Development and Validation of

Numerical Pedestrian Impactor Models

Authors:

Thomas Frank, Daimler Chrysler AG

Artur Kurz, LASSO Ingenieurgesellschaft mbH

Martin Pitzer, PENG GmbH

Michael Söllner, Porsche AG

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Introduction

During the last years a lot of activities have taken place in the European Union in order to improve pedestrian protection.
As a consequence the EU Commission and ACEA drafted a Negotiated Agreement [1] which is defined in the Industry Commitment and will come into effect in October 2005. In the following of this directive the front structures of all new certified cars will have to meet specific limits in pedestrian impactor tests.
Industry Commitment Phase I contains two different test configurations, one headform to bonnet test and one legform to bumper test. A prinicipal setup of these configurations is presented in Fig. 1. Upper legform to bonnet and adult headform to the windscreen will be performed for monitoring purpose.
The headform impactor for Phase I is called small adult headform and hits the bonnet top with an impact speed of 35 kph in free flight. Its orientation is 50 degrees with respect to the horizontal axis. Accelerations of the headform will be recorded and then integrated to the so called head performance criterion (HPC). The limit values are shown in Fig. 1.

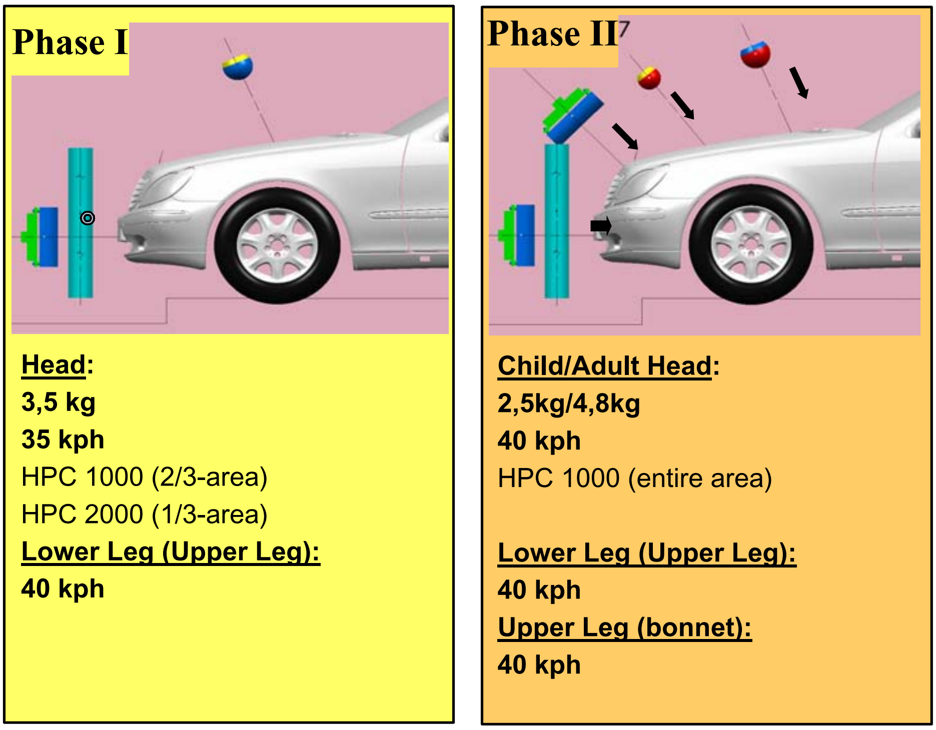


Fig. 1 European Directive Phase I and Phase II

An impact speed at 40 kph is defined for the legform to bumper tests. Limit values with respect to knee bending angle (<21°), tibia acceleration (<200g) and shear displacement (<6mm) have to be meet.
Phase II of the Industry Commitment, which will come into effect in 2010, should be defined till 7/2004 by ACEA and EU Commission. It should comply with the requirements set forth in EEVC-WG17 report [2] or other measures which are at least equivalent in protective effectiveness.
The actual Euro NCAP rating test procedure corresponds to the EEVC-WG 17 report. Herein two headform impactors, a child head (2.5 kg) and an adult head (4.8 kg) are defined. The impactor speed will be increased to 40 kph and the HPC may not exceed 1000 (Lower performance limit 1350) on the entire bonnet test area. The limits of the legform test Phase II are as follows: knee bending angle (<15°, Lower performance limit 20°), tibia acceleration (<150g, Lower performance Limit 200g), shear displacement (<6mm, Lower performance Limit 7mm) [6].
In addition to Phase I an upper leg form to bonnet leading edge test will be introduced. Depending on the shape of the car front structure the impactor speed, mass and angle are variable. Forces and bending moments will be recorded and have to meet the limit values: F<5 kN, M<300 Nm (Lower performance limit F<6,0kN, M<380Nm) [6].
Today all car manufacturers are developing design concepts for the European market to meet the requirements of the Industry Commitment which will be introduced in 10/2005. The virtual vehicle development process requires predictable CAE-models which are only achievable with reasonable well validated numerical impactor models. The authors have initiated a project to develop and validate FE-models of the pedestrian impactors during 2001 to support the virtual design process.
In preparing the validation procedure, an extensive testing program has been set up. It was decided to use more realistic test configurations than described in the proposals [1,2] for the certification of the impactors.

Numerical Pedestrian Impactor Models

Starting with the geometrical information of the pedestrian impactor types, the Finite Element models were generated.
Appropriate material laws were selected to model the constitutive behaviour of skin and foam materials. In order to characterise the specific material constants, quasistatic and dynamic specimen tests have been performed.
Then, a validation procedure has been set up consisting of configurations which represent typical behaviour of vehicle front structures.
Additional experience from applications with real car models was used to improve the FE-impactors.

Headform

All headform impactors are based on aluminium spheres which are covered by thick vinyl skins. The adult (4.8 kg) and small adult headform impactor (3.5 kg) have an outer diameter of 165 mm, the diameter of the child headform (2.5 kg) is 130 mm.

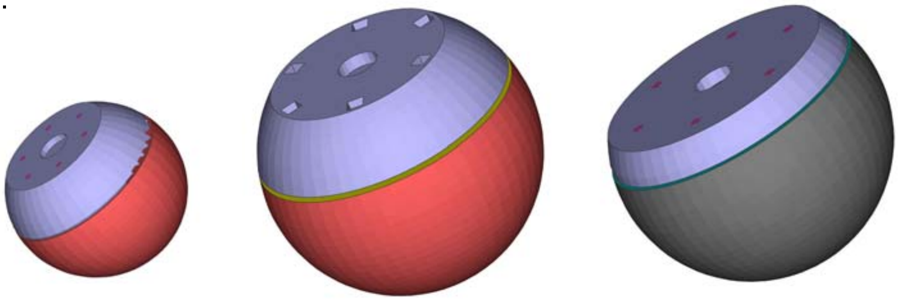


Fig. 2 Three heads – child - adult - small adult

The aluminium parts are extremely stiff in comparison to the vinyl skin. In the numerical model these parts are simplified to merged rigid bodies with specific mass and inertia properties.

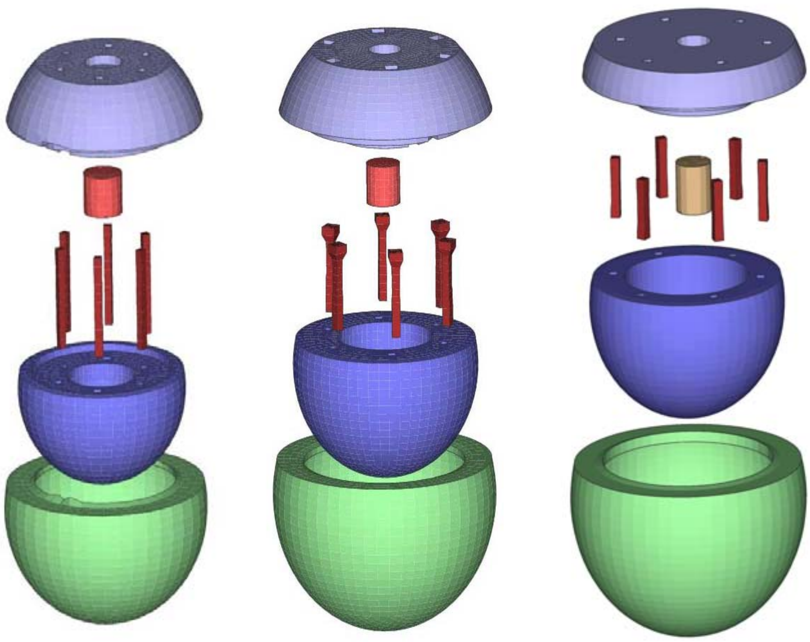


Fig. 3: child *Fig. 4: adult* *Fig. 5: small adult*

Fig. 3-5 Headform impactors, exploded illustration

To record acceleration, time history nodes at the mounting position of the accelerometer are defined. The main challenge is the reproduction of the physical behaviour of the vinyl skin.
To characterise the skin material, extensive testing was done at Fraunhofer Ernst Mach Institut (EMI), Freiburg. For these tests, specimen in form of cuboids and cylinders were cut out of a vinyl skin material.
The testing program comprises :

- quasistatic and dynamic compression
- confined quasistatic compression
- quasistatic and dynamic shear
- quasistatic tension

The material characterisation in these tests can be summarised as follows:

- the material takes a long time for reversibility
- at small strains and small strain rates the behaviour is nearly linear elastic
- with increasing strains the material behaviour becomes hyper elastic and visco elastic at dynamic loading
- dynamic shear and compression tests show high rate dependency
- the viscosity is assumed to be a dominant feature in the material response of the skin

STRAIN RATE	STRESS AT 10 % COMPRESSION
0 / s	0.2 Mpa
100 / s	0.45 Mpa
350 / s	> 1.10 Mpa

Table 1 Dynamic and quasistatic test results

The LS-DYNA MAT_OGDEN Rubber formulation [4] has been selected. The constitutive parameters were identified from uniaxial experiments. The following figures show test results (green) and the simulation (red).

- The results correlate well up to 50 % strain. No rupture was considered
- Quasistatic tension test allows to determine the coefficients of the Ogden energy functional

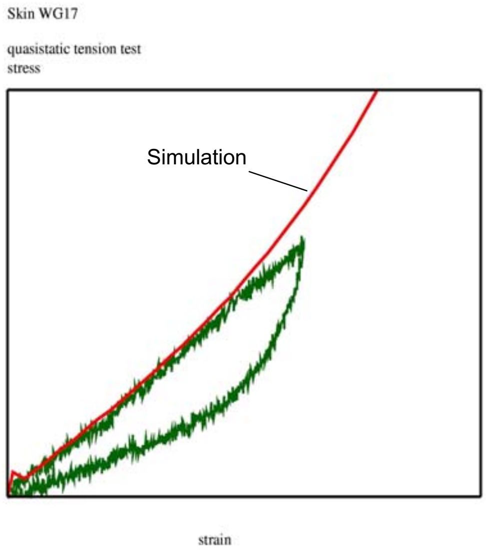


Fig. 6 Material model - quasistatic case

- Quasistatic confined compression test allows to determine the Poisson coefficient

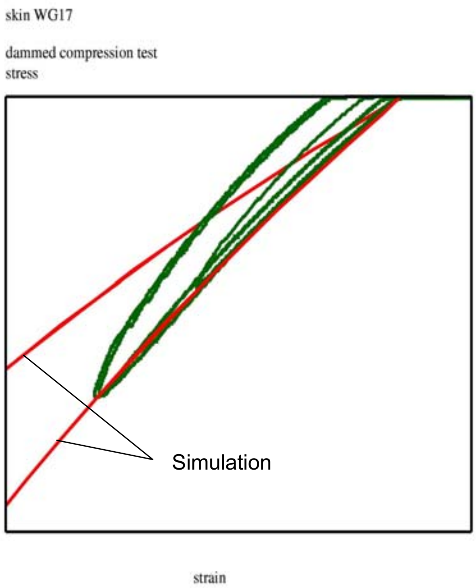


Fig. 7
Material model - quasistatic case

- Quasistatic-compression test shows no homogenious state of stress because of friction and is used as a validation load case

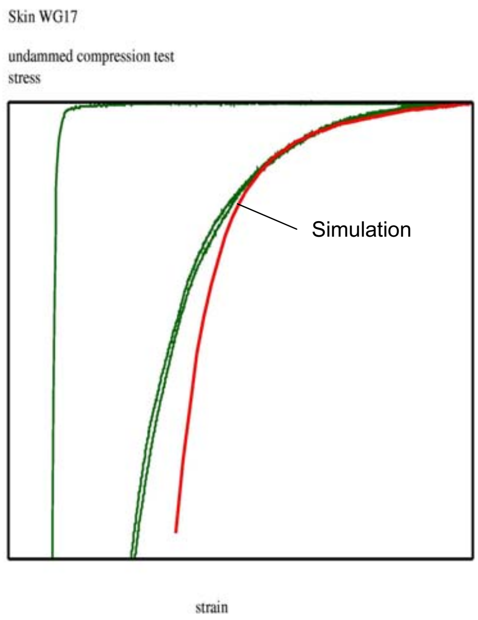


Fig. 8 Material model - quasistatic case

- Comparison between quasistatic and dynamic shear test allows to determine the coefficients in the relaxation function

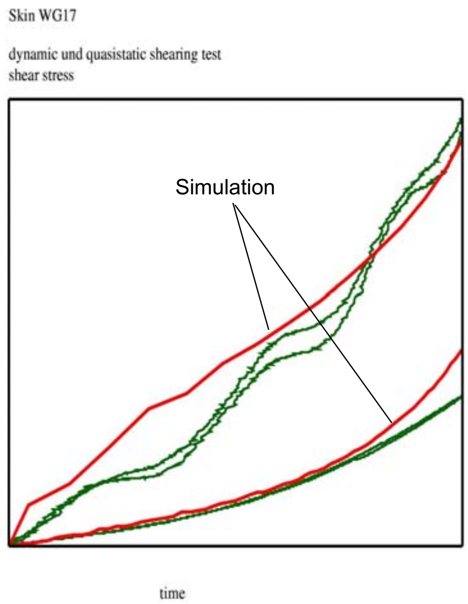


Fig. 9 Material model – dynamic case

- one term in the Prony series is sufficient to fit the small strain region
- large strain compressive behaviour can be matched by modifying the energy functional

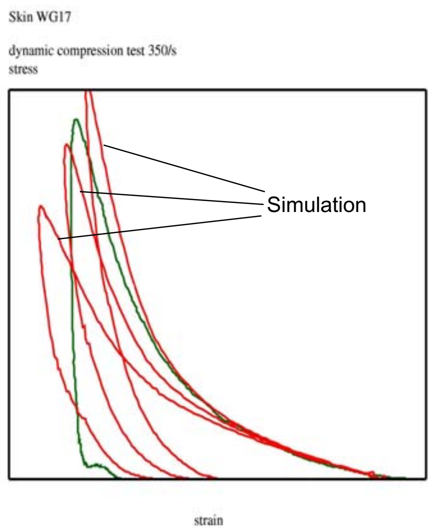


Fig. 10 Material model – dynamic case

Table 2 shows that additional ranges of deformation and deformation rate will be effected while the impactor hits a bonnet structure. This requires an extension to the parameter identification which is based on the specimen tests.

MATERIAL TESTS	IMPACT ON BONNET STRUCTURES
large strains	only smaller local strains
moderate strain rates < 350 /s	high strain rates at the point of impact up to 800 /s

Table 2 Different types of deformation

To consider strain-rate effects, additional terms (G_i, $ß_i$) of the relaxation function has to be used:

$$g_{(t)} = \sum_{i=1}^{n} G_i e^{-\beta_i t}$$

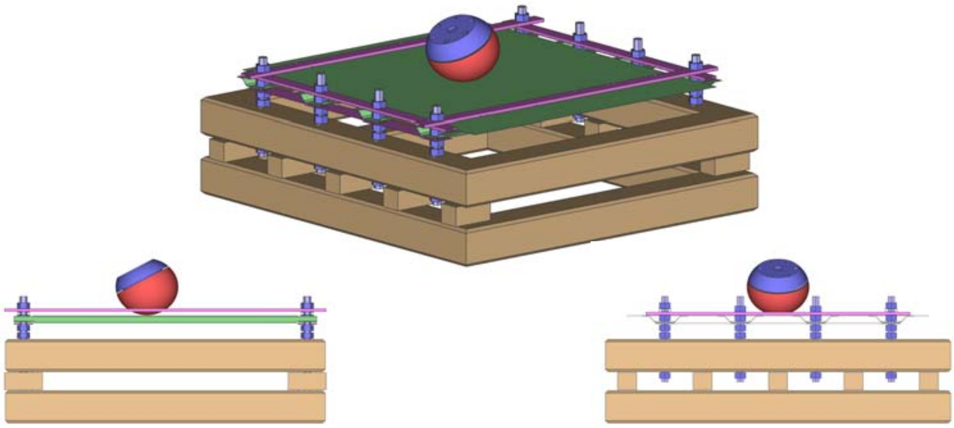


Fig. 11 “Box” test configuration

A specific test configuration was developed with the aim to represent the behaviour of a typical bonnet structure. This so called “box” configuration enables an extended validation of the head impactors under realistic conditions. The “box” test guarantees high repeatability in the experiment and is not complicated to describe in a FE-model.

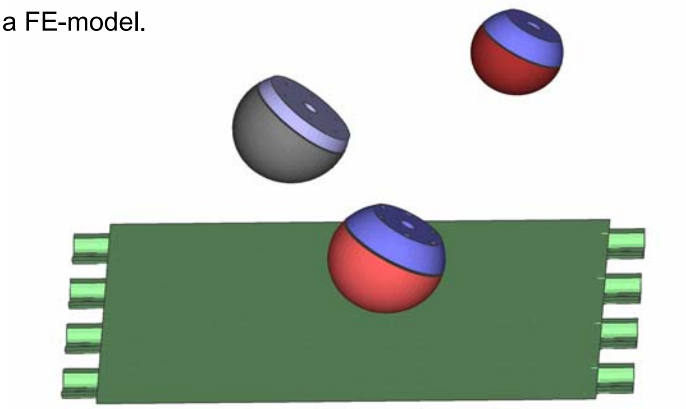


Fig. 12 Cover plate

The test component consists of a cover plate supported by trapezoidal sections connected internally with spot welds. This component is bolded together (4-8 bolds) with the rig. Correlation criteria are primarily the acceleration time histories and the HPC-value.

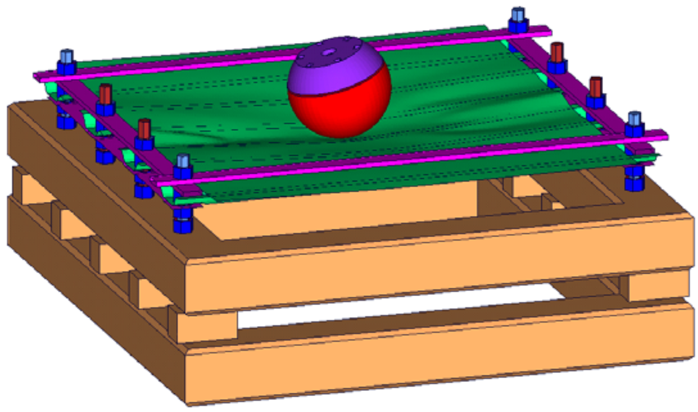
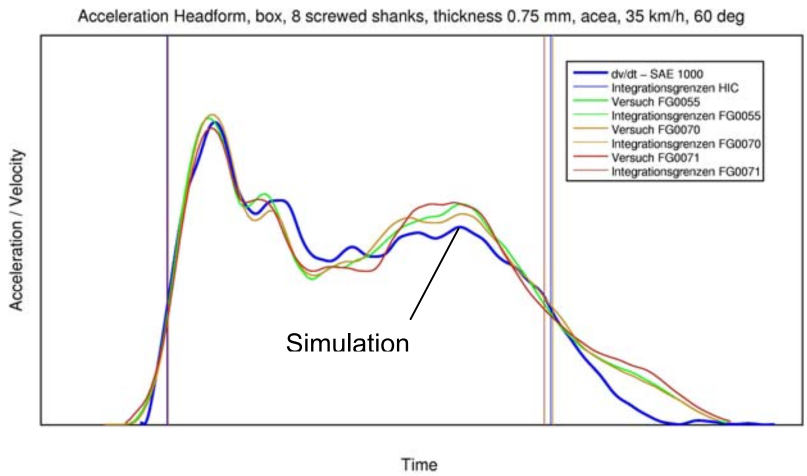


Fig. 13 "Box" - deformed state



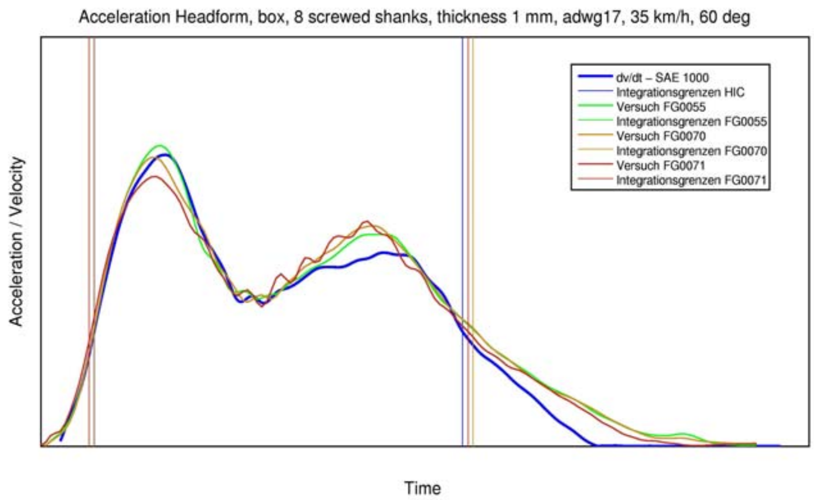


Fig. 14-15 "Box" configuration, correlation of experiment and computation

In addition, the model has also to fulfil the corridor of the dynamic certification test according to EEVC-WG17. In this procedure, the headform hangs free, supported by wires and impacted by a 1-kg-flat-faced certification impactor (figure 16). The impactor velocity depends on the type of the headform (adult head: 10m/s, child head: 7 m/s).

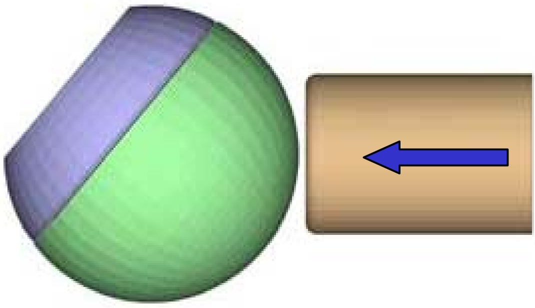


Fig. 16 Certification test according to EEVC-WG17

Legform Impactor

The legform impactor consists of two metal tubes with an outer diameter of 70mm representing tibia and femur. Physical properties like mass, moments of inertia and center of gravity for both, femur and tibia, are specified in the EEVC-WG17 report.
A layer of Confor foam (CF-45 1; thickness 25mm) is used to model the flesh. The impactor is covered by a 6 mm thick neoprene skin.

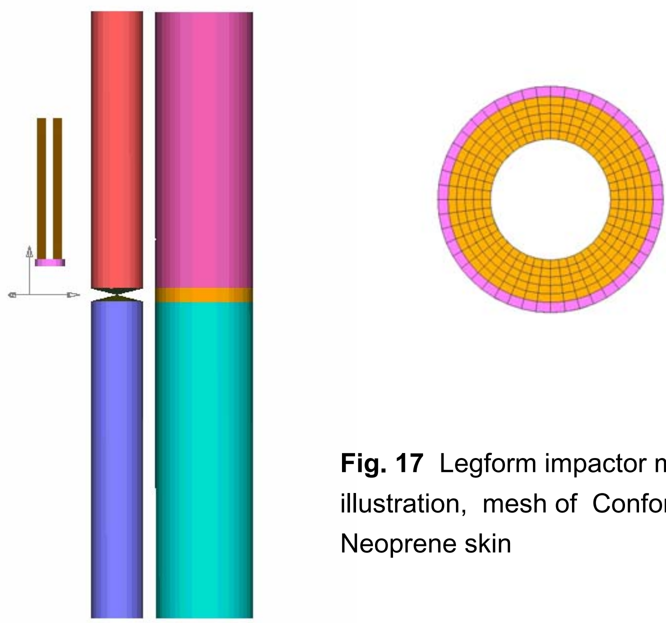


Fig. 17 Legform impactor model, exloded illustration, mesh of Confor-foam and Neoprene skin

Two flat metal plates are representing the so-called shear spring which is part of the femur section. The relative motion between femur tube and shear spring generates the shear displacement of the impactor. In 2002 the EEVC-WG17 legform impactor was modified by adding a shear damper in order to reduce the oscillations of the shear displacement.

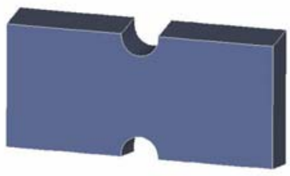


Fig. 18 Knee-joint ligament

The rotational degree of freedom of the knee joint is governed by two 7mm thick ligaments. The notches which are triggering the knee bending have a diameter of 6mm. The FE-Modelling is based on a discrete element in order to avoid very small time steps which will occur by using a solid element representation of the ligament. The ligament bending generates the bending angle of the legform impactor.

An uniaxial accelerometer is mounted in the inner rear part of the tibia tube at a location of 66mm below the knee joint.

Three physical properties will be calculated by using the legform impactor :

- Tibia Acceleration
- Knee Bending Angle
- Shear Displacement

The tibia acceleration is mainly depending on the material behaviour of the Confor Foam and Neoprene skin. The FE-Model for both materials is based on the FU-CHANG-FOAM formulation [4] and it uses the test results of several compression and tension tests at different strain rates up to 100 1/s and hydrostatic tests as well, (Fraunhofer Institute EMI, Freiburg, Germany). The original test data was directly implemented into the material load curves and has not been modified during the following validation procedure. The initial time step size of the FE-Model is 0.64 μs.

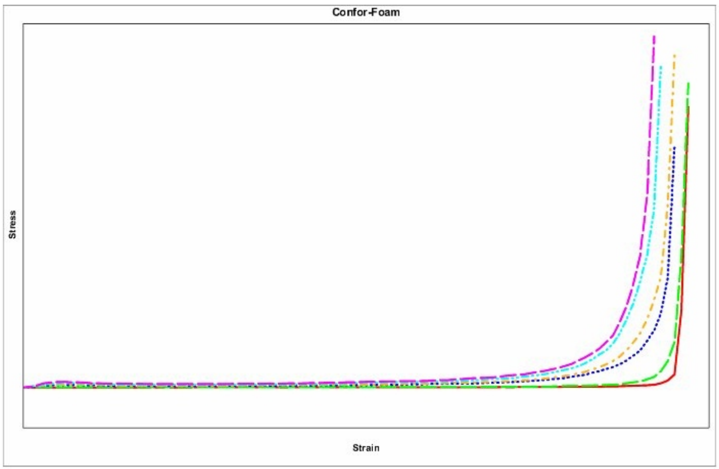


Fig. 19
Confor foam tests - stress-strain-curves

Corridors for the bending and shear stiffness behaviour are defined in the EEVC-WG17-Report together with the quasistatic certification test procedure for bending and shearing.

These quasistatic tests have been performed with the legform impactor model using the static implicit features of LS-DYNA970. The results are shown in Figures 20 and 21.

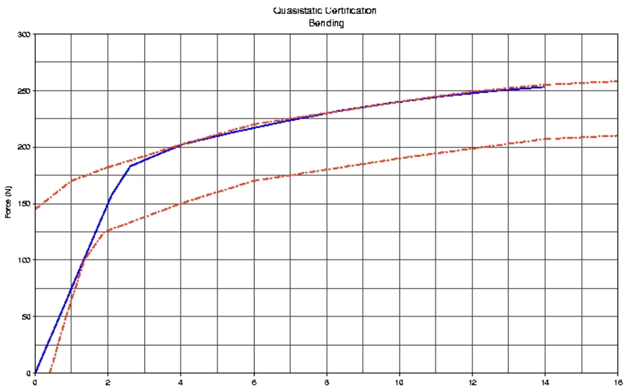


Fig. 20 Quasistatic bending

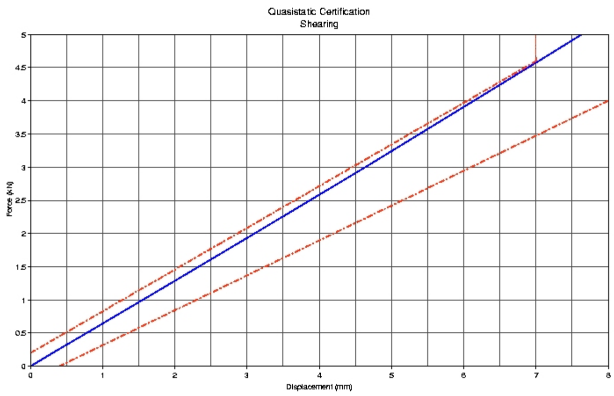


Fig. 21 Quasistatic sheare

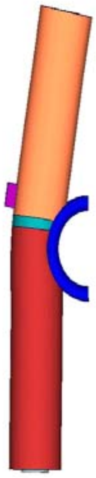


Fig. 22 Dynamic certification test

The original dynamic certification test proposed in the EEVC-WG17-Report (Fig. 22) was not considered to be an appropriate test procedure for the legform impactor since the test conditions have been changed substantially during the last two years. The mass of the certification impactor has been reduced from 16 to 9 kg and the specific corridors for all three measured quantities have been changed as well.
For extended validation a specific test configuration was designed (Fig. 23).

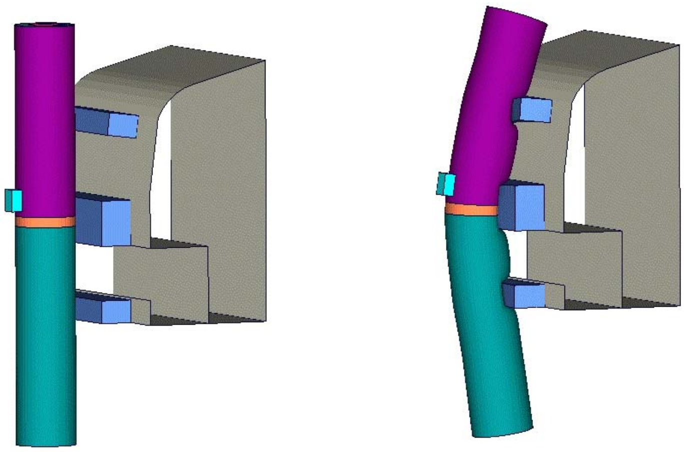


Fig. 23 Validation configuration

This target consists of a wooden solid block with three pieces of foam material on its face. Position, depth and stiffness of the foam blocks are variable. This parameters were adjusted to meet a reasonable range for all recorded signals (bending angle, tibia acceleration and shear displacement). Calibration of the foam material has been done by performing pre-tests with a steel cylinder hitting the foam.
In the validation test procedure several configurations have been investigated:

- tests at different speed (40, 35 kph),
- variation of vertical position of the legform impactor relative to the target and
- angular tests (up to 15°).

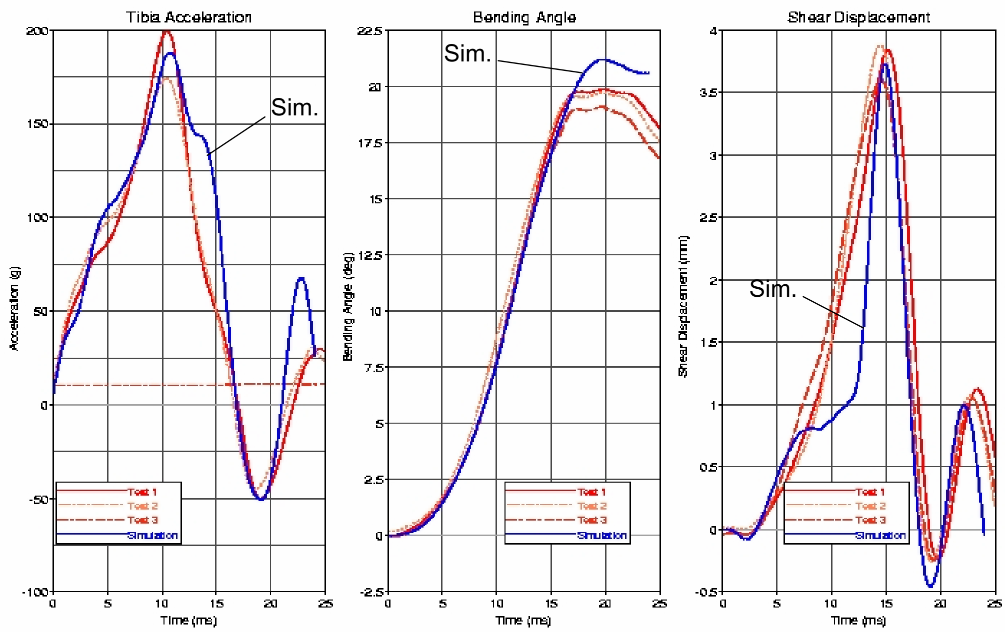


Fig. 24 Results – test vs. simulation

A typical result of the validation procedure is shown in Fig. 24. The main focus is an overall satisfying correlation of test and simulation.

Upper Leg Form

The Upper Leg Form consists of a metal structure where impacting forces and bending moments are measured. This kernel will be covered by two foam layers and a textile membrane.

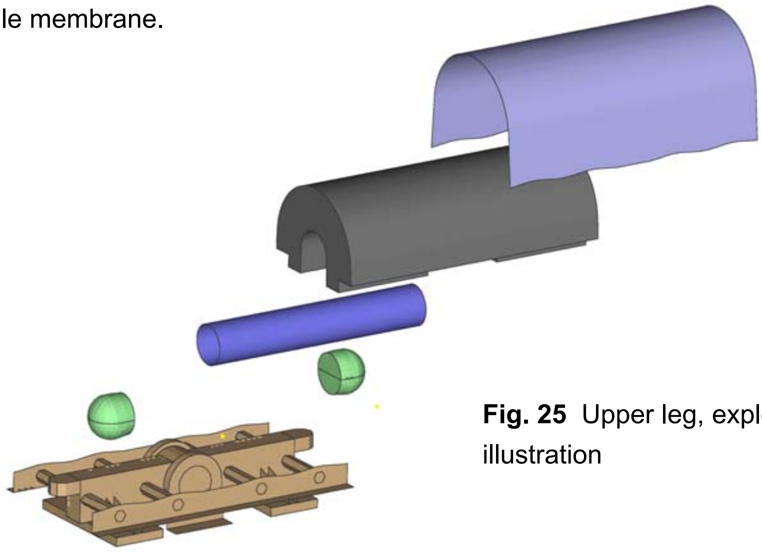


Fig. 25 Upper leg, exploded illustration

In the numerical model, the metal parts can be idealised as connected rigid bodies with a varying mass. The steel tube where the moments are measured has to be elastic. The load cells were simplified to beam elements. The material of the two foam layers is Confor blue CF-45, 1 inch thick. This material is known from the lower legform, further material tests were not necessary. The impactor validation is done with a specific test configuration (Fig. 26). The stiffness of this weak structure is fitted so that forces and moments are in an useful range near the limits defined in EEVC-WG 17 report [2].

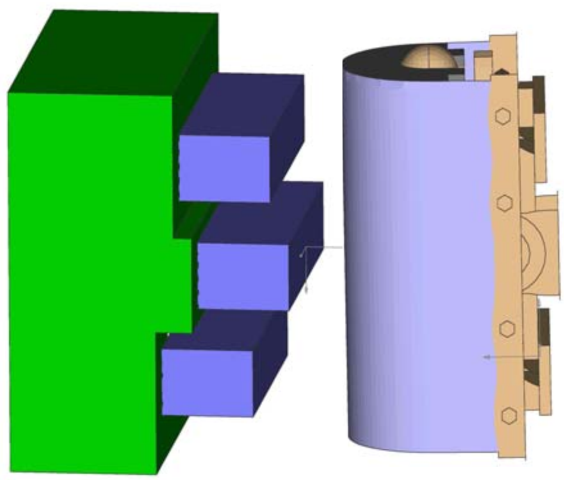


Fig. 26 Upper leg validation configuration

The upper leg impacting tests were performed with a wide range of velocities and weights of the Upper Leg. This spectrum of measured forces and moments was the base for the validation of the numerical Upper Leg Form.

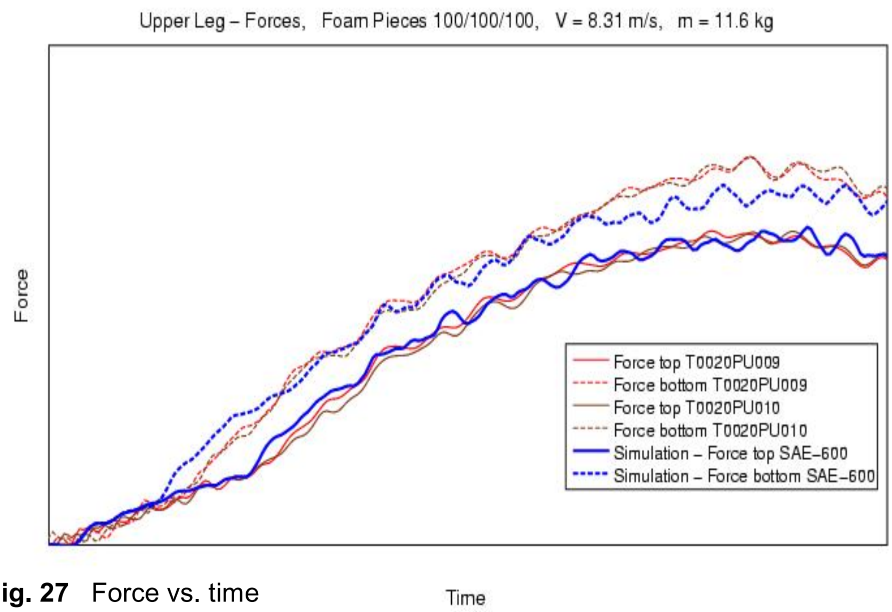


Fig. 27 Force vs. time

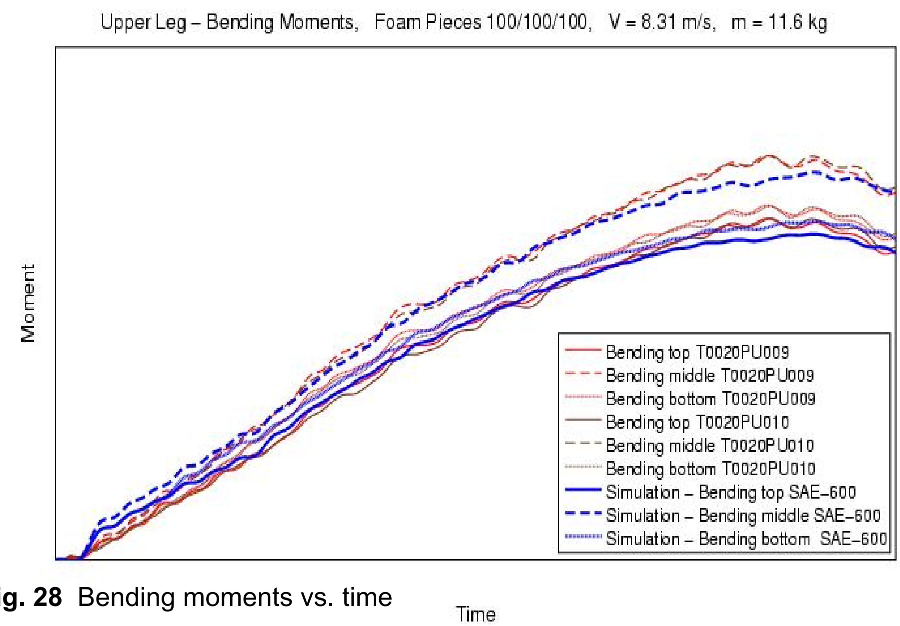


Fig. 28 Bending moments vs. time

Summary

A family of LS-DYNA pedestrian impactor models according to the Industry Commitment was developed and validated. Three headform impactors (child, child/small adult and adult), a legform- and an upper leg impactor are available.
In addition to the so-called certification tests more realistic validation tests have been performed in order to get a basis for the numerical validation procedure. The results show the correlation between test and simulation.
All presented models are used in real car simulations at DaimlerChrysler and Porsche. Experiences from these applications will influence the maintenance, improvement and further development of the pedestrian impactor models.
These models are available for use of other customers.

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