DEVELOPMENT OF LS-DYNA FE MODELS FOR SIMULATING EEVC PEDESTRIAN IMPACT

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ABSTRACT

Finite element models of adult head, child head, upper leg, and leg pedestrian impactors in LS-DYNA were developed and certified. The upper leg and leg impactor models were developed based on the descriptions in the Working Group 17 (WG17) Report of the European Enhanced Vehicle-Safety Committee (EEVC). The head impactors were developed based on the descriptions in the Working Group 10 (WG10) Report of the EEVC. Simulations of the certification tests described in the WG10 (head impactors) and WG17 (leg impactors) reports were performed. The results of these simulations for the head impactors compared well with the results from actual certification test results and fell within the acceptable range for certification. Results from the upper leg certification test simulation did not compare as well with the actual test results but were still within the acceptable range for certification. Test results for the leg impactor were not available for comparison, but the simulation results of the dynamic certification test fell within the allowable limits for certification.

Several additional impact simulations were performed for the adult and child head impactors and compared to tests. The additional tests included a wide range of impact velocities, and were used to calibrate the material behavior in the head impactor models so that the impactor models show similar energy absorbing characteristics when compared to the actual head impactors.

INTRODUCTION

In the European Union more than 7000 pedestrians and 2000 cyclists are killed each year in accidents with vehicles while hundreds of thousands are injured [1]. In the United States in the year 2000 there were over 4700 deaths and 78,000 injuries of pedestrians and 690 deaths and 51,000 injuries to cyclists [2], while in Japan there are about 2700 pedestrian deaths and 1000 bicyclist deaths annually [3]. The members of the European Enhanced Vehicle-Safety Committee as well as others have conducted numerous studies over the past decade concerning pedestrian-vehicle safety issues. In 1994 the EEVC combined the findings and recommendations of these studies into a publication entitled "EEVC Working Group 10 Report - Improved Test Methods To Evaluate Pedestrian Protection Afforded by Passenger Cars"[4]. In 1998 this document was updated based on further work of Working Group 17[1].

Based largely on the EEVC documents, the European Union has made proposals for vehicle tests and regulations concerning vehicle-pedestrian safety issues. These proposed regulations involve the impact of four different projectiles representing different parts of the human body into the front of a resting vehicle as shown in Figure 1. The proposed tests include the impacts of adult and child headforms into the hood of the vehicle, the impact of a legform into the front bumper of the vehicle, and the impact of an upper legform into the leading edge of the hood. The impactors used in these tests are instrumented with accelerometers, transducers, and strain gauges, and time histories of various accelerations, forces, and strains are recorded during the tests. The proposed regulations set limits on the peak values of various accelerations and forces that are recorded in the tests.

In addition to the pending EU pedestrian safety regulations the European New Car Assessment Programme (EuroNCAP), a consortium of several European governmental and non-governmental transportation safety organizations, have established a testing program for scoring vehicles based on the performance in a series of pedestrian impact tests [5]. This set of impact tests is also largely based on the work of WG10, and, as a result, the tests are very similar to the series of tests proposed by the EEVC for legislation. However, while the proposed pedestrian regulations are still under scrutiny, the EuroNCAP tests are performed on current vehicles sold in the European market and the results are published.

In order to address the pending EU pedestrian safety regulations several groups have turned to simulation to evaluate existing vehicle designs and suggest design changes that would perform well in the proposed pedestrian tests [6, 7, 8]. These studies have used a set of MADYMO pedestrian impactor simulation models developed by TNO [9].

This paper presents a description of the LS-DYNA [10] finite element models of the pedestrian impactors. Comparisons of the certification test results along with the simulation results of the certification tests are shown for each of the impactors. In addition, the paper describes testing and simulation of the impactors beyond the certification tests that were performed to further check that the behavior of the models is similar to the actual impactors.

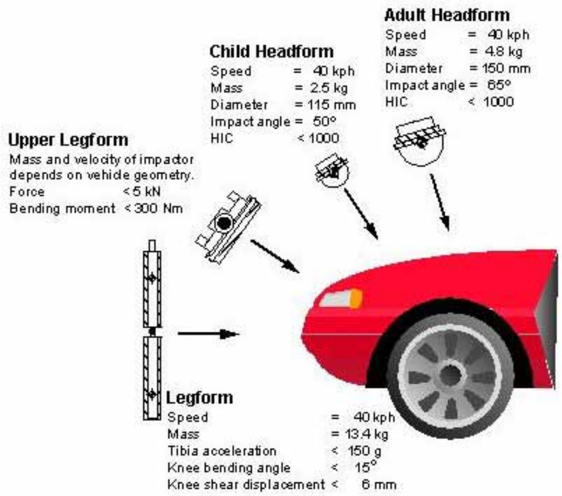

Figure 1. Proposed EEVC pedestrian impact safety tests.

Headform Models

Head Impactors Description

Due to the unavailability of the EEVC WG17 headform impactors at the time of this study, it was decided that our modeling work for the head impact test would concentrate on the WG10 specification.

The adult and child head impactors as described in the WG10 documentation consist of a 7.5mm thick rubber outer skin covering a semi-rigid polyurethane hollow sphere. A steel insert is included in the center of the sphere on which a triaxial accelerometer is mounted. This accelerometer is located at the geometric center of the sphere, which is also the center of mass of the impactor. Details of the dimensions and tolerances of the impactors can be found in [4], but a general description of the dimensions is given in Table 1.

Head Impactors CertificationTests

WG10 certification of the head impactors is performed with a drop tower test. The setup of this test is shown for the adult and child impactors in Figure 2. For the adult head impactor certification test, the drop angle in Figure 2 is 65 degrees and the drop height is 376mm. The values for drop angle and drop height for the child certification test are 50 degrees and 250mm, respectively. The only requirement for certification of the head impactors is that the maximum resultant acceleration value at the accelerometer location falls between 210G's and 260G's for the child impactor, and between 225G's and 275G's for the adult impactor, in the drop tower tests. Symmetry of the impactors as well as repeatability of the tests must also be demonstrated by rotating the impactors 120 degrees and 240 degrees about the axis of the neck and repeating the tests.

Table 1.
Summary of WG10 headform impactor properties with allowable tolerances and the finite element model values.

	Adult requirement (Model value)	Child requirement (Model value)
Headform Diameter (excluding skin)	150±2.0mm (150.2mm)	115±2.0mm (116.0mm)
Core material	Polyurethane (LS-DYNA elastic model)	Polyurethane (LS-DYNA elastic model)
Insert material	Steel (LS-DYNA elastic model)	Steel (LS-DYNA elastic model)
Skin material	Rubber (LS-DYNA viscoelastic Ogden rubber model)	Rubber (LS-DYNA viscoelastic Ogden rubber model)
Skin Thickness	7.5±0.1mm (7.56mm)	7.5±0.1mm (7.43mm)
Mass	4.8±0.1kg (4.80kg)	2.5±0.1kg (2.46kg)
Moment of Inertia*	0.0100±0.001kgm^2 (0.0097kgm^2)	0.0031±0.0003kgm^2 (0.0032kgm^2)

* About an axis passing through the center of mass and perpendicular to the plane of Figure 2.

Head Impactors Finite Element Models

The finite element models created for the adult and child head impactors are shown in Figures 3a and 3b, respectively. A summary of the impactor properties and material models is given in Table 1. Solid elements were used for all parts of the head impactors. LS-DYNA null shell elements were overlaid on the outside surface of the impactors to model the contact interface. A total of 3356 nodes, 2815 solid elements, and 725 null shell elements were used in each model.

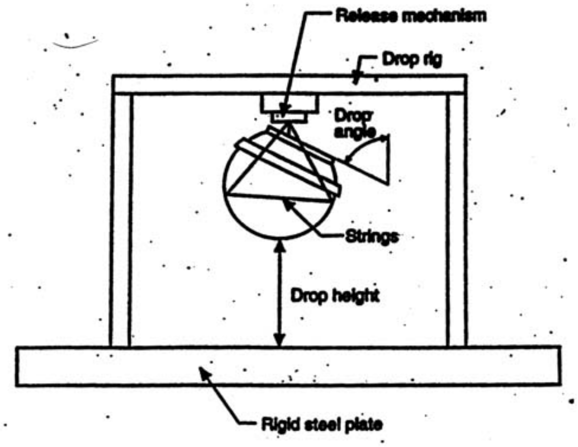

Figure 2. WG10 head impactor certification test setup.

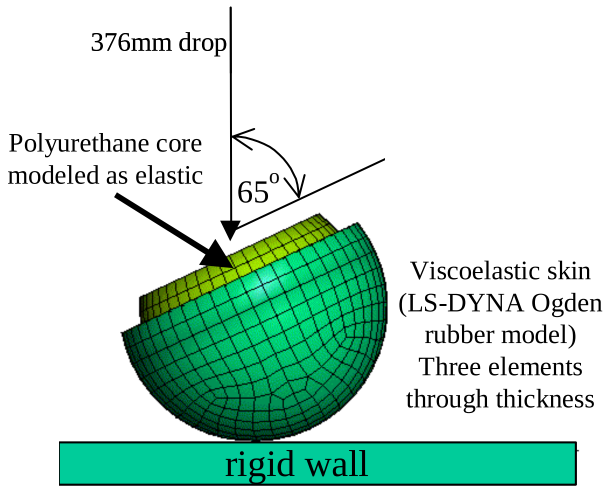

Figure 3a. FE model of WG10 adult head impactor certification test.

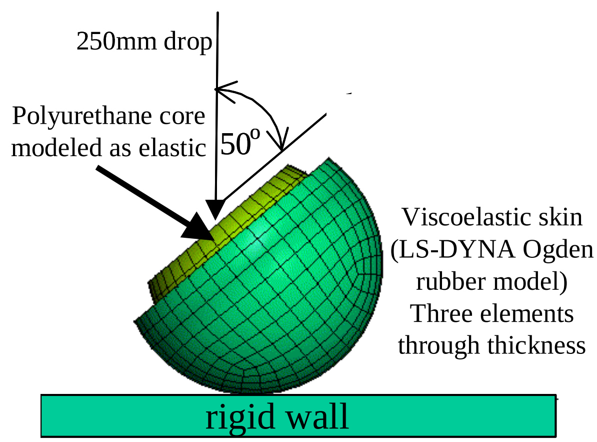

Figure 3b. FE model of WG10 child head impactor certification test.

Because the polyurethane core and the steel insert in the head impactors are much stiffer than the rubber skin, deformations of these two components are expected to be quite small. Therefore linear elastic material models were used for these components. The rubber skin was initially modeled with an elastic material as well. However, during the head impactor certification testing it was determined that the behavior of the head impactors was not elastic. Therefore, the material model used for the rubber skin was changed to an LS-DYNA Ogden rubber material model, which included a viscoelastic effect. The procedure to select the parameter values used in this material model will be described later in this section.

In order for the head impactors to be certified, it is required that their peak accelerations in the certification drop tower test fall within specified ranges that were described earlier. It is a relatively simple matter to build an impactor model that satisfies only this requirement. As was mentioned, the initial model of the adult head impactor was created with elastic material behaviors for both the interior core and the impactor skin. The elastic modulus for the skin was then adjusted so that the head impactor models experienced a peak acceleration that was similar to the peak acceleration recorded in the drop tower tests. The time history of the tests and this simulation are shown in Figure 4, where it is seen that the peak accelerations from both the tests and the simulation fall within the allowable range.

However, it was noted in the certification tests that the rebound velocity of the head impactors was significantly lower than the impact velocity. Since this indicated that there was a significant amount of energy absorbed by the impactors, it was decided that a viscoelastic behavior should be included in the skin material to model this energy absorption. Unfortunately, attempts to obtain these viscoelastic properties of the rubber skin material from the impactor supplier were unsuccessful, as were attempts to obtain a sample of the material for testing. Therefore, an empirical approach was used to determine the viscoelastic parameters of the skin that would be used in the finite element skin model.

This process began by conducting drop tower tests of each head impactor from three different drop heights. For each test a contact sensor was placed on the impactor so that the precise time of contact between the head and the stiff impact plate could be recorded. Based on this precise contact time, and integration of the acceleration time history from the accelerometer at the center of the head, a time history of the crush of the head impactor was calculated. The acceleration of the head, which is proportional to the force acting on the head, was then plotted as a function of the crush of the head.

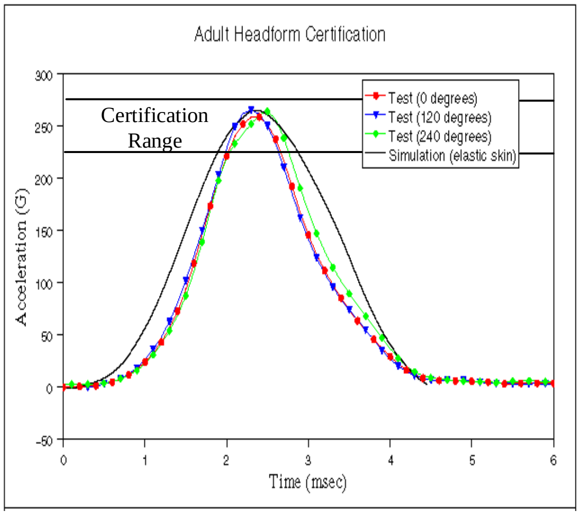

Figure 4. Acceleration time history for adult impactor certification test and certification test simulation with impactor model with elastic skin material model.

This procedure was repeated for three different drop heights for each head impactor, adult and child, and compared to simulation results. The viscoelastic parameters of the skin model were then adjusted to improve the comparisons between test and simulation results. The acceleration-crush plots of the tests and final simulation models are shown in Figure 5 for the adult and child head impactors. It can be seen that significant energy is absorbed in the head impactors as evidenced by the hysteresis of the acceleration-crush behavior. Also plotted for the adult impactor case is the simulation with the elastic skin material model for the drop height of 376mm. Even though the peak acceleration that results from the model with the elastic skin is very close to the value seen in the test, the energy absorption behavior of this model is very different from the test, and therefore, the viscoelastic skin model was deemed more appropriate.

Unfortunately, we found that it was necessary to use different material parameters in the viscoelastic skin model of the adult head impactor than those used in the child head impactor in order to get good agreement between test and simulation for all drop tower heights. This indicates that the LS-DYNA rubber model of the skin is not completely representative of the actual skin material. However, we feel that since we were able to match the results of drop tower tests at several different heights (and thus, impact velocities), our models should be relatively accurate in simulations of impacts with actual vehicle hoods.

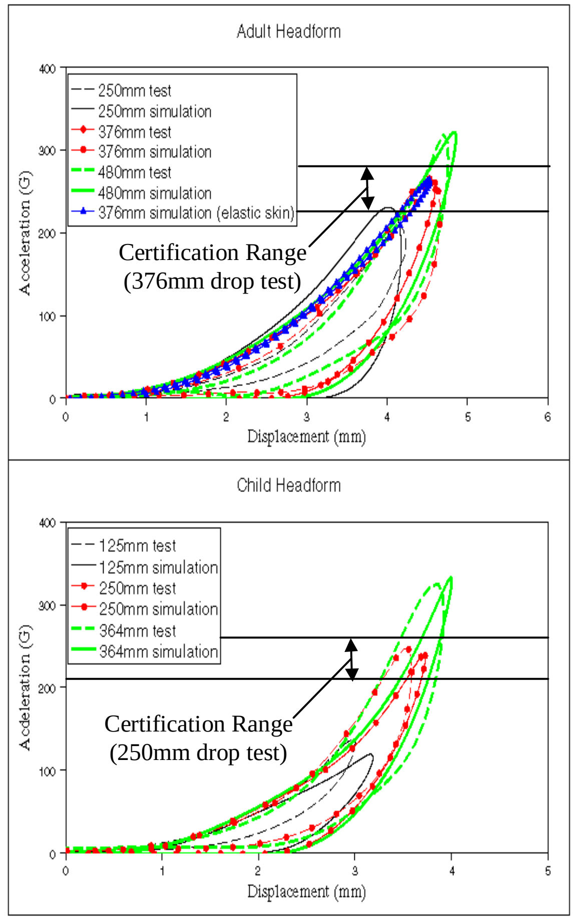

Figure 5. Acceleration vs. crush of adult and child head impactors in drop tower tests and simulations from different heights.

Upper Legform Model

Upper Leg Impactor Description

The EEVC WG17 upper leg impactor consists of a steel cylinder representing the human femur covered by two 25mm thick sheets of Confor^{TM} foam type CF-45 on the impact side of the cylinder, which represents the flesh of the human leg. In turn, this foam is covered with a 1.5mm thick fiber-reinforced rubber sheet to represent the skin. The ends of the steel cylinder are connected to a large adjustable mass, which is located behind the cylinder (opposite the impact side) as shown in the finite element model of the impactor in Figure 6. Force transducers are located at the connection points between the cylinder and adjustable mass. In addition, strain gauges are located at the three locations on the cylinder on the side opposite the impact region. These strain gauges are used to calculate the bending moment in the cylinder during the impact test. A detailed description of the upper leg impactor can be found in the WG17 report [1], but a summary of the key dimensions and characteristics is given in Table 2.

Upper Leg Impactor Certification Test

The finite element model of the certification test for the upper leg impactor is shown in Figure 6. This impactor is propelled with an initial velocity of 7.1m/s into a steel cylindrical pendulum, which is suspended from above by wires attached to its ends. The mass of the leg impactor for this test is set to 12kg and the mass of the target cylinder is 3kg. The wall thickness of the target cylinder is 3mm. The time histories of the forces measured at the two transducers in the leg impactor are recorded and the peak value of each of these forces must fall within a specified range of 1.2-1.55kN. The time histories of the strains at the three strain gauge locations are also recorded and then used to calculate time histories of the bending moment at these three locations. The peak bending moment at the center gauge location must fall within a range of 190 to 250Nm while the peak bending moment at the offset gauge locations must fall within a range of 160 to 220Nm.

Upper Leg Finite Element Model

The finite element model developed in this study for the upper leg impactor is shown in Figure 6. The model consists of 6121 nodes, 2153 shell elements, 2228 solid elements, and 2 beam elements which act as the force transducers between the front and rear portions of the impactor. Table 2 gives the material models, element dimensions, and resulting masses of the model. The steel cylinder of the impactor is modeled with shell elements, as is the large adjustable mass to the rear of the cylinder. The mass of the impactor, which varies in the vehicle tests based on the vehicle geometry, is adjusted by attaching lumped masses onto the nodes at the rear of the impactor. Null shell elements are overlaid onto the surfaces of the steel cylinder and both layers of foam to model the contact interfaces between these parts and also with the impacted vehicle.

The connection between the adjustable mass and the ends of the steel cylinder are modeled with the two beam elements. The node at one end of these beam elements is attached to the rear member, while the node at the other end is attached to the caps at each end of the impactor cylinder. The attachment to the impactor cylinder is comprised of a series of rigid connections that act as spokes out to the circumference of the cylinder cap. The axial force in these beam elements gives the force between the front and rear members, which is measured by the force transducers in the test. These beam elements are assigned a large cross sectional area to resist translational displacements, a large moment of inertia about an axis parallel to the impactor cylinder to resist bending about this axis, and a large polar moment of inertia to resist twisting of the beam. However, they are given a small moment of inertia about the z-axis of Figure 6, which allows rotation about this axis with very little resistance. This effectively models the pin joint connection between the force transducer and the front member cylinder in the actual impactor.

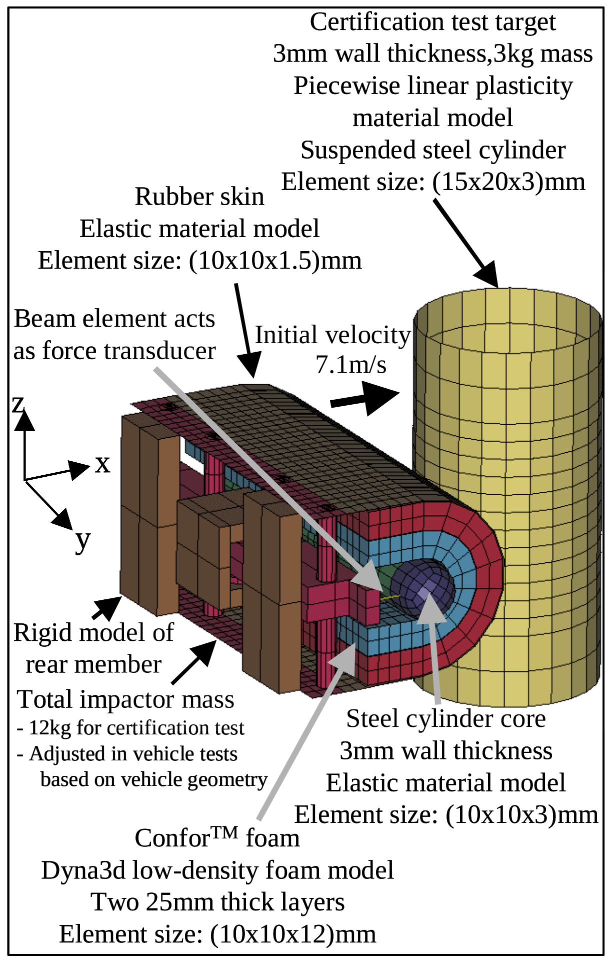

Figure 6. Finite element simulation model for the upper leg impactor certification test.

The bending moment in the front member cylinder is determined by two methods. The membrane strains in the shell elements at the strain gauge locations in the actual leg impactor are monitored and the bending moment is determined from these strain values. In addition, LS-DYNA cross sections are used to cut through the cross section of the cylinder, and the values of the moments at these cross sections are output. It was determined in simulation that these two methods gave nearly the same value of bending moment for the cylinder. Since cross section output is a more direct measure of the bending moment and is generally less noisy than the strain output, it was chosen as the preferred method for calculating the bending moment in the simulations.

Table 2.
Summary of upper legform impactor specifications for certification test and finite element model properties.

	Mass requirement in kg (Model mass)	Material (LS-DYNA model material type)	Element size in mm
Cylinder core	1.95±0.05 (1.952)	Steel (elastic)	(10x10x3) shell
Foam	0.60±0.10 (0.578)	Confor™ foam C-45 (low density foam)	(10x10x12) solid
Skin		Reinforced rubber (elastic)	(10x10x1.5) shell
Total for impactor front member	2.55±0.15 (2.530)		
Impactor rear member	9.45±0.15 (9.486)	Steel (rigid)	
Total impactor	12.00±0.10 (12.016)		
Impactor target	3.00±0.03 (3.000)	Steel (piecewise linear plasticity)	(15x20x3) shell
Total	15.00±0.13 (15.016)		

The LS-DYNA low-density foam material model was used to represent the Confor™ foam that wraps around the steel cylinder upper leg core. The properties of this foam were determined by quasi-static and dynamic crush tests performed at the Japanese Automotive Research Institute [11]. Several different tests were performed with different crush rates and at different ambient temperatures. A sampling of these test results is shown in Figure 7. The stress-strain curve corresponding to an ambient temperature of 20 degrees Celsius and a crush rate of 35km/h was used for the simulation model of the upper leg, as shown in Figure 7. Since the strain values in the tests did not exceed 70%, it was necessary to extrapolate the stress-strain behavior in the model for strain values above 70%. It was found that the force-time and moment-time results in the certification test simulation were quite sensitive to the foam material stress-strain curve in the 70%-100% strain range.

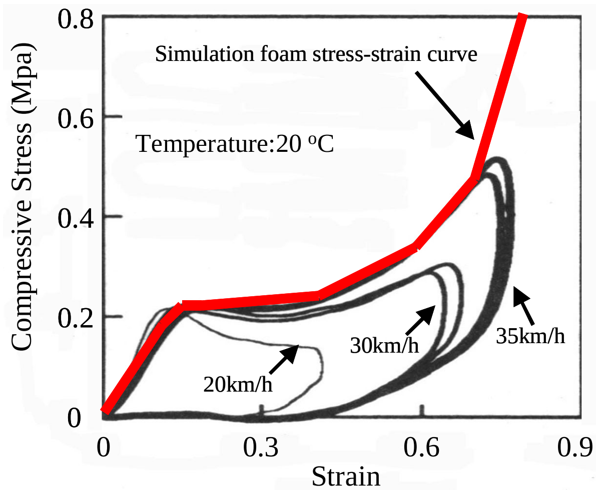

Figure 7. Confor™ foam dynamic compression test results [11] and simulation model stress-strain curve.

The comparison between the certification test and the final results of the simulation are shown in Figure 8. The top chart of Figure 8 gives the time history of one of the two force transducers, while the middle and bottom charts of Figure 8 show the bending moment at the center and the offset locations of the strain gauges on the cylinder core. As can be seen in this figure, both the test and the simulation results fall within the certification limits for this test. Furthermore, the agreement between test and simulation is good for the bending moments, but not for the force values.

Several simulations were performed with different values for the friction coefficients between the foam and the steel cylinders, and different values for the parameters that control the foam material model behavior, in an attempt to improve the correlation between test and simulation. None of these various simulations gave results that had an improved overall comparison to the test. Next, additional analyses were performed that seem to indicate it would be unlikely for the upper leg impactor to give the test results shown in Figure 8 and those that have been reported

[6, 9] for the upper leg dynamic certification test as described in the WG17 document (see the Appendix). This suggests that there may be some discrepancy between the upper leg impactor dynamic certification test setup used in the test in Figure 8 and in [6, 9] and the setup used in the certification test simulation in this paper.

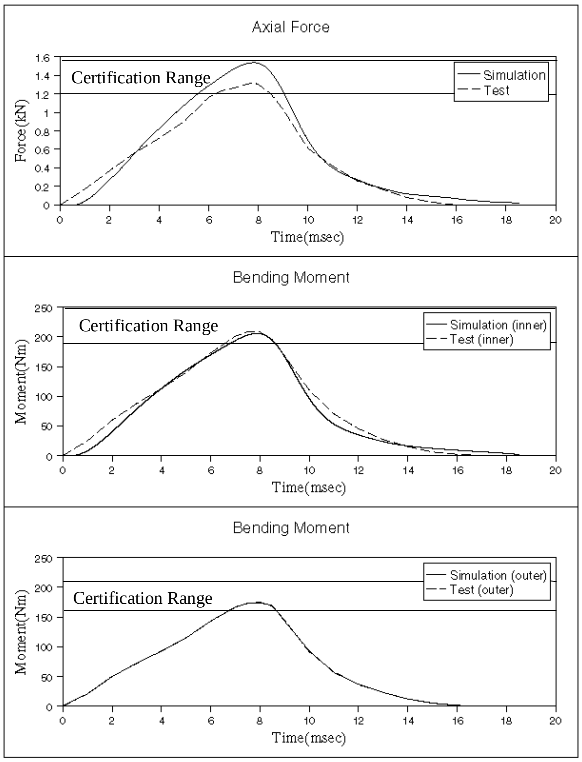

Figure 8. Axial force and bending moment results from test and simulation of upper leg certification. "Inner" corresponds to the bending moment at the center of the impactor and "outer" corresponds to the bending moment at a location offset 50mm from the center of the impactor.

Legform Model

Leg Impactor Description

The EEVC WG17 leg impactor consists of two 70mm diameter steel rods that represent the human femur (upper leg) and tibia (lower leg). They are connected by a joint that has bending and lateral displacement degrees of freedom, and acts as the knee of the assembly. The entire legform is wrapped in 25mm of Confor™ foam, type CF-45, to represent human flesh, and then 6mm of neoprene to represent the skin. The instrumentation of the legform includes an accelerometer located on the non-impact side of the lower steel rod, 10mm below the knee joint, angular transducers on each of the rods to measure bending of the leg, and a means to measure the relative shearing displacement of the rods at the knee location. Finally a damper element is placed on the non-impact side of the legform. The exact location and properties of this damper element are not specified so that they can be set to whatever is necessary to comply with the requirements of the static and dynamic certification tests. A detailed description of the leg impactor is given in [1], but for reference a summary of its mass properties is shown in Table 3.

Leg Impactor Certification Test

Certification of the leg impactor requires both static and dynamic tests, which are described in the EEVC WG17 document. For the static tests, acceptable corridors are prescribed for the force-rotation and force-displacement behavior of the knee joint. For the dynamic pendulum impact test, limitations on the peak acceleration at the accelerometer location, peak bending angle between the upper and lower segments of the legform, and peak shearing displacement at the knee location are specified.

Leg Impactor Finite Element Model

The finite element model of the leg impactor developed in this study is shown in Figure 9, and a summary of the model properties is given in Table 3. The steel rods of the leg impactor are modeled with rigid shell elements in the simulation model, while the foam is modeled with the same material model as was used in the upper leg impactor. The bending and shearing resistance of the knee joint is modeled with LS-DYNA rotational and translational springs, respectively, as shown in Figure 9. Null shell elements are overlaid on the surface of the foam to model the contact interface. The model consists of 5808 nodes, 948 shell elements, and 4 discrete spring/damper elements as shown in Figure 9.

Table 3.
Summary of the legform impactor specifications and finite element model properties.

	Mass requirement in kg (Model mass)	Mass moment of inertia# requirement in kgm^2 (Model inertia)	Center of mass distance to knee in mm (Model value)	Material (LS-DYNA model material type)	Element size in mm
Upper leg (femur)	8.6±0.1 (8.510)	0.127±0.01 (0.128)	217±10 (217)	Steel (rigid)	(18x12x0.5) shell
Lower leg (tibia)	4.8±0.1 (4.769)	0.120±0.01 (0.120)	233±10 (234)	Steel (rigid)	(18x12x0.5) shell
Foam	*			Confor™ C-45 foam (low density foam)	(18x12x12.5) solid
Skin	*			Neoprene (viscoelastic)	(21x18x6) solid
Total	13.4±0.2 (13.279)				

* Included in upper and lower leg mass.
# About an axis perpendicular to the axis along the length of the leg and passing through center of mass of the part.

The non-linear stiffness of the springs was calibrated so that the results of the simulation of the static certification tests fell within the acceptable bounds as shown in Figure 10. It should be noted in the shear test in Figure 10 that the corridor for the force-displacement behavior is essentially unbounded when the displacement exceeds 7mm. Since no test results were available for the leg certification test, there was no way to establish the shearing resistance behavior for values of shear displacement that exceed 7mm. Therefore, it is possible that simulation results may not compare well with tests for in any case where the shearing displacement exceeds this critical value.

Once the joint properties were established by calibrating the model to fall within the acceptable limits in the static certification tests, the simulation of the dynamic certification test was used to adjust the damping element coefficients so that the results of the dynamic simulation fell within acceptable levels. The simulation results of the final finite element model of the legform are shown in Figure 11 for the dynamic certification test. Note that these results are for a leg impact in the local x-direction of figure 9. Again, because no actual certification test results were available for the leg impactor, the model was calibrated only to meet the certification requirements, which are shown with the simulation results in Figure 11.

SUMMARY

LS-DYNA finite element models of adult head, child head, upper leg, and leg pedestrian impactors were developed. It is intended that these models will be used to predict the performance of vehicle front structures in the proposed European Union Pedestrian Protection legislation and in the pedestrian EuroNCAP (New Car Assessment Program) tests, which are currently performed in Europe. Therefore, it was necessary for the pedestrian impactor finite element models that were developed in this study to meet the certification requirements established in the EEVC Working Group 10 and Working Group 17 documentation. Both the proposed pedestrian legislation and the pedestrian EuroNCAP testing are largely based on these documents.

The head impactor models developed in this study are based on the WG10 document rather than the more recent WG17 document. A WG10 child and a WG10 adult head impactor have been tested including drop tower tests and vehicle impacts. Attempts to acquire WG17 head impactors have been unsuccessful, and it was decided that it would be very difficult to develop head WG17 head impactor models without the ability to test actual WG17 impactors.

The child and adult head impactors developed in this study satisfy all the requirements for certification as described in the WG10 documentation. In addition, drop tower tests of the head impactors were performed at several different heights in addition to the height required for certification. Simulations of these drop tower tests were performed and parameters controlling the viscoelastic behavior of the skin material model were adjusted so that the energy absorbing characteristics of the head impactor matched that seen in the tests at all the different heights.

The upper legform impactor model developed in this study is based on the WG17 document. It was found that the behavior of this model in the certification test was quite sensitive to the stress-strain behavior of the foam in the model for values of strain exceeding 70%. Unfortunately, the material test data used in the development of these models did not show strains exceeding 70%, so we were forced to extrapolate the stress-strain behavior at these high strain values. The final upper legform impactor model developed in this study satisfies all the requirements necessary for certification based on the WG17 documentation.

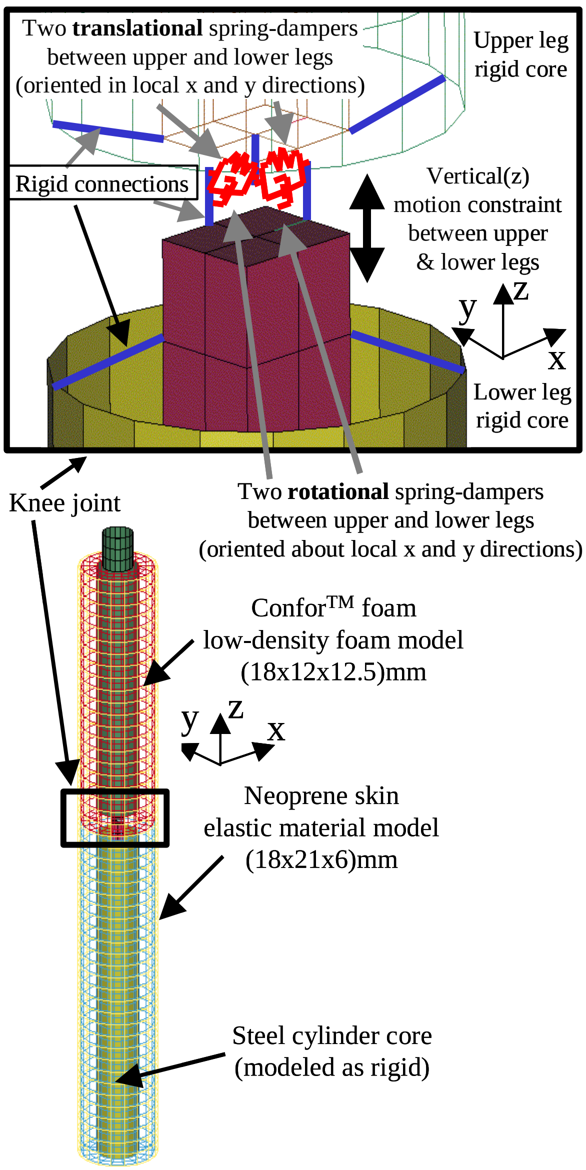

Figure 9. Finite element model of the leg impactor.

The legform impactor model developed in this study is also based on the WG17 documentation. Although no certification test data was available for comparison, the impactor model did satisfy all the requirements of the static and dynamic certification tests as described in the WG17 document.

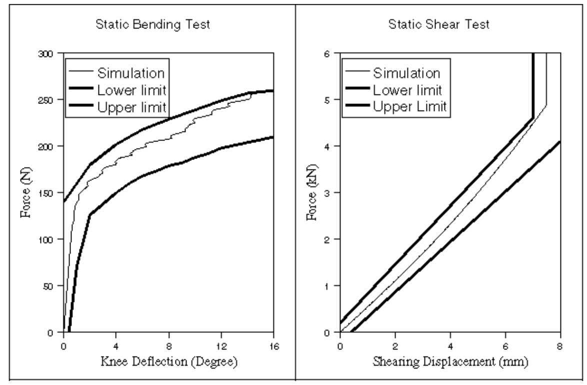

Figure 10. Leg impactor static bending and shear test and simulation results.

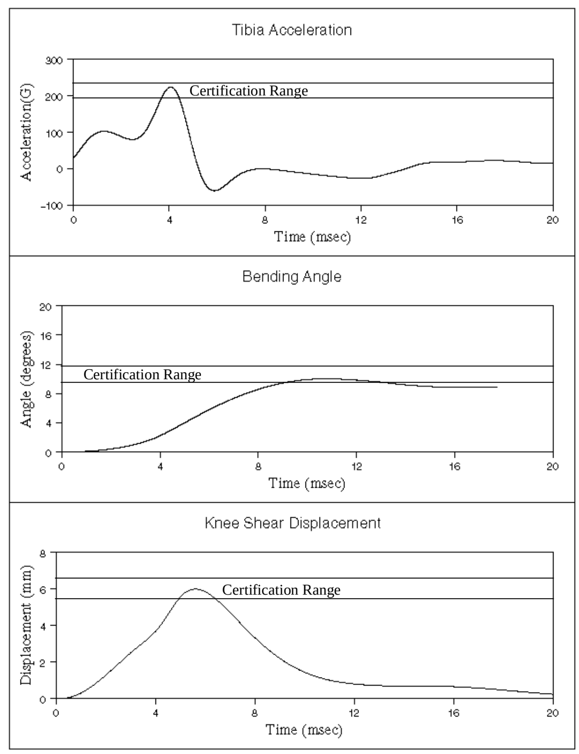

Figure 11. Results of leg impactor certification test simulation. (No test was available.)

ACKNOWLEDGMENTS

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APPENDIX

Upper Leg Certification Test Analysis

Figure A1 shows a simple schematic of the upper leg impactor dynamic certification test. In this test the upper leg impactor is essentially a simply supported beam. It is supported from below (in Figure A1) by the two force transducers and loaded from above by the target cylinder. As impact first occurs, the loading on the impactor cylinder is similar to a three-point loading of a simply supported beam. The solution to the three-point-bending loading case would result in a force to moment ratio of 6.45. The force to moment ratio calculated from the results of the finite element simulation with the impactor model described in this report is 7.5, while this ratio calculated from the test results of Figure 8 is 6.3. The ratios for two other sets of results reported in the literature are 5.4 [6], and 6.4 [9].

The fact that the force to moment ratios in the tests are lower than the static, three-point-bending case is surprising, since this type of loading case should result in the largest bending moment for a given transverse force. For example, if the end conditions were built-in rather than simply supported, the result would be a lower bending moment for a given transverse load. Likewise, if the transverse load were distributed to some extent along the length of the beam rather than concentrated at the center, the result would also be a lower bending moment for a given value of transverse load.

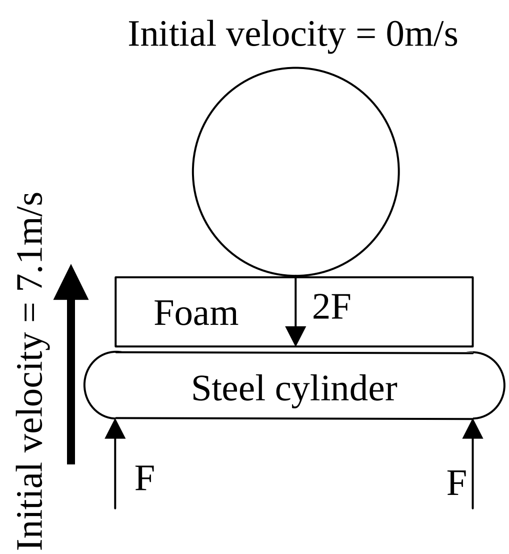

Figure A1. Schematic of the upper leg impactor dynamic certification test.

During the impact between the impactor and target cylinder, the foam of the impactor will continue to crush until the velocity difference between the impactor and target becomes zero. As the foam crushes the load acting on the impactor will be distributed across the contact region as shown in Figure A2, although the precise distribution of the contact force along the contact length would be a function of the foam force-crush behavior. It can be expected that at some value of crush, the foam will become compacted and will be quite stiff, and just as that happens the force distribution would look something like that shown in Figure A3. This sharp increase in the force at the center of the cylinder would, in turn, cause a sharp increase in the bending moment.

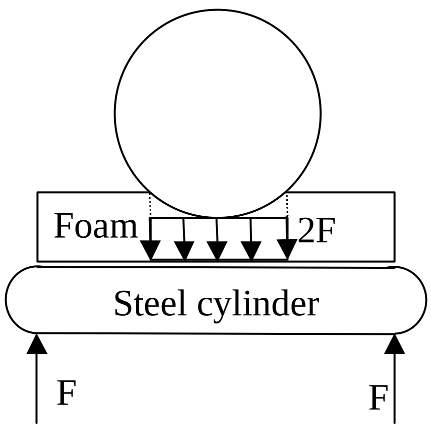

Figure A2. Schematic of the upper leg impactor dynamic certification test.

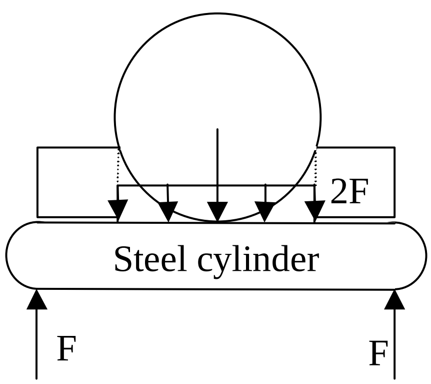

Figure A3. Schematic of the upper leg impactor dynamic certification test.

With the preceding discussion in mind, a short program was written in an attempt to determine the maximum bending moment that could be expected in the dynamic upper leg impactor certification test. This program simulates the dynamic impact of the upper leg impactor and target cylinder. As the impactor foam crushes it exerts forces on the target cylinder so that the difference in the velocities of the impactor and target cylinder slowly decreases. Just as this velocity difference becomes zero, the total contact force is calculated. If this contact force is less than 3100N, (the maximum allowable in the certification test), an additional force is added at the center of the cylinder as shown in Figure A3 so that the total contact force acting on the impact cylinder is 3100N. This additional force would result if the foam at the center of the impactor cylinder became fully compacted just as the relative velocity between the impactor and target cylinder became zero. This additional force will increase the bending moment in the impactor cylinder, and since the objective is to find the largest possible bending moment for a contact force of 3100N, the force is included in the analysis.

This program that models the dynamic impact was run for many different cases of foam force-crush behavior. During these runs the following assumptions were made:

- The foam cannot crush more than 50mm, the total thickness of the foam.
- The foam exerts a force only in the direction of impact, and the value of this force at a location along the length of the impactor is a function only of the crush of the foam at that location.
- The foam crushes only where the target cylinder contacts it.
- The target cylinder and the steel cylinder of the impactor do not deform significantly.
- The force-crush behavior of the foam is monotonic, i.e., the foam does not soften with increasing crush.

The force-crush behavior of the foam that resulted in the largest bending moment was a constant force behavior. This resulted in a bending moment of 211N and a force to moment ratio of 7.35. Note that the value of this ratio for the finite element results shown in Figure 8 is approximately 7.5, which is slightly higher than the minimum found with the simple analysis described here. This simple analysis suggests it is unlikely that any changes made to the force-crush behavior of the foam would significantly reduce the force to moment ratio found in the finite element simulation.