Development and Validation of the FAT Finite Element Model for the Side Impact Dummy „EUROSID-1“

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ABSTRACT
A new deformable model for the side impact dummy EUROSID-1 is described, which is based on existing finite model for European dummy. The model incorporates new meshes for key components as well as detailed viscoelastic material descriptions. Various material, component and sled test results were used to calibrate and validate the model, providing a more accurate evaluation of the dummy performance than previous studies which were limited to certification and sled tests [1,2]. This paper presents various features of the dummy models and some key results of the validation work. The models were realized in the explicit finite element code PAM-CRASH [3].

INTRODUCTION
A joint project involving the FAT (Research association of German car makers) and various software companies was initiated in 1997 with the goal of developing reliable finite element models for the side impact dummy EUROSID. The starting point was an existing finite element model, which was to be refined to provide better agreement with experiment.

The development work was organised in three phases, covering the following aspects:
1. Material modelling
2. Component modelling
3. Sled test validation.

In the first phase, material model parameters were varied to provide best agreement with measured tensile, compressive and shear data for various foams and skins from different parts of the dummy. Next, the main components of the dummy were separately analyzed and model parameters calibrated to provide good agreement with pendulum and drop tests. Finally, a series of sled tests with different barriers, velocities and dummy configurations were simulated and compared with available experimental data. A total of sixteen sled test configurations were investigated, providing an accurate assessment of the model quality.

MATERIAL MODELLING
The most important materials in the dummy are foam and rubber. Due to the high deformation rates occurring during a side impact, the strain rate dependency of these materials needs to be considered. Compression and shear tests on cubic samples provided an appropriate base for calibrating constitutive models as documented in [4]. These foam cubes were extracted from the dummy arm, ribs, abdomen and pelvis.

Two models were selected from the different constitutive models of the finite element code used. The first represents the nonlinear viscoelastic model shown schematically in figure 1a. The parameters $E_1$ and $\eta$ of this model are possibly nonlinear functions of strain. The procedure to calibrate the model is explained in figure 1b, which shows the typical response of the model for impact load in case of linear viscoelasticity. Obviously the parameters $E_1$ and $E_2$ are easily obtained from the two main slopes of the curve.
The viscosity $\eta$ can be calculated from the stress at the slope changes (e.g. $\sigma_1$ or $\sigma_2$) and the corresponding strain rate of the test. Based on this information and the stress-strain relation for a Newton fluid, the viscosity $\eta$ is the ratio between stress and strain rate. Finally, the nonlinearity of the model is considered by modifying $E_1$ as follows:

$$E_1 = E_1^{lin} \left( \frac{V}{V_0} \right)^n$$

For $n=0$ the parameter $E_1$ is equal to the value obtained for the linear model. Values of $n$ for foams used in the dummy typically lie between 2 and 5. Samples of an important foam “Pink confor” were removed from the dummy and tested. The dynamic behaviour of this foam directly influences the acceleration of the ribs and the pelvis. For this foam a comparison between test and simulation for different strain rates of a drop test is given in figure 2b. Figure 2a shows the fit with the linear model for a certain strain rate which is considered as the first step of the fitting procedure.

The second constitutive model used has the capability to directly employ measured characteristics as input. This model was used, when a good fit with the viscoelastic model was impossible. Finally it is important to
note that the size of the cube has an influence on stress-strain behaviour. The conclusion is, that during the validation of the components, a slight modification of the foam behaviour is necessary. For the simulation of rubber, the models described above were also used. The disadvantage of the different Money-Rivlin laws, which are often used for rubber, is that they provide no strain rate dependency.

COMPONENT MODELLING

Tests were conducted for the main components of the dummy. The following sections describe the experimental setup and compare measured and simulated results for some typical tests. In some cases, mathematical optimisation techniques were applied to obtain the best model fit.

Head drop test

The head was dropped from two different heights in order to realise impact velocities of 3.0 m/s and 4.5 m/s. Three different angles were used for the tests, during which head accelerations were recorded. A nonlinear viscoelastic constitutive law was used to model the 10 mm thick skin. The stiffness and the viscosity of this skin are the main parameters for calibrating the model. Figure 3 shows the test setup and for an impact velocity of 3.0 m/s the comparison between measured and simulated acceleration.

Neck pendulum test

For this test a special head form was used instead of the head, and the neck was mounted on the pendulum bar. The pendulum bar is released at a certain velocity which changes when contact is made with an honeycomb block. The rotation of this head form was measured during the impact test. The most interesting parts for the finite element model of the neck are the central section and the circular section buffers (Figure 4). The circular section is modelled by solid elements with a viscoelastic constitutive law. The circular section buffers are made of rubber and modelled by nonlinear springs. Based on appropriate parameters for the viscoelastic law and the springs a good fit was possible.
Figure 5 shows the test setup and the comparison between test and experiment for the rotational angle at 3.5 m/s impact velocity. In addition, tests at 2.0 m/s and 5.0 m/s were performed.

Figure 5: Test setup and comparison between experiment and simulation for the neck pendulum test

**Lumbar Spine pendulum test**

This test is quite similar to the test described for the neck. Again the rotational angle of the head form is measured at impact velocities of 2.0 m/s, 4.0 m/s and 8.0 m/s. The load case for the spine is more of a bending than a shear. Side impact of the whole dummy shows that shear is also important. For this reason, additional tests were carried out in order to overcome this lack of data. Figure 6 shows the test setup and the comparison between test and experiment for the rotational angle at an impact velocity of 4.0 m/s.

Figure 6: Test setup and comparison between experiment and simulation for the lumbar spine pendulum test at 4.0 m/s

**Damper drop test**

The damper is one of the main parts of the thorax as shown in figure 7. In addition to the hydraulic damper the return spring was used during the tests. Tests at impact velocities of 2.0 m/s, 4.0 m/s, 6.0 m/s and 8.0 m/s were performed, while measuring the axial compression of the damper and the reaction force.
In order to find a good fit between simulation and experiment a nonlinear viscous damping function for the hydraulic damper was used. Additionally this viscous damping is multiplied with a nonlinear displacement dependent function. For the return spring a linear spring model was sufficient. With this complex model a good fit was possible. Figure 8 shows the test setup and the comparison between test and experiment at an impact velocity of 8.0 m/s.

Figure 8: Test setup and comparison between experiment and simulation for the damper drop test at impact velocity of 8.0 m/s

**Single rib and thorax impact test**

The next step was the introduction of the validated damper into the rib module. This rib module is shown in figure 9. The dynamic behaviour is mainly given by the damper, the tuning spring, the steel hoop and the foam which covers the steel hoop. The behaviour of this “Pink confor” foam was slightly modified in order to have a better correlation for the rib accelerations. For the simulation an exact mass distribution is essential. The rib module was tested in three different positions at 2.0 m/s, 4.0 m/s and 6.0 m/s impact velocity. Figure 10 shows the test setup and the comparison between test and experiment at an impact velocity of 4.0 m/s.

The same tests were made for the thorax. The thorax consists of three ribs. Therefore no additional validation was done. The response of the thorax is quite similar to the response of the rib module.
Abdomen impact test

The abdomen is shown in figure 11. A test was performed where it was mounted on a pendulum bar. The velocity of the impactor was 3.0 m/s and 6.0 m/s. For the validation of the abdomen it is necessary to compare the abdomen forces. In order to calculate these forces in the FE dummy the force transducers are modelled with solid elements and the section force through the solids is used. The foam cover and the lead plates are modelled with viscoelastic material. Due to the different stiffness of these two foam materials, a good fit was possible. Figure 12 shows the test setup and the comparison between test and experiment for the force transducer in the middle of the abdomen at an impact velocity of 6.0 m/s.

Figure 11: Abdomen

Figure 12: Test setup and comparison between experiment and simulation for the abdomen impact test at 6.0 m/s impact velocity
Pelvis impact test

The pelvis is shown in figure 13. Sacrum block and femur bones are modelled as rigid bodies. Essential for the response of the pelvis are the pelvis plug foam, the pelvis foam and the stiffness of the iliac wings. The pelvis plug is made of “Pink confor” and is important for the acceleration measured within the pelvis. The stiffness of these wings is important for the pubic force because the force transducer is located between these wings. The test setup for the pelvis is the same as for the abdomen. Impactor velocities of 3.0 m/s and 6.0 m/s were used. Figure 14 shows the test setup and the comparison between test and experiment for pubic force at an impact velocity of 6.0 m/s.

![Figure 13: Pelvis](image)

![Figure 14: Test setup and comparison between experiment and simulation for the pelvis impact test at 6.0 m/s impact velocity](image)

SLED TEST VALIDATIONS

Various sled tests were simulated with a modified version of the EUROSID FE model incorporating the validated component models described above. Comparisons between simulated and measured accelerations, forces and displacements provided a good picture of the model accuracy. Figure 15 provides an overview of the used configurations, which included different impact velocities. Note that in some cases, the dummy was also used without a jacket or an arm in order to eliminate the influence of these components. The most important load case is the impact with the flat barrier. The purpose of the other configurations is to check the behaviour of the validated components during a sled test.

For the test with the abdomen barrier, the abdomen response is important and so was checked. Finally, the curves for the flat barrier are most interesting and were compared for:

- the acceleration of the head, the upper and lower spine, the ribs, the pelvis,
- the pubic and the abdomen force
- the intrusion of the ribs.

Considering the complexity of the EUROSID dummy, it is considered that there is a generally good agreement between test and simulation results.
Figure 15: Different sled test configurations

For the flat barrier, figure 16 shows the comparison for the measured and simulated curves for the EUROSID-1.
CONCLUSIONS

The paper describes some of the work that was performed to improve the reliability of a FE model for the EUROSID dummy. The performance of the complete dummy is based on the validated material and component tests. That means that no ‘calibration’ was performed at the sled test level, which is considered to be a major improvement over many previous dummy modelling approaches.

Further improvements of the model are planned and will follow the same methodology; namely, validation will be performed at the material and component level with final validation using detailed full model tests. It is considered that this model is now sufficiently accurate to be a useful predictive tool for the evaluation of new vehicles under side impact loading.

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