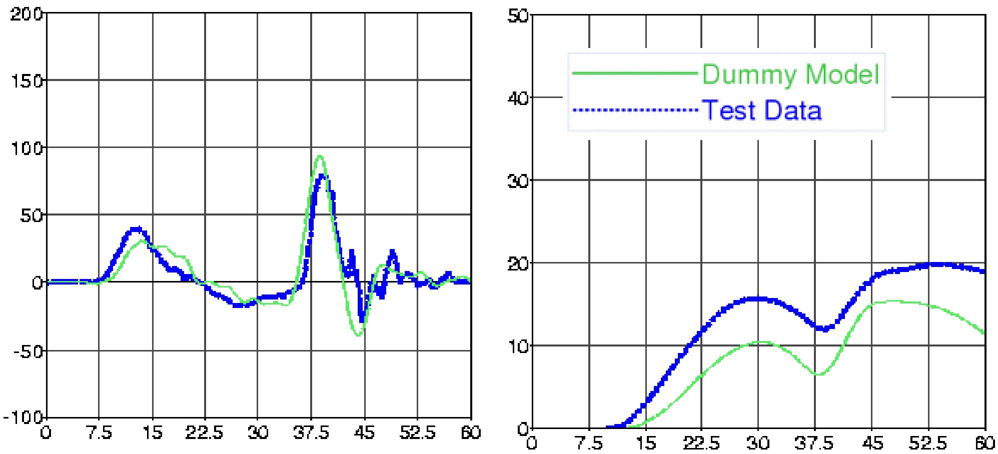


Figure 11 Upper rib acceleration and intrusion. Graphs show acceleration [g] and deflection [mm] vs. time [ms], respectively

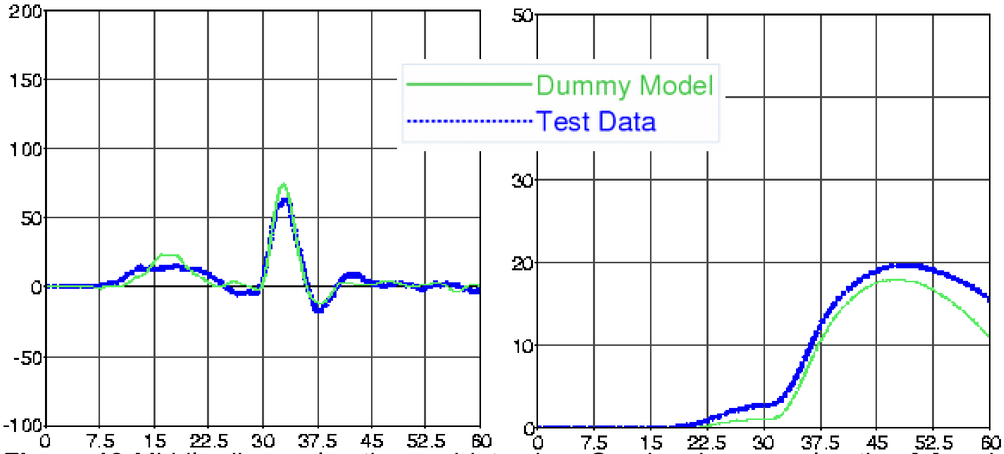


Figure 12 Middle rib acceleration and intrusion. Graphs show acceleration [g] and deflection [mm] vs. time [ms], respectively

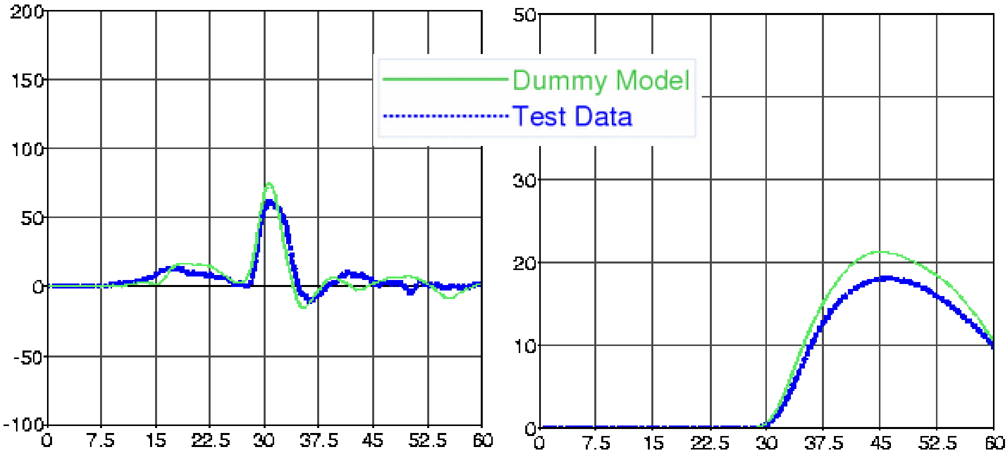


Figure 13 Upper rib acceleration and intrusion; graphs show acceleration [g] and deflection [mm] vs. time [ms], respectively

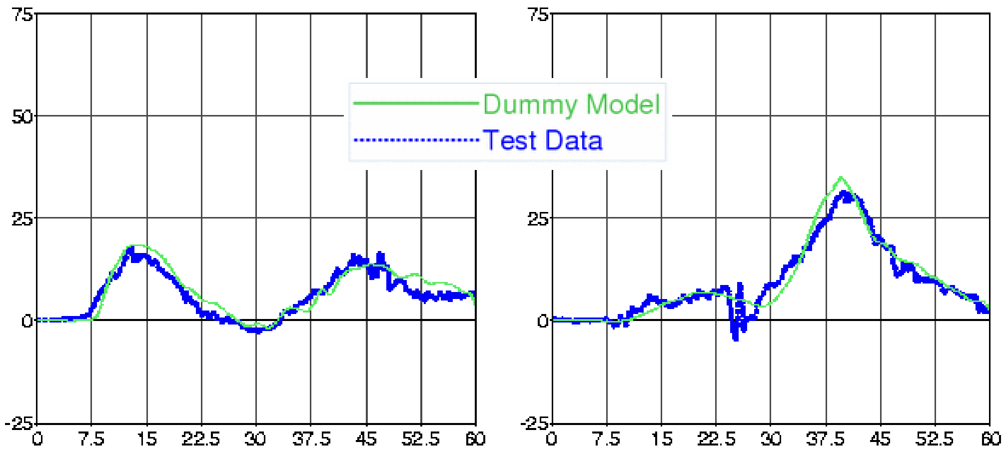


Figure 14 Spine performance: Upper spine T1 (left) and lower spine T12 (right); graphs show acceleration [g] vs. time [ms]

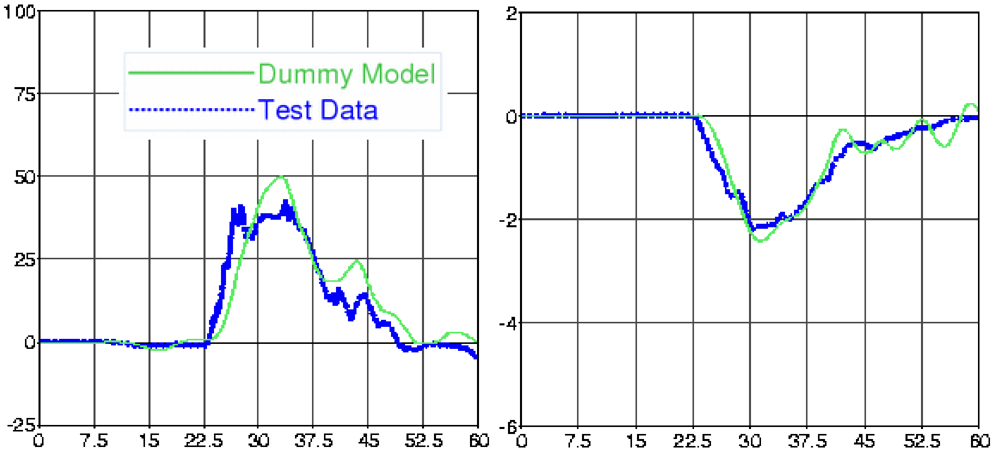


Figure 15 Pelvis performance: Pelvis accelerations (left) and pubic sympysis force (right); graphs show acceleration [g] vs. time [ms] and force [kN] vs. time [ms], respectively

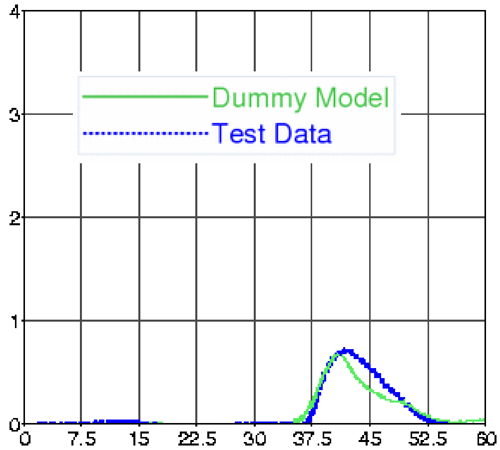


Figure 16 Abdominal resultant force; graph shows force [kN] vs. time [ms]

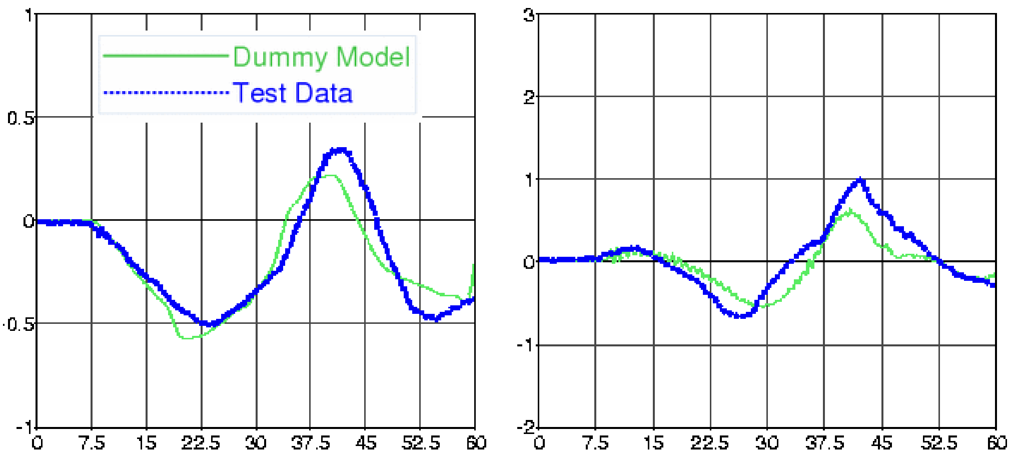


Figure 17 Y-Force of force transducer T1 (left) and T12 (right); graphs show force [kN] vs. time [ms]

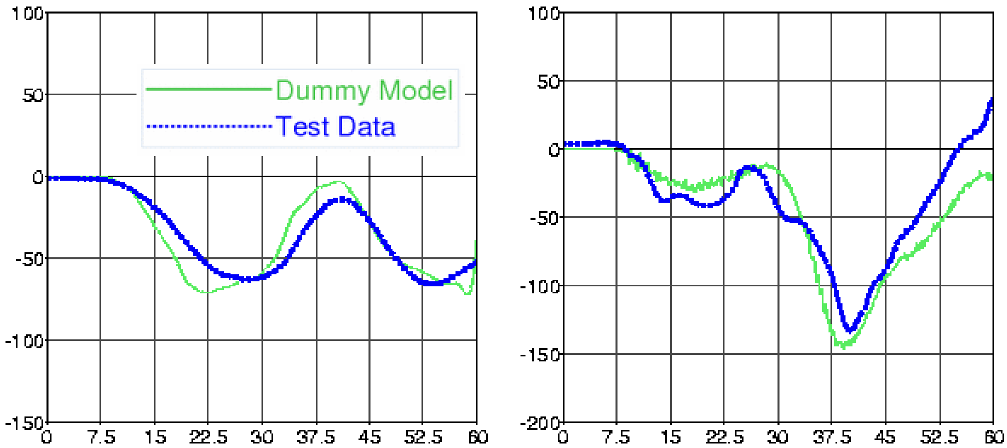


Figure 18 X-Moment of Force transducer T1 (left) and T12 (right); graphs show moment [Nm] vs. time [ms]

The performance of the fully assembled ES-2 model impacted by a planar rigid barrier with a limited height is presented in the following. Figure 19 depicts on the left the model before impact. Figures 19 on the right and Figures 20 to 25 depict the correlation of the dummy model in the test results.

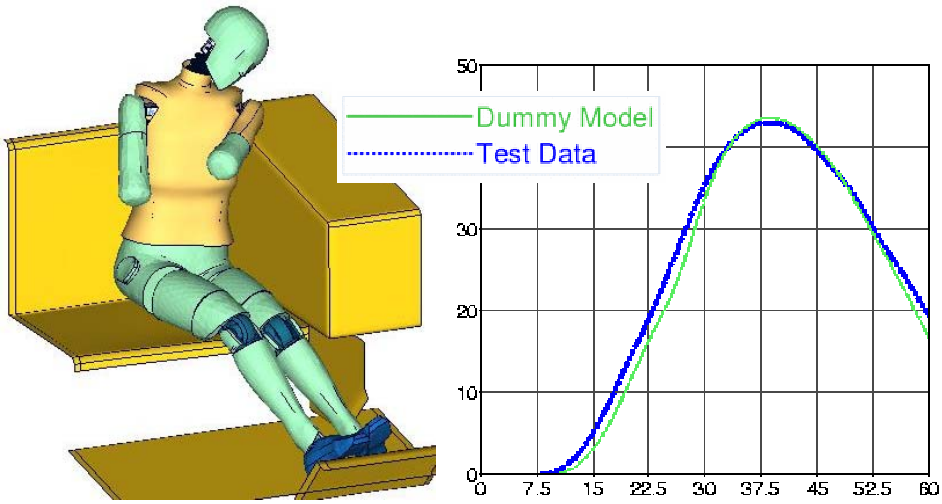


Figure 19 Dummy model during impact (left) and performance of upper rib (right); graph shows intrusion [mm] vs. time [ms]

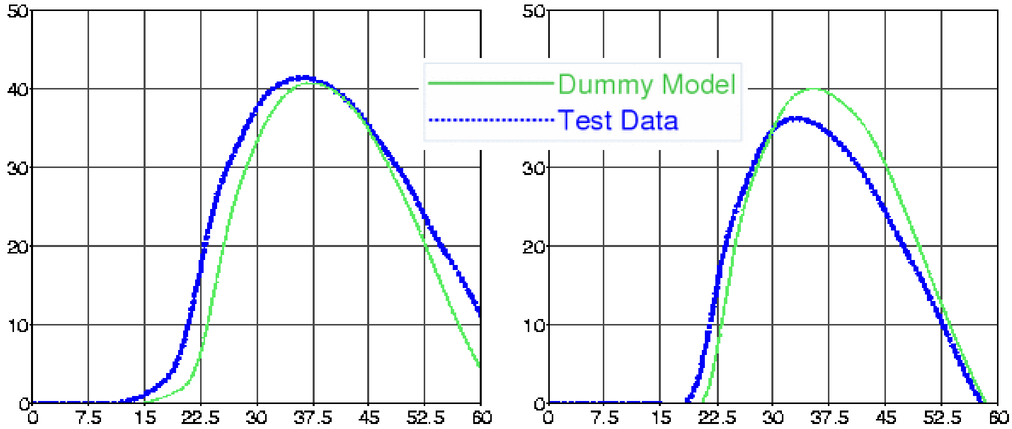


Figure 20 Rib performance: Middle rib (left) and lower rib (right); graphs show deflection [mm] vs. time [ms]

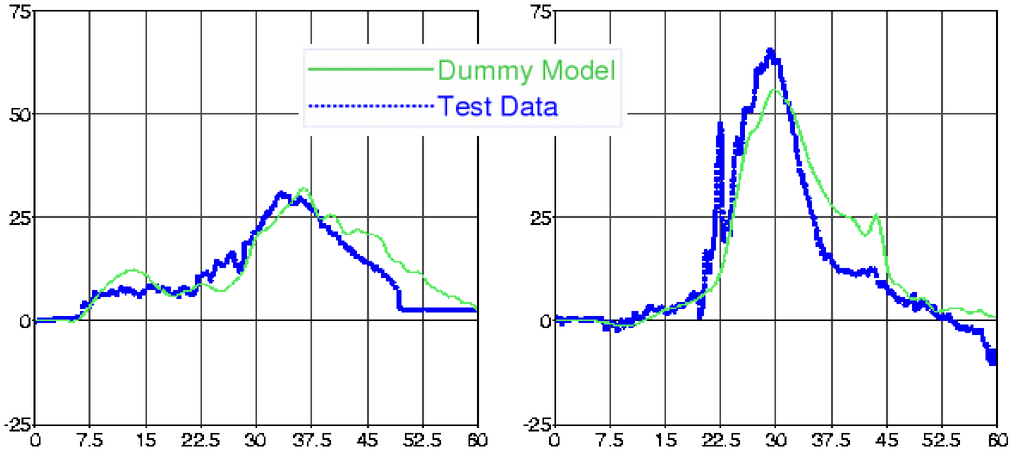


Figure 21 Spine performance: Upper spine T1 (left) and lower spine T12 (right); graphs show acceleration [g] vs. time [ms]

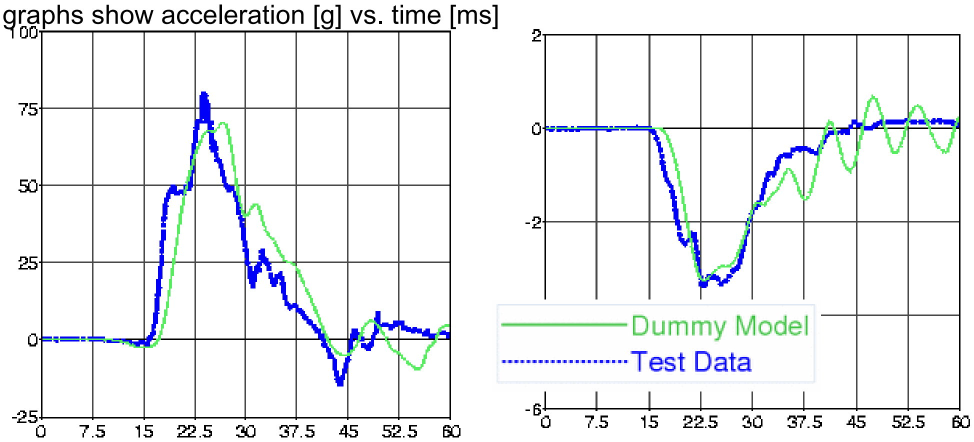


Figure 22 Pelvis performance: Pelvis accelerations (left) and pubic symposis force (right); graphs show acceleration [g] vs. time [ms] and force [kN] vs. time [ms], respectively

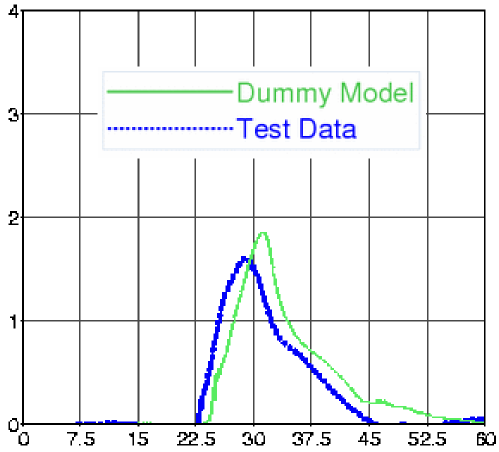


Figure 23 Abdominal resultant force; graph shows force [kN] vs. time [ms]

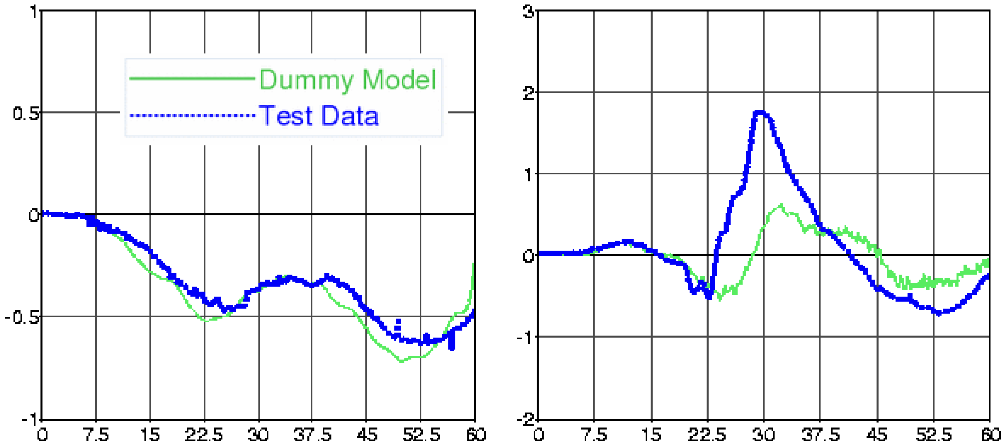


Figure 24 Y-Force of force transducer T1 (left) and T12 (right); graphs show force [kN] vs. time [ms]

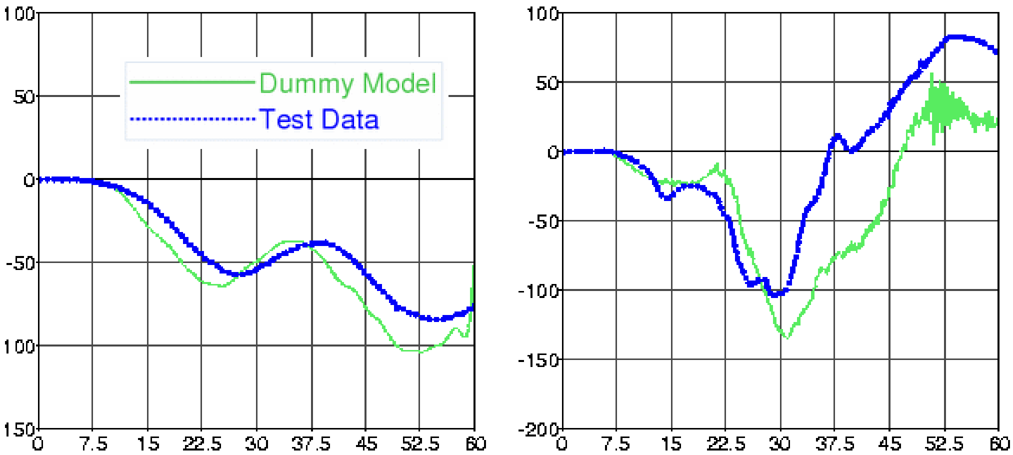


Figure 25 X-Moment of Force transducer T1 (left) and T12 (right); graphs show moment [Nm] vs. time [ms]

CORRELATION IN BARRIER TESTS EUROSID-1 MODEL

The performance of the fully assembled EURSID-1 model impacted by a planar rigid barrier is presented in the following. Figure 25 depicts on the left the model before impact. Figure 25 (right) and Figures 26 to 29 depict the correlation of the dummy model with the test results.

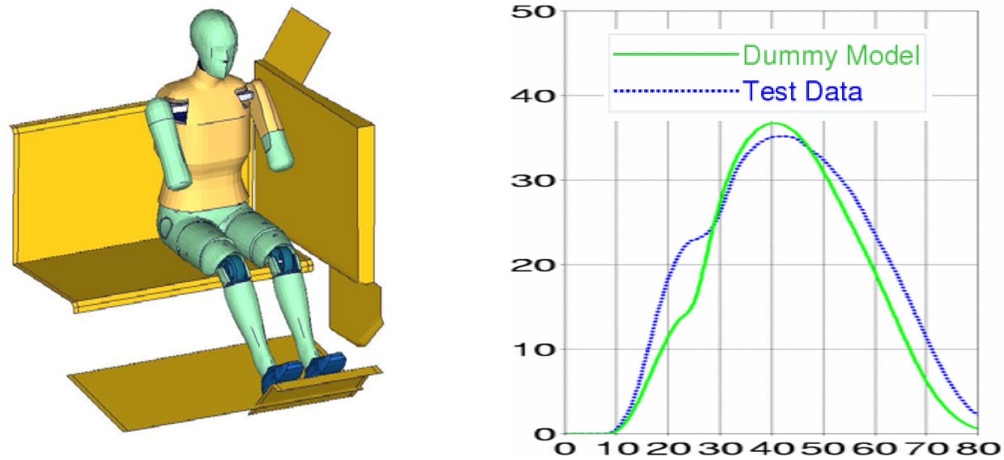


Figure 25 Dummy model before impact (left) and performance of upper rib (right); graph shows intrusion [mm] vs. time [ms]

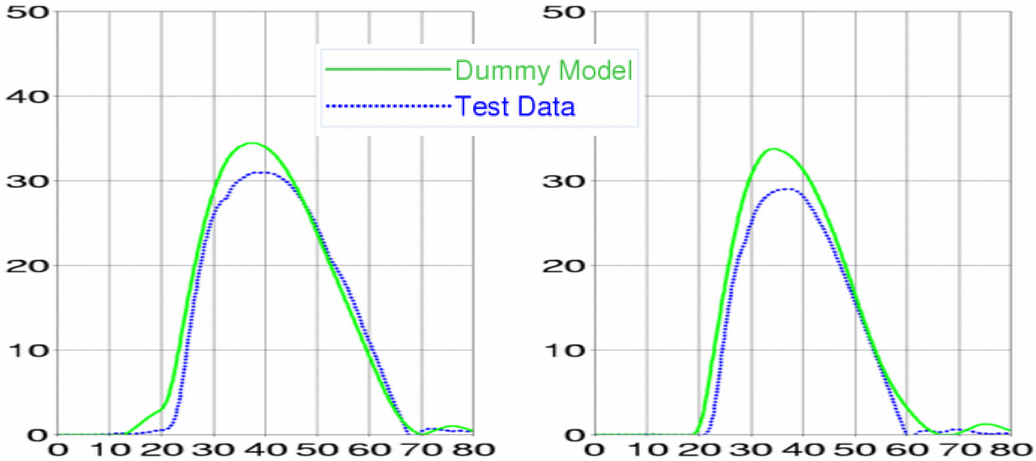


Figure 26 Rib performance: Middle rib (left) and lower rib (right); graphs show deflection [mm] vs. time [ms]

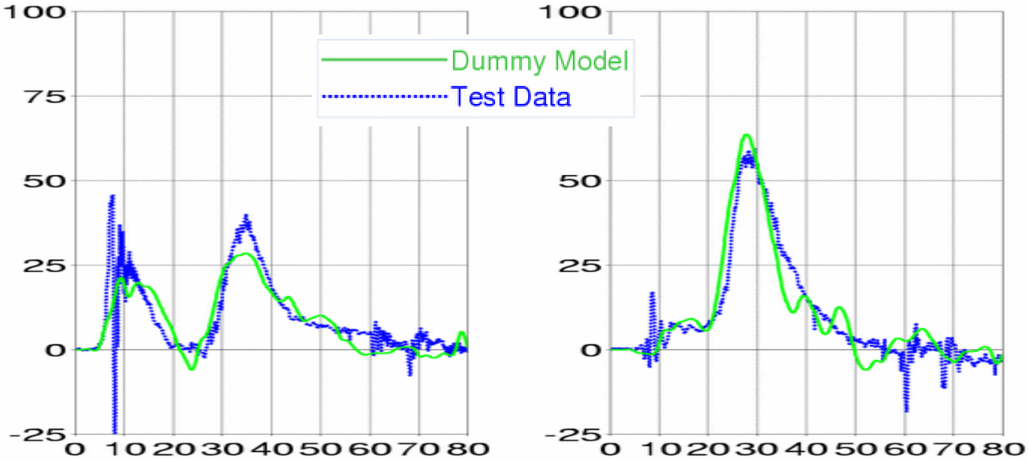


Figure 27 Spine performance: Upper spine T1 (left) and lower spine T12 (right); graphs show acceleration [g] vs. time [ms]

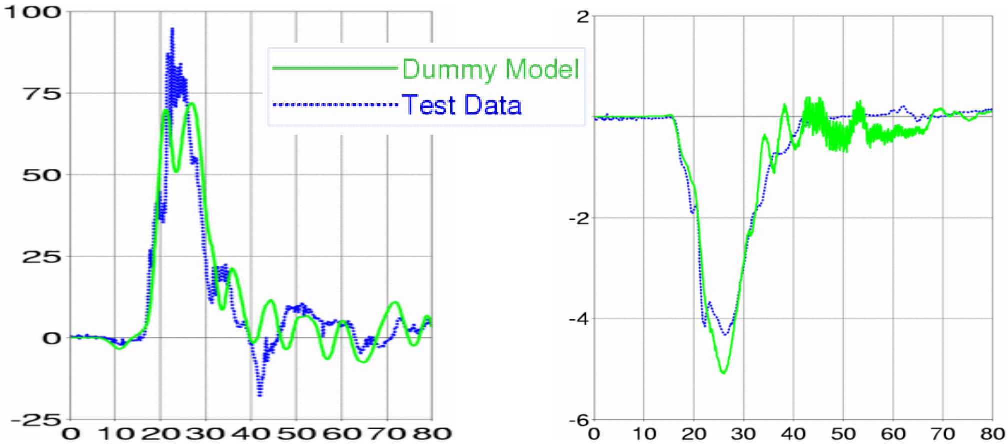


Figure 28 Pelvis performance: Pelvis accelerations (left) and pubic sympysis force (right); graphs show acceleration [g] vs. time [ms] and force [kN] vs. time [ms], respectively

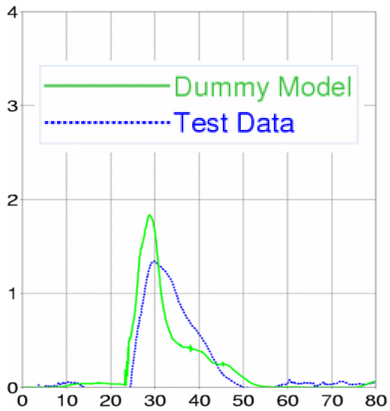


Figure 29 Abdominal resultant force; graph shows force [kN] vs. time [ms]

The performance of the fully assembled EUROSID-1 model impacted by a planar rigid barrier with limited height is presented in the following. Figure 30 depicts on the left the model before impact. Figure 30 (right) and Figures 31 to 34 depict the correlation of the dummy model with the test results.

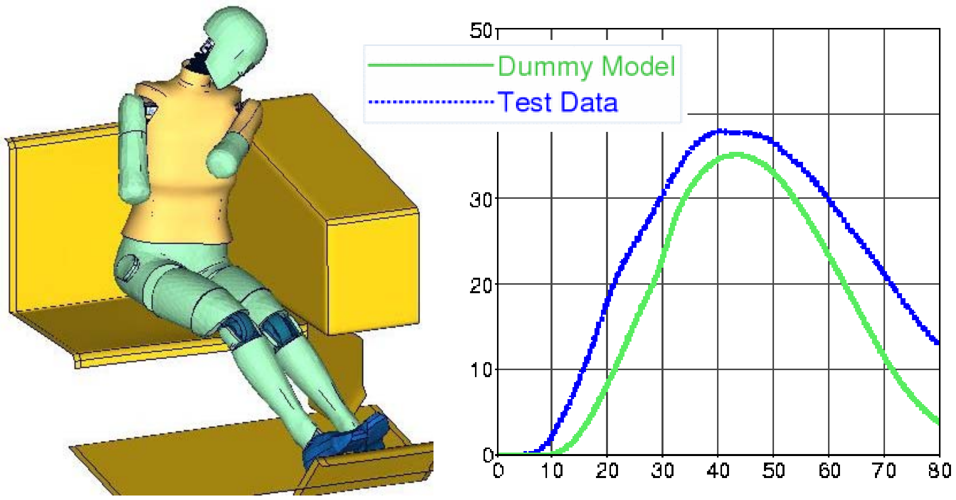


Figure 30 Dummy model during impact (left) and performance of upper rib (right); graph shows intrusion [mm] vs. time [ms]

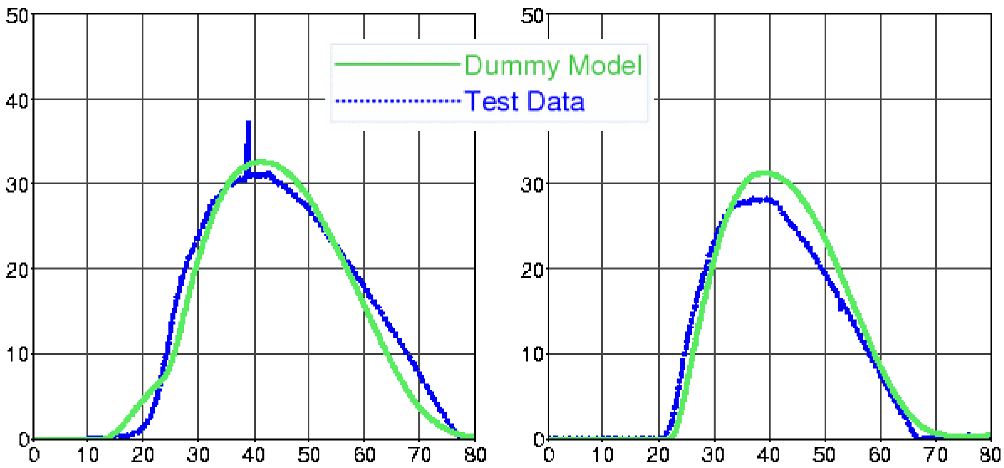


Figure 31 Rib performance: Middle rib (left) and lower rib (right); graphs show deflection [mm] vs. time [ms]

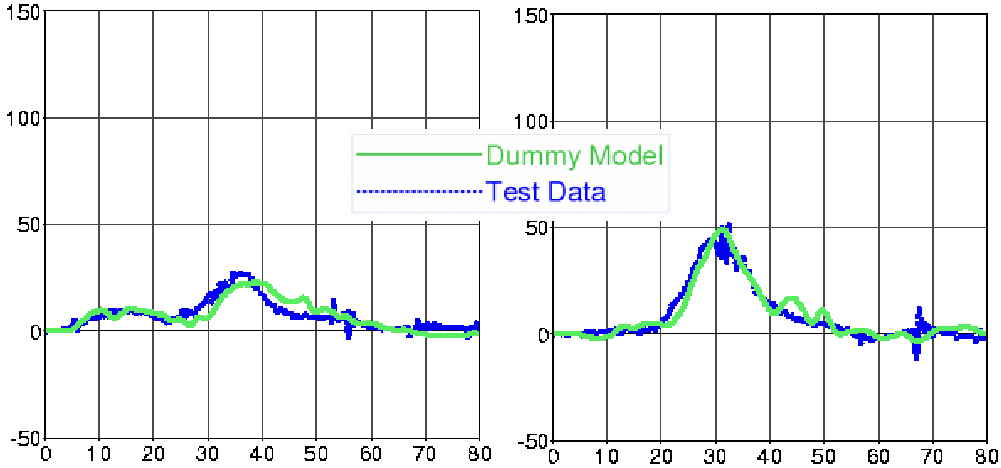


Figure 32 Spine performance: Upper spine T1 (left) and lower spine T12 (right); graphs show acceleration [g] vs. time [ms]

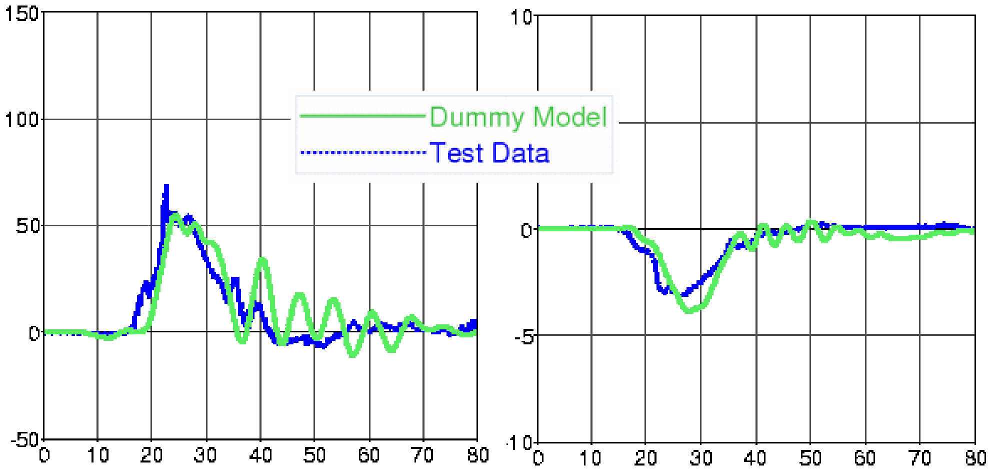


Figure 33 Pelvis performance: Pelvis accelerations (left) and pubic sympysis force (right); graphs show acceleration [g] vs. time [ms] and force [kN] vs. time [ms], respectively

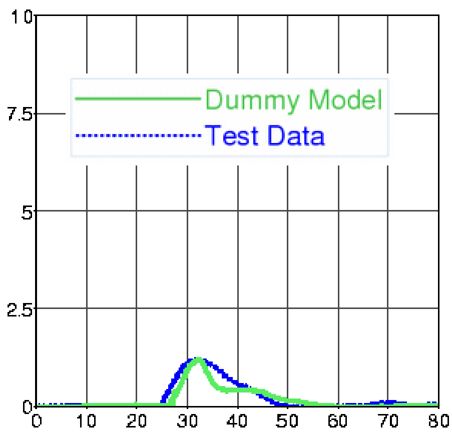


Figure 34 Abdominal resultant force; graph shows force [kN] vs. time [ms]

CORRELATION IN BARRIER TEST USSID MODEL

The performance of the fully assembled USSID model impacted by a planar rigid barrier is presented in the following. Figure 35 depicts on the left the model before impact. Figure 35 (right) and Figures 36 to 38 depict the correlation of the dummy model with the test results.

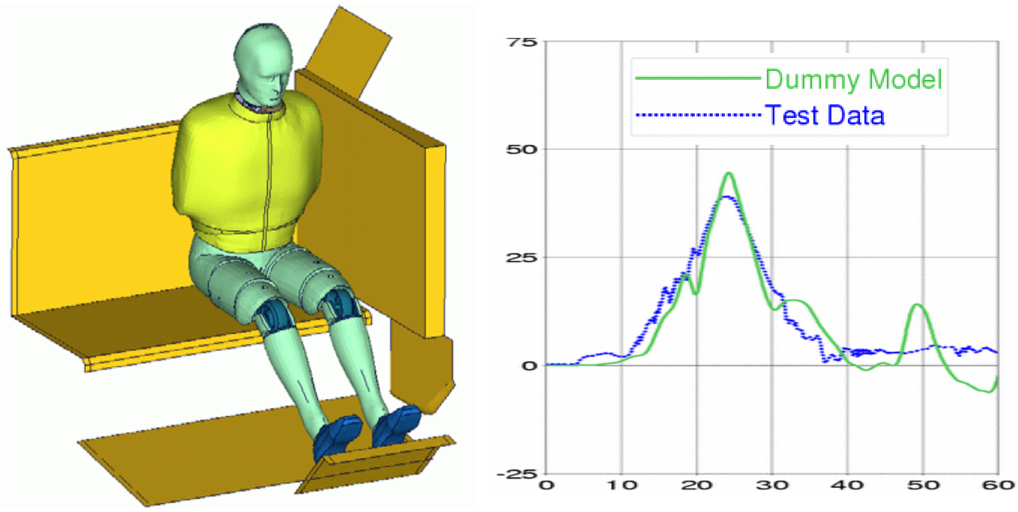


Figure 36 Dummy model before impact of plane barrier (left) and performance of pelvis (right); graph shows acceleration [g] vs. time [ms]

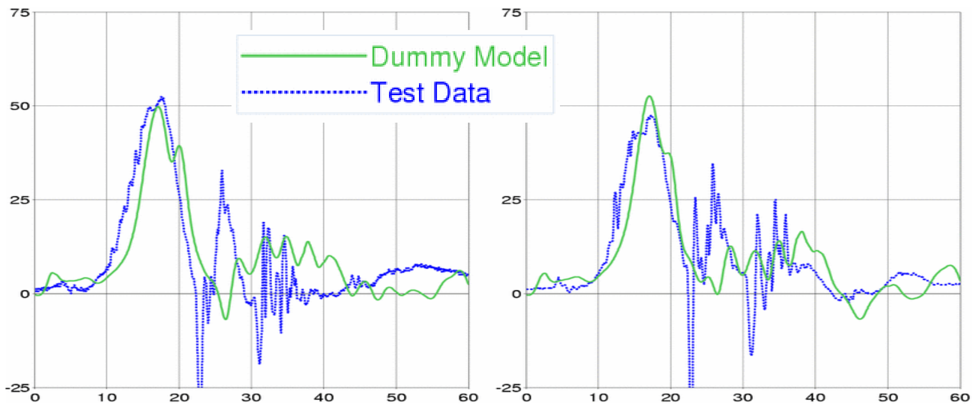


Figure 37 Rib performance: Upper rib (left) and lower rib (right); graphs show acceleration [g] vs. time [ms]

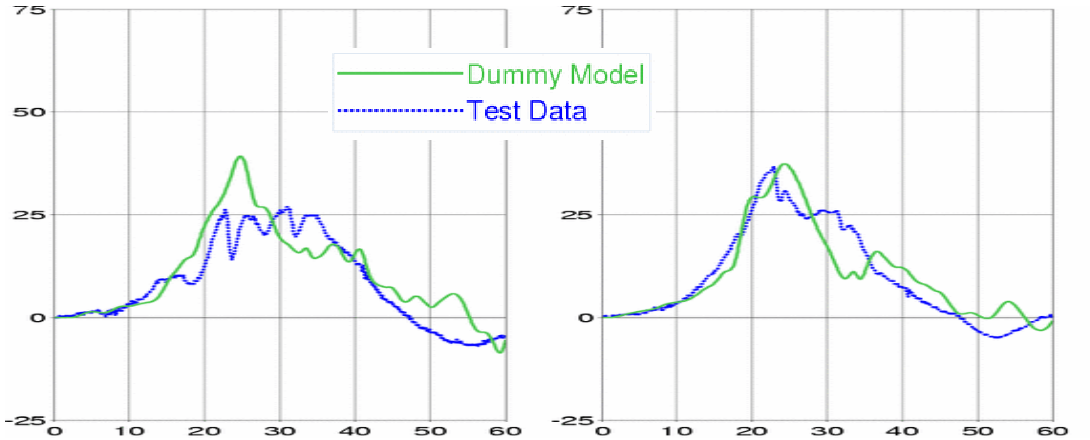


Figure 38 Spine performance: Upper spine (left) and lower spine (right); graphs show acceleration [g] vs. time [ms]

The performance of the fully assembled USSID model impacted by a planar rigid barrier is presented in the following. Figure 39 depicts on the left the model before impact. Figure 39 (right) and Figures 40 to 41 depict the correlation of the dummy model with the test results.

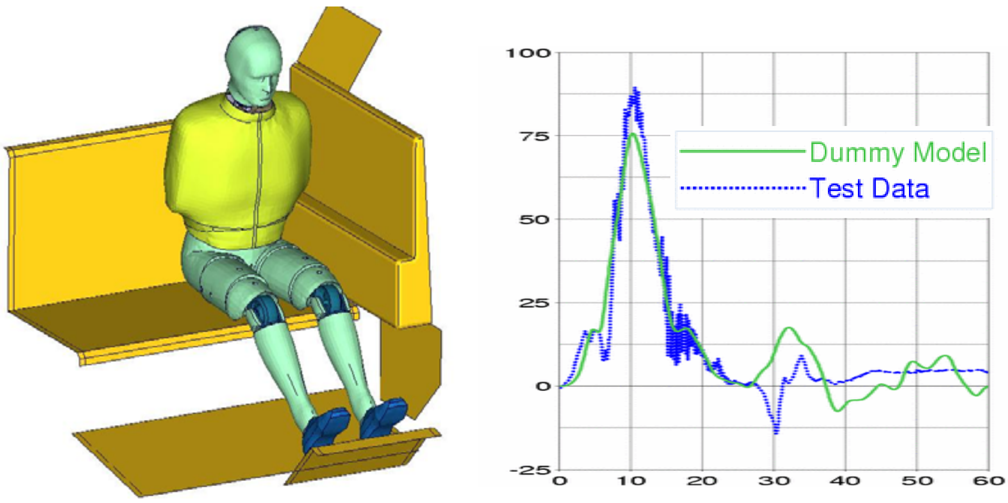


Figure 39 Dummy model before impact with barrier with pelvis impactor (left) and performance of pelvis (right); graph shows acceleration [g] vs. time [ms]

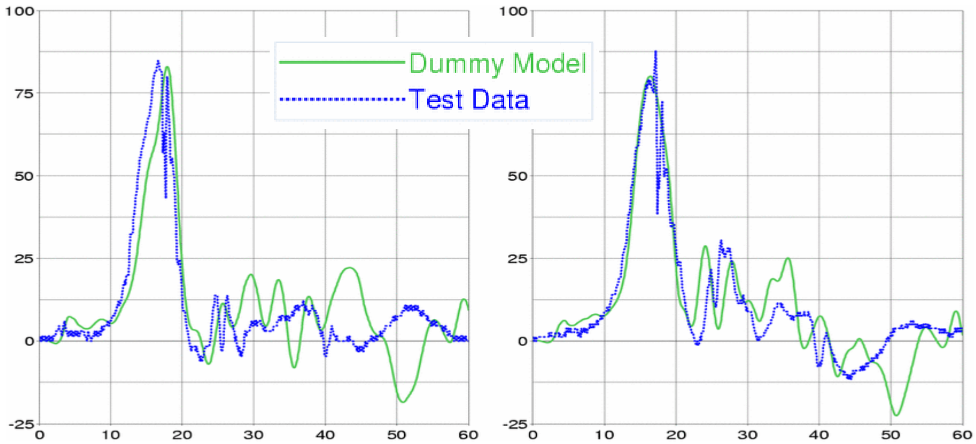


Figure 40 Rib performance: Upper rib (left) and lower rib (right); graphs show acceleration [g] vs. time [ms]

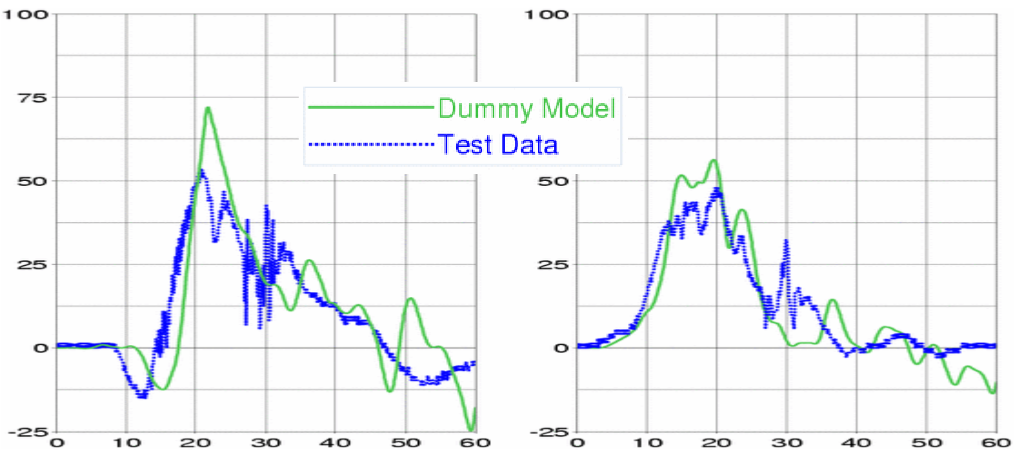


Figure 41 Spine performance: Upper spine (left) and lower spine (right); graphs show acceleration [g] vs. time [ms]

CONCLUSIONS

The LS-DYNA models of the side impact dummies USSID, EUROSID-1 and ES-2 developed by DYNA*more* together with a consortium of the German automotive industry (FAT) are presented. The models are based on a broad test database including test results at the material, component and full assembly level.

Potential pitfalls and questions arising during the everyday work with the models are described. The effects due to changes in different parameters are illustrated by various graphs. An attempt has been made to classify various parameters according to their ease or difficulty to correlate them with numerical data. In order to achieve good correlation with the test results in case of the most difficult quantities considerable efforts have to be made in order to model the initial and boundary conditions as accurately as possible.

The feedback by users and additional tests performed by the FAT lead to the recent enhancements of the models described in this paper. The majority of modifications in the latest releases were modifications in detail. The additional tests helped to extend the quality of the models.

The development resulted in accurate finite element models with good predictive capabilities of the occupant injury criteria. The models are commercially available by the local LS-DYNA distributors. The FAT dummy models are in use at many car manufacturers and automotive suppliers worldwide.

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