TEG-141

Report

Flexible Pedestrian Legform Impactor

Flex GTR Evaluation Tests

A Joint Project of
ACEA - The European Automobile Manufacturer's Association
and
BASt - The German Federal Highway Research Institute

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1 Introduction

In an effort to harmonize the various activities of different countries and organisations on improvements of the pedestrian protection of vehicles, the “Informal Group Pedestrian Safety” (INF GR PS) was established within the UNECE WP29/GRSP[1] in 2002, to develop a regulation for assessing the pedestrian protection capabilities of vehicles, including dynamic impact tests. On January 26th, 2009, the global technical regulation (gtr) no. 9 “Pedestrian Safety” was published. This regulation demands headform impactor tests to the bonnet as well as tests with the EEVC WG17[2] legform impactor to the bumper. However, in the preamble of the gtr, the future use of a newly developed flexible legform impactor has already been considered. Meanwhile, Japan has officially proposed an amendment to the gtr introducing this new legform.

In 2005, a sub-group of the INF GR PS was founded to evaluate the new legform, called “Flex-TEG” as an abbreviation of “**Flex**ible Pedestrian Legform Impactor **T**echnical **E**valuation **G**roup”, also referred to as Flex-PLI sub-group. The intention was to invite all interested parties to accompany the final phase of the development of the new impactor. Members of this group are pedestrian protection experts from governmental and research institutes and from the automotive industry as well as their suppliers.

The impactor has been in development in Japan by the “Japan Automobile Research Institute Inc.” (JARI) since 2002. As a result of its more biofidelic design it is supposed to show higher similarity to the human leg than the established impactor, especially regarding its behaviour in impact tests, including the test results.

Contrary to the EEVC WG 17 legform impactor, the new design accounts for the flexibility of the human bone by introducing a segmented construction for the femur and tibia sections of the legform. Therefore the impactor is called Flex-PLI - **Flex**ible **P**edestrian **L**egform **I**mpactor.

Equipped with strain gauges on the central longbones inside the impactor, the legform is enabled to measure bending moments on the femur and tibia. Inside the central knee joint, whose design is based on the human knee, four position transducers are geometrically arranged to measure elongations in the positions of the human cruciate ligaments as well as the medial collateral ligament.

The gtr prescribes tests with the legform impacting the vehicle bumper at 40 km/h to provide data on the impact, which will allow for estimates of injury severity in comparable real-life accidents.

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[1] UNECE: United Nations Economic Commission for Europe
WP29: World Forum for Harmonisation of Vehicle Regulations
GRSP: Groupe de Rapporteurs sur la Sécurité Passive (Working Party on Passive Safety)

[2] EEVC WG 17: European Enhanced Vehicle-safety Committee Working Group 17

In order to assess the usability, repeatability and reproducibility of the new impactor, impact tests with different development versions of the legform were conducted by the Flex-TEG members with selected cars at various test institutes, especially driven by ACEA, BASt and JAMA/JARI. Furthermore, JARI performed several series of numerical simulations. However, a validated simulation model of the new impactor is not yet available.

Based on the results of these research projects and the input received from associated partners, the development of the legform impactor was continued. The current development state of the impactor is called Flex-GTR and is the latest version of the prototype legform.

For the purposes of this project, the first three prototypes of the Flex GTR were used immediately after their production. All three legforms were similar to each other except their data acquisition capabilities. Legform no. 1 was equipped with standard cables for use with off-board data acquisition systems. Legforms no. 2 and 3 were equipped with on-board data acquisition systems; legform no. 2. with an “M=Bus” system of Messring GmbH, Germany, and legform no. 3 with a “Slice” system of DTS Inc., USA (see fig. 1).

The aims of this project were to assess repeatability, reproducibility, symmetry, durability and handling of the impactors. In addition, the test results should be compared to those of the previous versions Flex GTα and Flex GT[3], and – if necessary and possible – the deviation should be quantified.

For this evaluation project, two test configurations were used with all three impactors: Inverse tests with the legform being struck by a deformable impactor and vehicle tests with different vehicle types. In addition, several pendulum function tests were carried out to test or ensure the functionality of the legform including its instrumentation.

[3] Flex GTα was the name of the prototype version of the Flex GT. The changes from Flex GTα to Flex GT are presented in annex 6.

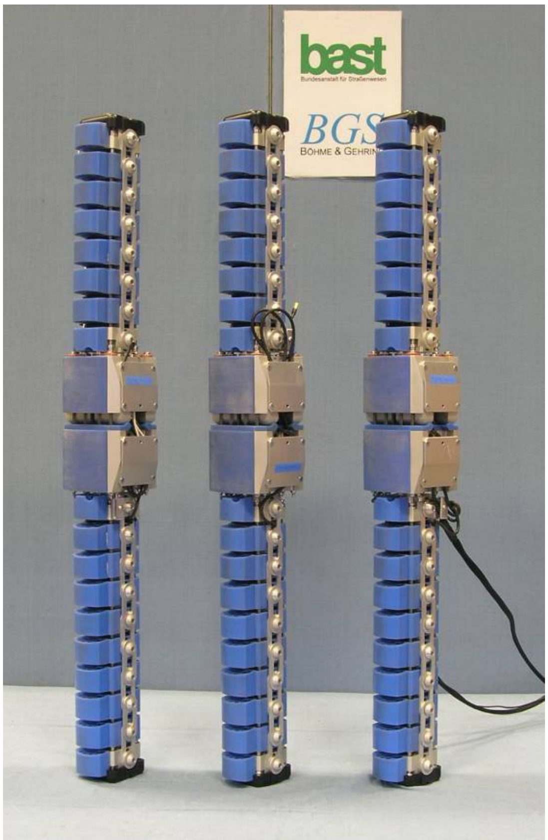

Fig. 1: The three Flex GTR legform impactors
(assemblies without flesh and skin representing parts)

2 Test Configuration

2.1 Test Subject

The GTR version of the Flex-PLI is the latest version of the prototype legform, incorporating all improvements suggested by the Flex-TEG and expected to be at least almost ready for use for regulatory purposes.

The Flex GTR consists of flexible femur and tibia sections and a central knee joint. The inner structure is covered by a multilayer skin and flesh simulation, made of neoprene and rubber, whose outermost layer is a one-piece neoprene skin, which covers the whole length of the legform (see fig. 2).

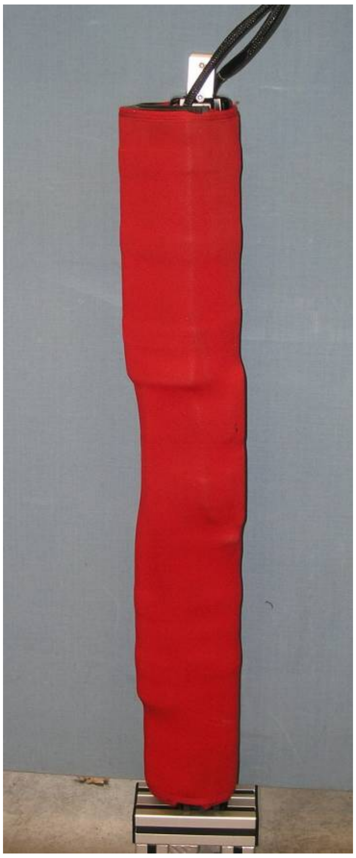

Fig. 2: Flex GTR

The impactor measures 926 mm in length, weighs 12.4 kg and has a cross-section-dimension of 140 mm for the femur and 132 mm for the tibia section.

The femur is made of eight individual segments aligned on a central bone core, made of glass fibre reinforced plastic (GRP) and simulating the human femur bone. The individual segments are held in place by metal brackets attached to their sides, keeping them flexibly aligned. The tibia is built similar to the femur but consists of ten segments. All segments are made of plastic, except for the ones at the upper and lower ends of femur and tibia, which are made of aluminium. Both, femur and tibia are equipped with four steel cables with ball ends, guided through the edges of the segments, to limit the bending of the legform. At either end of the legform, plastic covers provide some protection to the end segments. The impact side of the legform is covered with rounded plastic mouldings. Figure 3 shows the whole impactor without flesh and skin.

The knee assembly, manufactured from aluminium, consists of upper and lower halves, which are held together by twelve steel cables bedded in compound springs to limit bending and shearing of the knee. As earlier reviews of the legform design had shown, a few design changes had to be made since e.g. the asymmetrical design of the knee joint in the earlier version Flex GT showed limitations in assessing the (symmetric) sides of vehicle front ends. The design was reviewed and the knee joint was rebuilt as a now almost symmetrical part. In the knee assembly, space is provided for the displacement sensors and an on-board data acquisition system. Figure 4 shows the disassembled knee joint of the impactor.

Figure 5 shows the three separated sections of the impactor: Femur, knee, tibia.

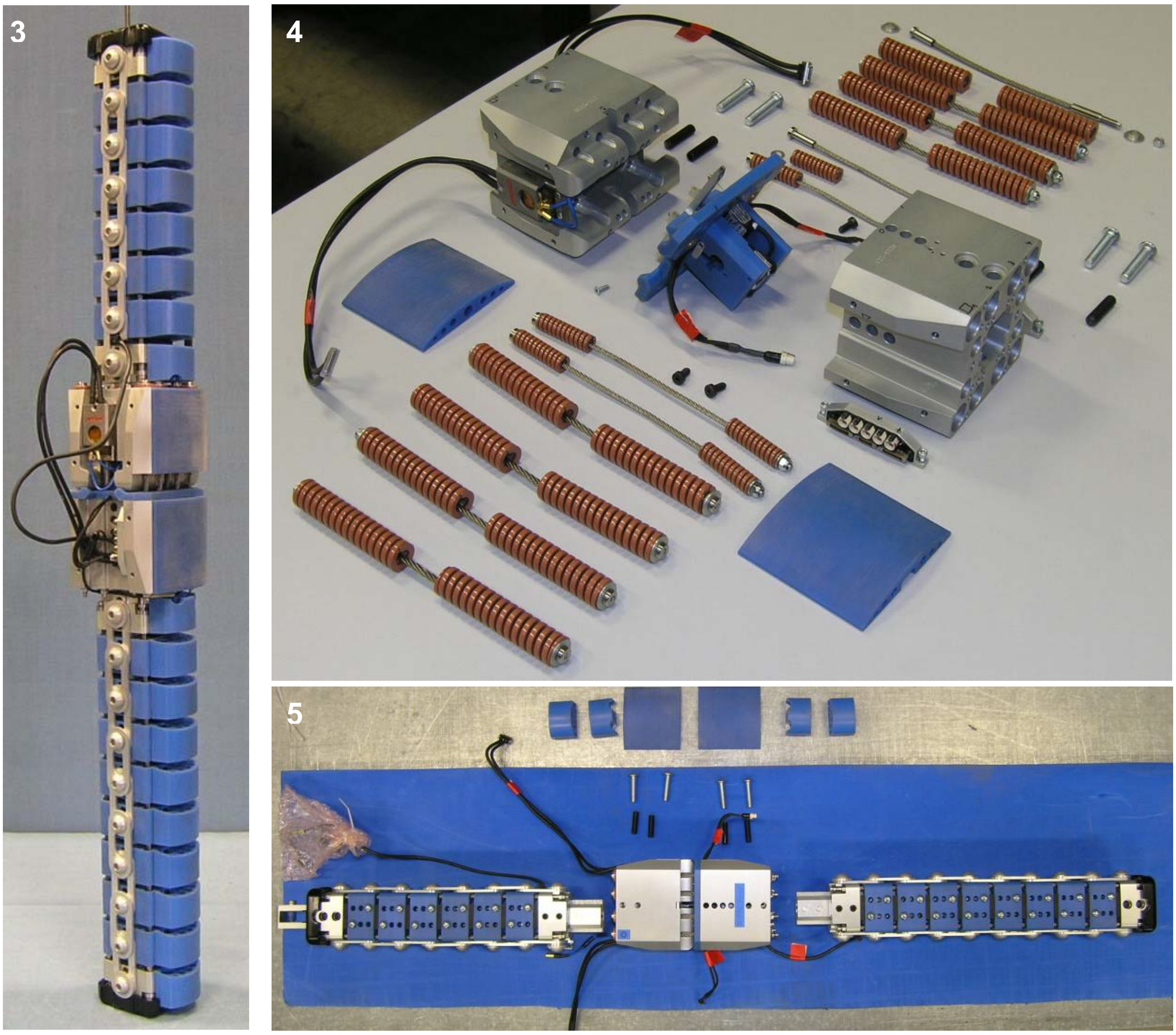

Fig. 3-5: Assembly pictures of the Flex GTR

The standard measurement equipment of the impactor consists of strain gauges in the femur and tibia and displacement sensors in the knee.

The knee displacements are measured by an arrangement of four position transducers: two string potentiometers for the cruciate ligaments (anterior and posterior) and another two for the collateral ligaments (medial and lateral).

The bending moments in the femur as well as in the tibia are measured by strain gauges mounted to the bone cores. There are three strain gauges located in the femur and four in the tibia of the impactor. In former build levels of the impactor, each strain gauge was set up redundantly. One set of seven strain gauges was placed on the impact side of the bone cores while another complete set of transducers was placed in the same positions on the non-impact side. Now, in the GTR version the two strain gauges on each position are electronically connected to form one sensor.

2.2 Test Setup

The tests were conducted at the vehicle component test facility (FKTA) of the German Federal Highway Research Institute (BASt). BASt runs an accelerator of the type "Hydropropulsator" built by IST GmbH, Germany (fig. 6). All of BASt's pedestrian protection tests as well as impactor certifications and other impact tests are conducted with this facility.

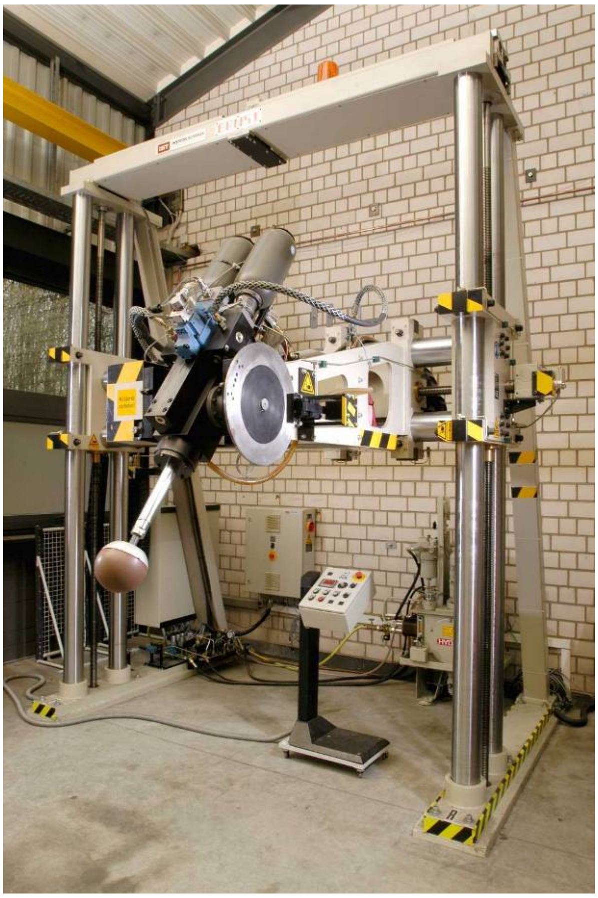

Fig. 6: Vehicle Component Test Facility of BASt

2.2.1 Vehicle Tests

For pedestrian legform impact tests with complete vehicles a guiding device, which is driven by the piston rod of the propulsion system, is placed in front of the component test stand. The legform is attached to this device using a special support rig. The guiding is positioned in an angle of approximately 4° to the horizontal so that a parabolic flight trajectory is achieved. The vehicle is placed in front of the device with a specific distance between the system and the car chosen to match the highest point of the parabolic trajectory of the impactor.

The car is placed on ramps to enable the legform to impact the bumper at the required height, without touching the ground before or during the impact. Figure 7 shows an overview of a vehicle test, here one of the oblique configurations.

Fig. 7: Vehicle test configuration - overview

2.2.2 Inverse Tests

For the inverse test the catapult module with the piston rod of the test stand was adjusted horizontally and a linear guiding rig with flat impactor module was mounted to the catapult module. An aluminium honeycomb was attached to the module face as an exchangeable, deformable impactor. To protect the legform skin, the honeycomb was wrapped tightly with paper.

Fig. 8: Legform support rig for inverse tests

To support the legform, a special test rig with quick release was placed in front of the test stand and fixed to the ground (fig. 8). The legform was attached to the rig using its guide-roller. The guide roller was positioned on a pin-jointed hook, which was pre-tensioned by a spring to enable a sudden release and to minimize the influence of the support on the test results.

Figure 9 shows the setup of the inverse tests.

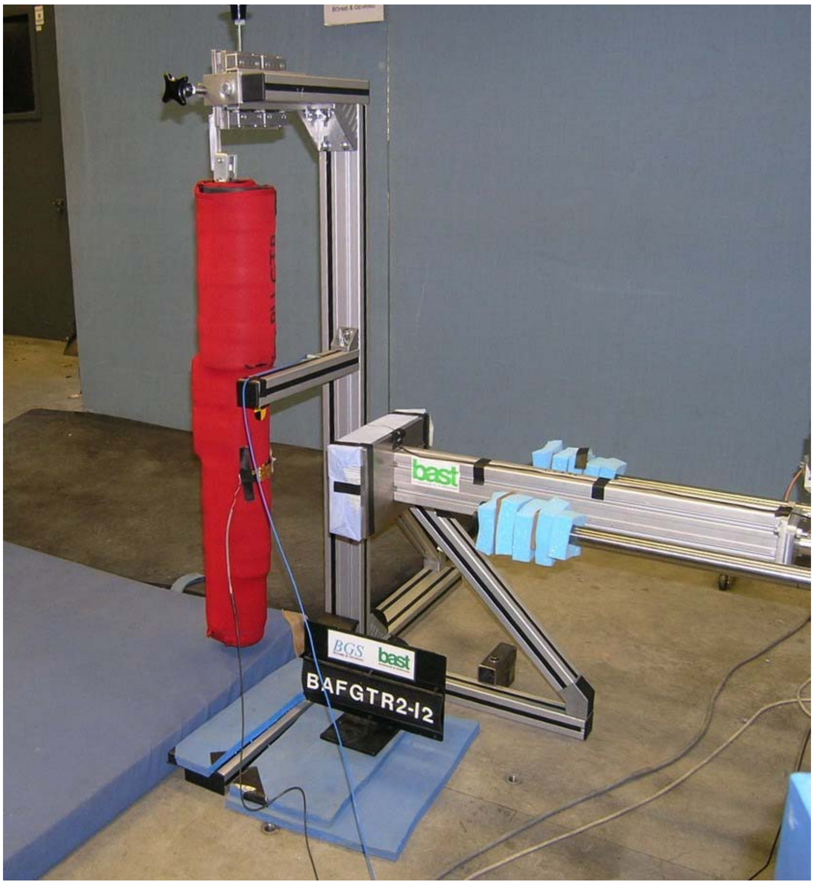

Fig. 9: Inverse Test Setup

2.2.3 Function Tests

The function test performed with the legform is a pendulum test, where the legform is suspended from a fixed pendulum frame using a pin joint with the skin and flesh simulation removed. A padding made from neoprene and rubber, replacing the skin and flesh simulation, is attached to the cross beam of the pendulum frame. The legform is lifted up to 15° above the horizontal where it is released. The knee of the legform impacts the cross beam when it reaches the vertical, bending the knee and the longbones.

The configuration above describes the pendulum test configuration of the Flex GT version. During the development of the Flex GTR the configuration and the test rig were modified and an additional mass to the legform and changing to an upside down position were introduced. However, as these tests as part of the project were only used for trying out or ensuring the general functionality of the legforms, it was agreed by the project partners to keep the Flex GT test setup.

Figure 10 shows the pendulum function test setup.

Fig. 10: Pendulum Test Setup

2.3 Measurement System

To record data of the tests the internal sensors of the impactor were used. The measurement system of the Flex-PLI consists of four string potentiometers to record knee displacements, seven strain gauges which record the bending moments on the longbones and an accelerometer mounted to the knee, which is an optional feature.

The position transducers of the type Space Age 170-0161 (datasheet see annex 5) are geometrically arranged to measure elongations in the positions of the Anterior Crucial Ligament (ACL), the Posterior Cruciate Ligament (PCL) as well as the Medial Collateral Ligament (MCL) and the Lateral Collateral Ligament (LCL).

The type of strain gauges on the longbones is Kyowa KFEL-5-350 (datasheet see annex 5). They are serially numbered from the knee to the ends: Tibia A1 to Tibia A4 and Femur: Femur A1 to Femur A3.

The measurement of the impact velocity was achieved using a calibrated light-barrier system by Hentschel GmbH, Germany, which consists of an infrared pulser with receiver and a counter.

The impact accuracy was documented by a paint spot. In the vehicle tests, the impact height was measured by a light barrier system during the impact.

2.4 Film and Photo Documentation

For each inverse test and each vehicle test a comprehensive photo documentation was made prior to and after the test. All of these photographs are included in annex 1 of this report.

In addition, a high-speed video camera was used to record an overview of the impact and to capture the whole trajectory of the legform in every test. For a better evaluation of the kinematics of the test, a second camera was used for the vehicle tests. The recording frequency of the cameras used was 1000 frames per second.

A complete file listing and all the high speed films are included in annex 2 of this report.

3 Test Execution

3.1 Test Plan

The original test plan read as follows:

No.	Test vehicle/ test setup	Test configurations	No. of test configura-tions	No. of im-pactors	No. of repetitions	No. of tests	Objective/ Remarks
1	Inverse test setup	standard	1	3	3	9	Repeatability, Reproducibility
2	Golf V	y=51, y=-357	2	1	3	6	Repeatability, Comparison
3	A-Class	y=-232, y=530	2	1	3	6	Repeatability, Comparison
4		y=0/ α=-30°, α=+30°	2	1	3	6	Symmetry, Repeatability
5	Mondeo	y=450	1	1	3	3	Repeatability, Comparison
6		y=0	1	3	3	9	Repeatability, Reproducibility, Comparison
8	Inverse test setup	standard	1	1	3	3	Durability, Repeatability

Table 1: Test plan

3.2 Chronological Order Of Tests

Due to the availability of the three legforms, the vehicles and the required spare parts, the tests were executed in the following order:

No.	***Date***	***Test No.***	***Impactor***	***Test Type***	***Vehicle***
1	14.01.09	SN01-Functiontest-1	SN01	Pendulum	
2	15.01.09	SN02-Functiontest-1	SN02	Pendulum	
3	15.01.09	SN02-Functiontest-2	SN02	Pendulum	
4	16.01.09	BAFGTR1-I1	SN01	Inverse	
5	16.01.09	BAFGTR1-I2	SN01	Inverse	
6	16.01.09	BAFGTR1-I3	SN01	Inverse	
7	16.01.09	SN03-Functiontest-1	SN03	Pendulum	
8	16.01.09	SN03-Functiontest-2	SN03	Pendulum	
9	19.01.09	BAFGTR2-I1	SN02	Inverse	
10	19.01.09	BAFGTR3-I1	SN03	Inverse	
11	19.01.09	BAFGTR3-I2	SN03	Inverse	
12	19.01.09	BAFGTR3-I4	SN03	Inverse	
13	20.01.09	BAFGTR2-I2	SN02	Inverse	
14	20.01.09	BAFGTR2-I3	SN02	Inverse	
15	22.01.09	SN02-Functiontest-3	SN02	Pendulum	
16	23.01.09	BAFGTRG357-1	SN02	Vehicle	Golf
17	23.01.09	BAFGTRG357-2	SN02	Vehicle	Golf
18	23.01.09	BAFGTRG51-1	SN02	Vehicle	Golf
19	26.01.09	BAFGTRG51-2	SN02	Vehicle	Golf
20	26.01.09	BAFGTRG51-3	SN02	Vehicle	Golf
21	27.01.09	BAFGTRG357-3	SN02	Vehicle	Golf
22	28.01.09	SN02-Functiontest-4	SN02	Pendulum	
23	28.01.09	BAFGTRM0-1	SN03	Vehicle	Mondeo
24	30.01.09	BAFGTRM0-2	SN03	Vehicle	Mondeo
25	30.01.09	BAFGTRM0-3	SN03	Vehicle	Mondeo
26	30.01.09	SN03-Functiontest-3	SN03	Pendulum	
27	03.02.09	BAFGTRM0-4	SN02	Vehicle	Mondeo
28	04.02.09	BAFGTRM0-5	SN02	Vehicle	Mondeo
29	04.02.09	BAFGTRM0-6	SN02	Vehicle	Mondeo
30	10.02.09	BAFGTRG357-4	SN02	Vehicle	Golf
31	10.02.09	BAFGTRG51-4	SN02	Vehicle	Golf
32	11.02.09	SN01-Functiontest-2	SN01	Pendulum	
33	11.02.09	BAFGTRM0-7	SN01	Vehicle	Mondeo
34	12.02.09	BAFGTRM0-8	SN01	Vehicle	Mondeo
35	12.02.09	BAFGTRM0-9	SN01	Vehicle	Mondeo
36	18.02.09	SN01-Functiontest-3	SN01	Pendulum	
37	04.03.09	BAFGTRM450-1	SN02	Vehicle	Mondeo
38	04.03.09	BAFGTRM450-2	SN02	Vehicle	Mondeo
39	05.03.09	BAFGTRM450-3	SN02	Vehicle	Mondeo
40	06.03.09	SN02-Functiontest-5	SN02	Pendulum	
41	06.03.09	BAFGTRA530-1	SN02	Vehicle	A-Class
42	06.03.09	BAFGTRA530-2	SN02	Vehicle	A-Class
43	09.03.09	SN02-Functiontest-6	SN02	Pendulum	
44	09.03.09	BAFGTRA530-3	SN02	Vehicle	A-Class
45	09.03.09	BAFGTRA232-1	SN02	Vehicle	A-Class

46	09.03.09	BAFGTRA232-2	SN02	Vehicle	A-Class
47	09.03.09	BAFGTRA232-3	SN02	Vehicle	A-Class
48	11.03.09	SN02-Functiontest-7	SN02	Pendulum	
49	11.03.09	BAFGTRA-30-1	SN02	Vehicle	A-Class
50	11.03.09	BAFGTRA-30-2	SN02	Vehicle	A-Class
51	11.03.09	BAFGTRA-30-3	SN02	Vehicle	A-Class
52	12.03.09	SN02-Functiontest-8	SN02	Pendulum	
53	12.03.09	BAFGTRA+30-1	SN02	Vehicle	A-Class
54	12.03.09	BAFGTRA+30-2	SN02	Vehicle	A-Class
55	13.03.09	BAFGTRA+30-3	SN02	Vehicle	A-Class
56	13.03.09	SN02-Functiontest-9	SN02	Pendulum	
57	13.03.09	BAFGTR2-I4	SN02	Inverse	
58	13.03.09	BAFGTR2-I5	SN02	Inverse	
59	16.03.09	BAFGTR2-I6	SN02	Inverse	
60	20.03.09	SN02-Functiontest-10	SN02	Pendulum	
61	23.03.09	SN02-Functiontest-11	SN02	Pendulum	
62	24.03.09	BAFGTRM0-10	SN02	Vehicle	Mondeo
63	26.03.09	BAFGTRM0-11	SN02	Vehicle	Mondeo

Total:
17 Pendulum Function Tests
12 Inverse Tests
34 Vehicle Tests
(8 Golf, 14 Mondeo, 12 A-Class)
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63 Tests

3.3 Inverse Tests

The general inverse test configuration is to vertically align the upper surface of the honeycomb with the middle of the knee joint. Horizontally the centreline of the honeycomb is aligned with the vertical axis of the legform impactor. This alignment was checked and adjusted if necessary before every test (fig.11).

The honeycombs were 250 mm wide, 160 mm high and 60 mm thick “Aluminium Honeycomb 3.1 3/16 5052” cuboids with a crush strength of 75 PSI according to the certificate of the manufacturer, Cellbond Composites Ltd., England. The material was chemically post-processed to provide the required crush strength.

Altogether 12 inverse tests were carried out. Three tests with each of the three impactors were used to assess the repeatability, reproducibility and differences with former versions of the legform. In addition, after the vehicle test series, another set of three tests were performed to assess long-term repeatability (“reliability”) of the legform. For these three tests legform no. 2 was used because this impactor had been used for the majority of the vehicle tests.

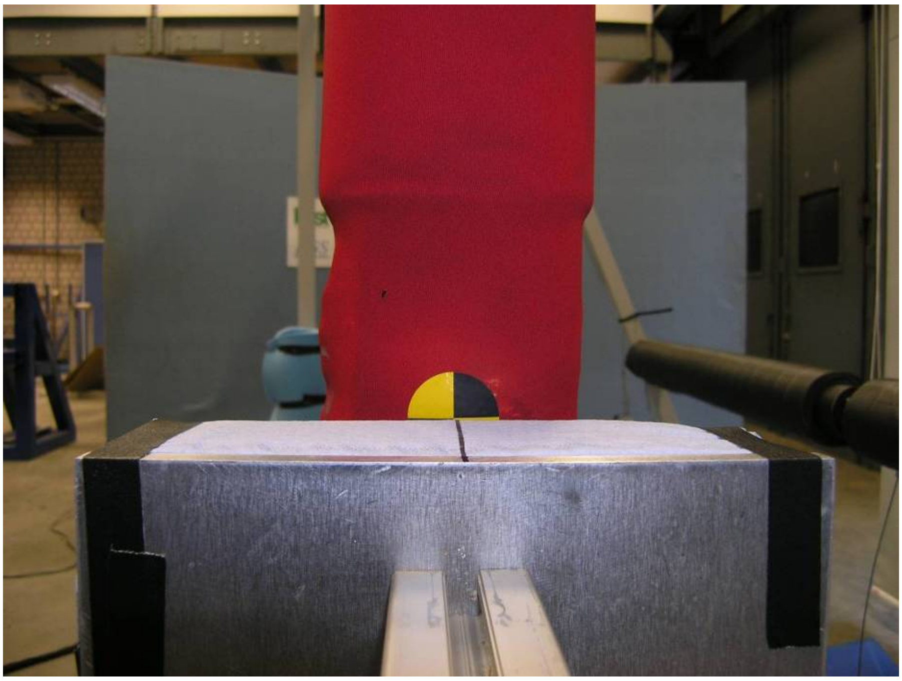

Fig. 11: Alignment of the honeycomb with the legform

3.4 Vehicle Tests

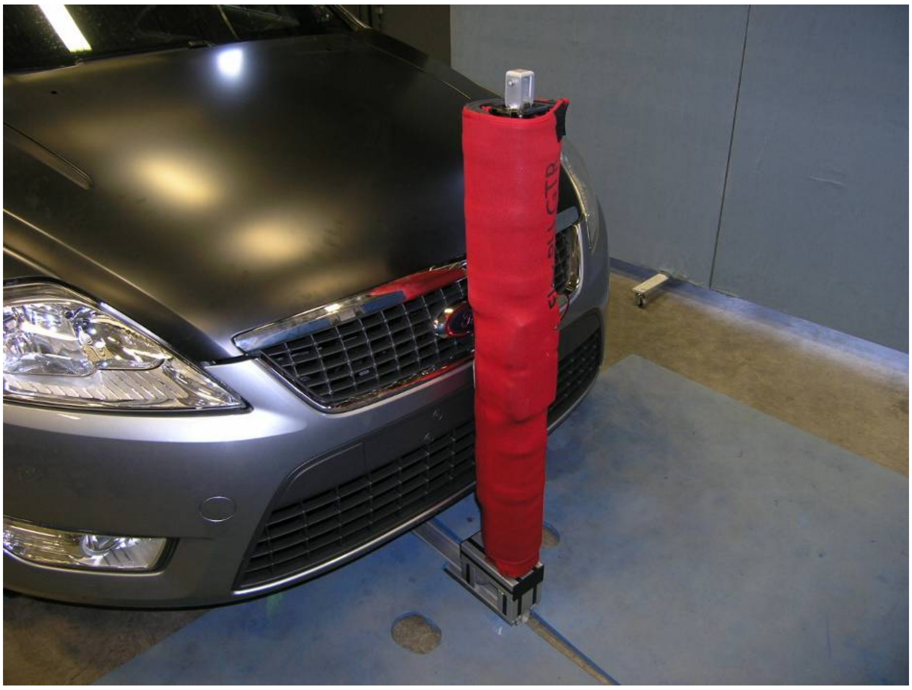

Fig. 12: Test setup for vehicle impacts

For the impact tests on vehicles, the legform used was propelled in a parabolic trajectory, impacting the bumper at the highest point of the trajectory. Since the propulsion system used to accelerate the impactor was bolted to the ground, the car had to be aligned with the propulsion system, for the impactor to hit the bumper at the desired location. Figure 12 shows the impact situation.

For the oblique tests, to be able to test an impact point on the vehicle at a specific angle, the car had to be placed in front of the propulsion system in the desired angle with the impact location at the highest point of the trajectory of the impactor.

The impact points chosen at the vehicles were locations that had been tested before with the former version of the legform, Flex GTα.

With the Volkswagen Golf, eight tests were carried out. Initially, six tests were planned to be performed: three repetitions on two impact positions (see fig. 13). During the first two tests, vibrations occurred in the measurement signals, especially in the bending moments. After investigations on this issue, it was found out that the legform started vibrating during the acceleration phase. This problem could be solved by introducing an additional back support to the knee area of the guiding system. Consequently, the first two tests were repeated.

Figure 13: Two impact locations at the Golf: Y = 51 mm and Y = -357 mm

Fourteen tests were performed with the Ford Mondeo. In order to assess repeatability and reproducibility in real car tests, three tests with each of the three impactors were performed on the middle position (Y=0 mm) of the car. Furthermore, another three tests with legform no. 2 were executed to a different impact location (fig. 14).

Figure 14: Two impact locations at the Mondeo: Y = 0 mm and Y = -450 mm

During the tests with the Mondeo, one issue arose concerning the length of the rubber sheets inside the legform. These sheets did not cover the whole length of the legform (fig. 15). It was assumed that a great scatter in the measurement signals of the lower tibia section may result from the fact that the lower load path of the vehicle was impacted by the section of the tibia where the lower ends of the rubber sheets were situated. Accordingly it was proposed that longer rubber sheets that cover the whole length of the impactor should be introduced to avoid this problem (fig. 16 and 17). To assess the impact of the longer rubber sheets on the test results, two more tests were performed with these longer rubber sheets. To complete this test series to a number of three tests, Ford Germany carried out one more test with this configuration. The results of this test were also used for the assessment of this issue and can also be found in the annex.

Fig. 15: Short rubber sheet

Fig. 16: Long rubber sheet

Fig. 17: Detail view of fig. 16

Another twelve tests were carried out with the A-Class. Again, two impact points were tested with three repetitions each (fig. 18 and 19).

Figure 18 and 19: Two impact locations at the A-Class: Y = -232 mm and Y = 530 mm

Furthermore, on the middle position of the A-Class front (Y=0 mm), oblique tests were executed with the vehicle standing in an angle of +30° and -30° to the impact direction (fig. 20 and 21). These tests were also performed with three repetitions each.

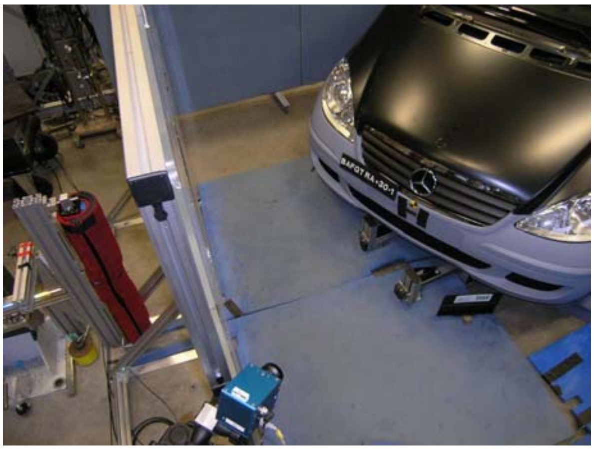

Fig. 20: Oblique vehicle test setup: +30°

Fig. 21: Oblique vehicle test setup: -30°

4 Test results

The results of the function tests, the inverse tests as well as the results of the tests with the different vehicles are presented in tables two and three below. The raw data of the tests in ASCII format can be found in annex 3 of this report, the measurement data plots are presented in annex 4.

For the test numbers, the code of letters reads as follows:

BA = BASt/ACEA
FGTR = Flex GTR
SN = Legform serial number
I = Inverse test
A = A-Class
G = Golf
M = Mondeo

Inverse Tests

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
BAFGTR1-I1	SN01	11,13	89,50	156,10	210,60	251,40	234,30	186,20	108,90	10,10	5,00	21,30	14,50	235,00
BAFGTR1-I2	SN01	11,18	89,90	154,20	206,80	257,90	236,60	184,90	111,80	11,50	5,30	21,30	14,80	341,00
BAFGTR1-I3	SN01	11,18	84,00	139,10	192,20	262,00	236,10	186,80	112,70	10,90	5,40	20,80	14,60	343,90
BAFGTR2-I1	SN02	11,21	91,90	155,80	207,00	262,70	251,30	194,90	114,50	10,80	5,50	19,00	15,00	252,10
BAFGTR2-I2	SN02	11,14	82,90	145,70	200,30	254,00	241,20	188,40	108,90	10,00	5,30	20,10	14,70	241,30
BAFGTR2-I3	SN02	11,24	95,50	150,30	205,70	256,10	240,90	185,10	110,50	10,70	5,40	20,20	14,60	260,40
BAFGTR3-I1	SN03	11,17	80,30	135,50	191,70	254,20	243,20	209,00	111,50	9,40	5,50	20,80	14,80	236,50
BAFGTR3-I2	SN03	11,23	82,30	138,90	195,00	255,80	243,70	207,90	113,60	9,90	5,80	20,80	14,90	243,10
BAFGTR3-I4	SN03	11,20	93,20	154,10	206,90	255,60	245,80	204,00	112,60	10,00	6,00	21,60	*	253,90

* Sensor failed

Inverse Re-Tests SN02

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
BAFGTR2-I4	SN02	10,94	90,2	156,4	201,6	261,8	250,7	193,2	109,5	12,1	5,1	20,9	14,3	245,7
BAFGTR2-I5	SN02	10,94	88,4	153	198,1	259,7	244,4	190,4	107,4	11,7	5	20,5	15,1	249,3
BAFGTR2-I6	SN02	10,96	87,6	151,9	197,8	260,4	245,3	192,1	107,9	11,4	5,2	20,6	15,5	248,8

Function Tests

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
SN01-Functiontest-1	SN01	n/a	100,30	133,50	153,80	135,90	110,40	78,30	39,30	4,80	3,60	14,40	-2,70	76,40
SN01-Functiontest-2	SN01	n/a	97,30	132,50	157,90	137,90	113,60	82,10	41,90	4,90	3,60	14,40	-2,70	95,30
SN01-Functiontest-3	SN01	n/a	102,70	138,20	157,90	137,60	115,40	84,80	43,70	5,30	3,40	14,60	-2,80	72,80
SN02-Functiontest-1	SN02	n/a	107,40	143,80	166,20	147,70	118,90	87,10	47,80	4,70	4,00	14,30	-3,00	79,70
SN02-Functiontest-2	SN02	n/a	107,50	143,00	164,40	143,70	115,90	85,40	47,30	4,70	4,00	14,10	-2,90	79,30
SN02-Functiontest-3	SN02	n/a	107,70	140,10	163,40	140,40	115,50	82,80	44,40	4,90	3,80	14,90	-3,30	78,30
SN02-Functiontest-4	SN02	n/a	107,70	140,80	162,40	143,90	116,20	85,70	46,80	4,50	3,90	13,80	-3,00	80,50
SN02-Functiontest-5	SN02	n/a	118,80	152,80	170,40	151,30	126,80	96,80	53,90	5,10	4,00	15,30	-4,00	86,70
SN02-Functiontest-6	SN02	n/a	110,30	145,40	165,20	139,60	116,50	85,50	45,90	5,60	3,20	14,00	-3,20	69,20
SN02-Functiontest-7	SN02	n/a	111,90	145,30	162,90	143,00	119,00	89,80	49,10	4,70	3,80	14,30	-3,30	83,20
SN02-Functiontest-8	SN02	n/a	114,20	147,50	162,00	139,40	118,50	86,50	46,30	5,60	3,10	13,70	-2,80	68,70
SN02-Functiontest-9	SN02	n/a	109,80	143,70	161,70	140,60	119,50	87,10	46,40	5,30	3,20	14,00	-3,20	70,40
SN02-Functiontest-10	SN02	n/a	112,20	143,90	162,70	139,60	120,50	89,70	48,10	4,80	3,70	14,00	-3,50	71,20
SN02-Functiontest-11	SN02	n/a	106,80	138,80	153,60	134,00	114,40	84,10	44,90	4,10	3,40	12,70	-2,20	71,90
SN03-Functiontest-1	SN03	n/a	107,80	142,90	163,30	140,20	113,20	76,30	15,40	2,80	3,40	7,70	-3,00	75,10
SN03-Functiontest-2	SN03	n/a	108,60	143,50	163,80	139,20	117,20	89,90	43,10	4,60	4,10	14,50	-3,60	73,70
SN03-Functiontest-3	SN03	n/a	106,90	141,30	161,30	138,10	117,70	90,20	44,10	4,50	4,00	14,10	0,00	81,40

Table 2: Inverse Test Results and Pendulum Function Test Results

Mondeo Tests

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
BAFGTRM0-1	SN03	10,96	170,5	288,5	296,2	220,2	179,7	292,8	183,6	6,1	5,7	19,4	*	207
BAFGTRM0-2	SN03	10,97	163,1	272,8	284,4	195,2	159	310,8	197,4	5,1	6	16,4	*	187,7
BAFGTRM0-3	SN03	10,99	172,7	269,3	275,4	186,4	151,9	312,5	211,6	4,9	6,6	15,9	*	211,4
BAFGTRM0-4	SN02	10,94	165,6	263,9	276,1	204,1	160,1	263,1	221,1	5,1	5,5	16,7	13,3	195,8
BAFGTRM0-5	SN02	10,95	159,5	248,5	274	207,5	165,9	250,4	220,3	5	4,7	17,3	14	203,9
BAFGTRM0-6	SN02	10,96	159	247,6	274,6	201,8	162	243,1	206,9	5	4,4	17,1	13,7	185,7
BAFGTRM0-7	SN01	11,01	121,6	229,1	259,5	194,9	146,8	228	218,7	5,4	4,8	17,5	14	188,1
BAFGTRM0-8	SN01	10,98	134,6	230,1	251,6	186,6	139,1	243,5	216,7	5,6	5,2	16,7	13,2	181,6
BAFGTRM0-9	SN01	11,02	129,5	232,3	253,7	190,5	141,4	225,6	212	5,7	5,1	17,5	14	172,7
BAFGTRM0-10	SN02	11,20	146,1	229	260,7	189,9	143	261,9	230,5	5,3	5,6	17,3	13,1	189,6
BAFGTRM0-11	SN02	11,23	167,5	244,4	252	178,6	149	283,7	221,6	4,7	4,6	15,2	12,1	172,2
BAFGTRM450-1	SN02	10,92	164,5	278	308,9	198,7	162,1	226,7	160	7,5	6,5	22,1	15,5	246,7
BAFGTRM450-2	SN02	10,98	149,7	259,9	298,7	209,1	167,8	216,6	146,2	7,5	6,5	21,8	14,6	230,1
BAFGTRM450-3	SN02	10,92	161,6	277,5	307,9	196,4	154,2	224,3	158,4	7,6	7	21,5	14,6	237,7

* Sensor failed

Golf Tests

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
BAFGTRG357-1	SN02	11,03	161,00	267,50	275,80	287,70	306,00	245,30	188,00	9,30	6,20	17,20	12,00	197,00
BAFGTRG357-2	SN02	10,91	160,10	280,50	335,90	318,20	327,60	268,30	165,30	9,10	7,60	20,30	15,70	191,90
BAFGTRG357-3	SN02	10,97	163,00	278,10	300,10	323,40	325,90	260,80	175,70	8,90	7,10	19,50	13,10	180,60
BAFGTRG357-4	SN02	10,98	146,30	255,20	303,00	293,90	325,50	265,50	191,50	7,40	7,80	19,20	11,50	169,60
BAFGTRG51-1	SN02	10,97	156,00	279,50	318,50	180,50	238,00	214,80	160,90	7,30	6,90	19,80	16,00	167,20
BAFGTRG51-2	SN02	10,94	177,30	319,30	356,00	238,20	284,00	243,30	168,60	6,60	5,90	21,80	18,60	160,40
BAFGTRG51-3	SN02	10,96	170,10	321,70	355,10	245,30	276,70	248,70	151,90	6,60	7,60	21,30	16,90	159,60
BAFGTRG51-4	SN02	10,94	165,80	302,20	349,90	233,70	286,10	238,50	174,40	6,30	5,80	20,80	17,70	141,10

A-Class Tests

Test No	Legform S/N #	Velocity [m/s]	Femur A3 [Nm]	Femur A2 [Nm]	Femur A1 [Nm]	Tibia A1 [Nm]	Tibia A2 [Nm]	Tibia A3 [Nm]	Tibia A4 [Nm]	ACL [mm]	PCL [mm]	MCL [mm]	LCL [mm]	Accel. [g]
BAFGTRA530-1	SN02	11,05	141,1	190,2	203,6	237,7	276,2	280,3	193,4	7,9	6,5	13,2	9,9	188,7
BAFGTRA530-2	SN02	11,05	157	203,1	209,4	256,7	291,3	277,2	180,3	7,2	6,7	13,8	10,1	183,1
BAFGTRA530-3	SN02	10,96	117,4	164,4	177,2	249,8	302,2	306,4	214,5	6,6	6,4	12,1	10,7	179,5
BAFGTRA232-1	SN02	11,00	178	256,8	257,3	270,2	331,6	278,4	154,3	4,8	5,7	16,6	14,2	133,7
BAFGTRA232-2	SN02	10,98	199,1	271,1	264,4	284,4	344,2	287,6	154,8	5	5,3	16,6	14,7	141,7
BAFGTRA232-3	SN02	10,91	177,3	254,8	253,7	274,1	336,8	282,6	168,9	4,6	5	15,6	13,6	137,8
BAFGTRA-30-1	SN02	10,99	99,9	185,4	219,6	233,5	277,5	216,9	124	5	10,5	15,1	5,9	96,6
BAFGTRA-30-2	SN02	11,00	132	235,8	259	257,6	289,7	241,4	139,1	5,9	9,9	17,2	4,4	93,3
BAFGTRA-30-3	SN02	10,98	131,5	236,5	259,8	265,8	300,1	250,9	135,9	6,6	10,3	16,4	4,6	98,7
BAFGTRA+30-1	SN02	11,01	160,2	288,7	287,2	263,2	303,6	236,4	124	6,3	7,1	17,2	5,6	107,8
BAFGTRA+30-2	SN02	10,96	164,6	293,6	290	267,1	290,7	229,4	129,9	6,3	6,6	18,5	9,4	98,1
BAFGTRA+30-3	SN02	10,96	159	272,6	270,7	260,5	293,2	239,1	136,9	6,9	7,8	18,2	6,4	105,7

Table 3: Vehicle Test Results

5 Evaluation of test results

5.1 Inverse tests

5.1.1 Repeatability and Reproducibility

For this evaluation, the results of nine similar inverse tests were used, three with each legform impactor. It has to be considered that nine tests may only show a tendency but cannot be sufficient for a final assessment of repeatability and reproducibility. Table 5 shows the coefficient of variation (CV) and its rating for each of the legform sensor outputs. The rating is based on the best practice guidelines for dummies whereas the reproducibility criteria are the same as for repeatability. The following classification is applied:

$$\text{Coefficient of Variation} = \frac{\text{Standard Deviation}}{\text{Mean Value}}$$

CV < 3%: good
CV 3% - 7%: acceptable
CV 7% - 10%: marginal
CV > 10%: not acceptable

Sensor	Femur A3	Femur A2	Femur A1	ACL	PCL
CV	6,2	5,5	3,6	6,3	5,3
Rating	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
Tibia A1	Tibia A2	Tibia A3	Tibia A4	MCL	LCL
1,4	2,2	5,2	1,8	3,8	1,1
Good	Good	Acceptable	Good	Acceptable	Good

Table 5: Coefficients of Variation (in %)

For all of the legform channels, the coefficient of variation is calculated between 1.1% and 6.3%. Thus the reproducibility is rated to be at least acceptable for all measurements.

5.1.2 Comparison of Flex GTR and Flex GT

In 2007 a number of test series were performed with the predecessor of the Flex GTR legform which was called Flex GT. The average values of the results of these tests were compared to the average values of the results of the current test series.

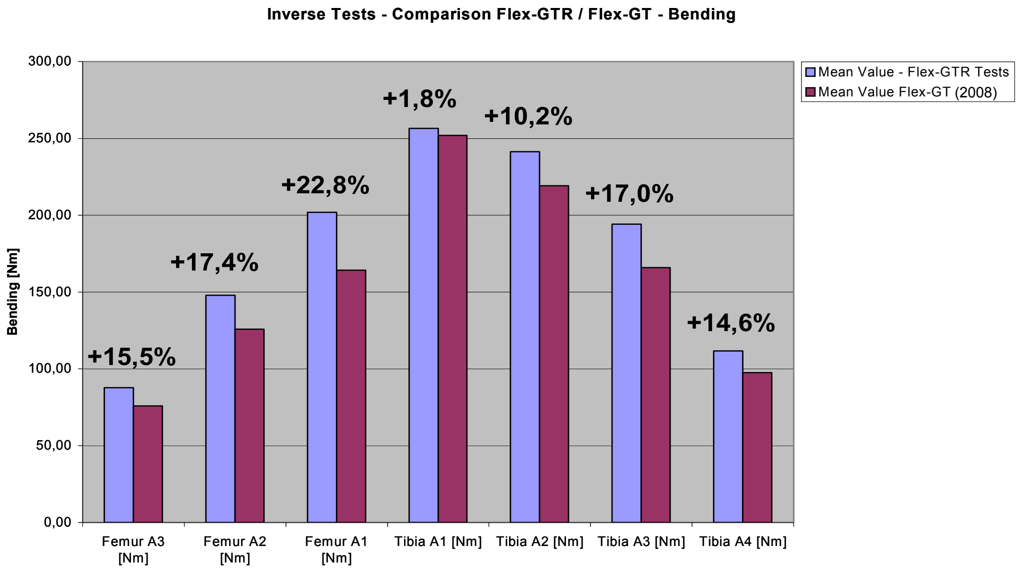

Figure 22: Comparison of Flex GTR and Flex GT: Bending moments – inverse test

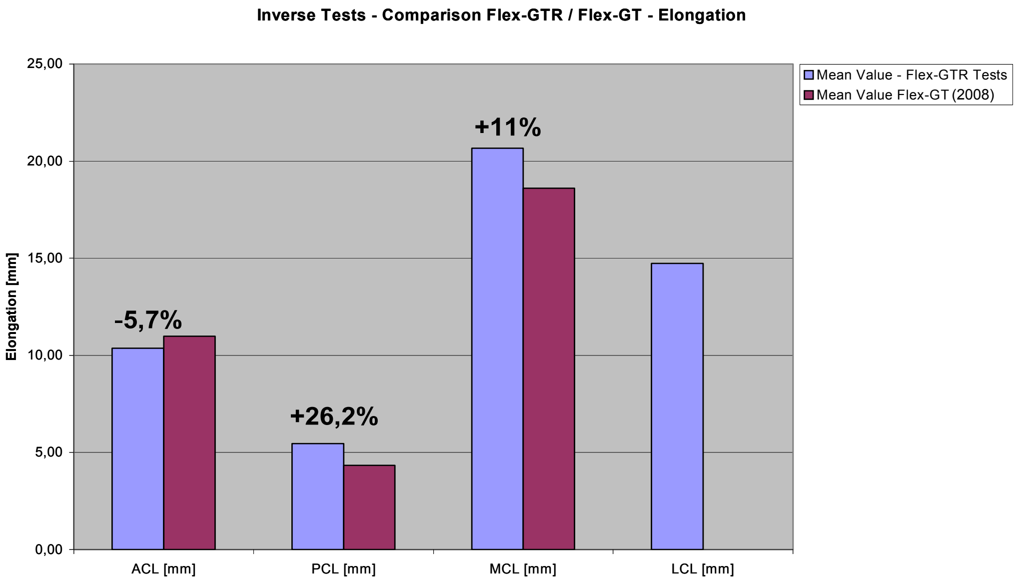

Figure 23: Comparison of Flex GTR and Flex GT: Knee elongations – inverse tests

The comparisons illustrated in figure 22 and 23 show that almost all of the results have increased significantly, except ACL which decreased by 5.7 %. The increase was between 1.8% and 26.2 %

5.1.3 Long-term repeatability (reliability)

To get a first impression of the repeatability of test results after the legform was used in a large number of vehicle tests, three inverse tests were performed at the end of the whole test series and compared with the first three inverse tests which were executed at the very beginning of the project.

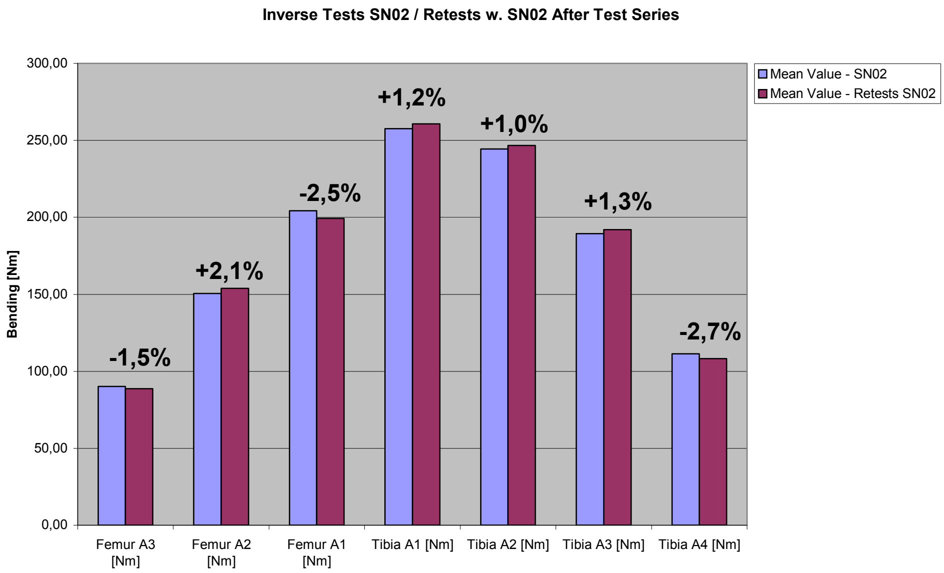

Figure 24: Long-term repeatability: Average bending moments

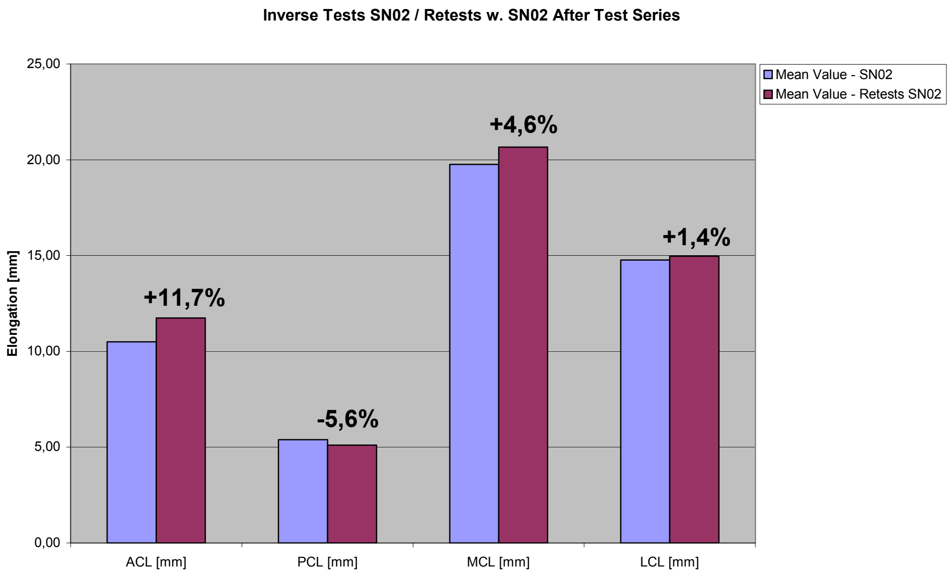

Figure 25: Long-term repeatability: Average elongations

As seen in the above figures, the repeatability of the results seems to be very good for the bending moments as the deviation between the first three tests and the tests after 40 vehicle impacts is only max. 2.7%. The difference in test results in the knee elongations is higher: Between 4.6% and 11.7%. The most relevant measurement channels MCL, ACL and tibia A1, A2 and A3 show a slight tendency for higher values after many tests.

5.2 Vehicle tests with Volkswagen Golf

The test results with the Golf were compared with test results obtained during the 2007 project at the same impact locations using the Flex GT prototype (Flex GTα). The comparison was made between the mean values of three tests each.

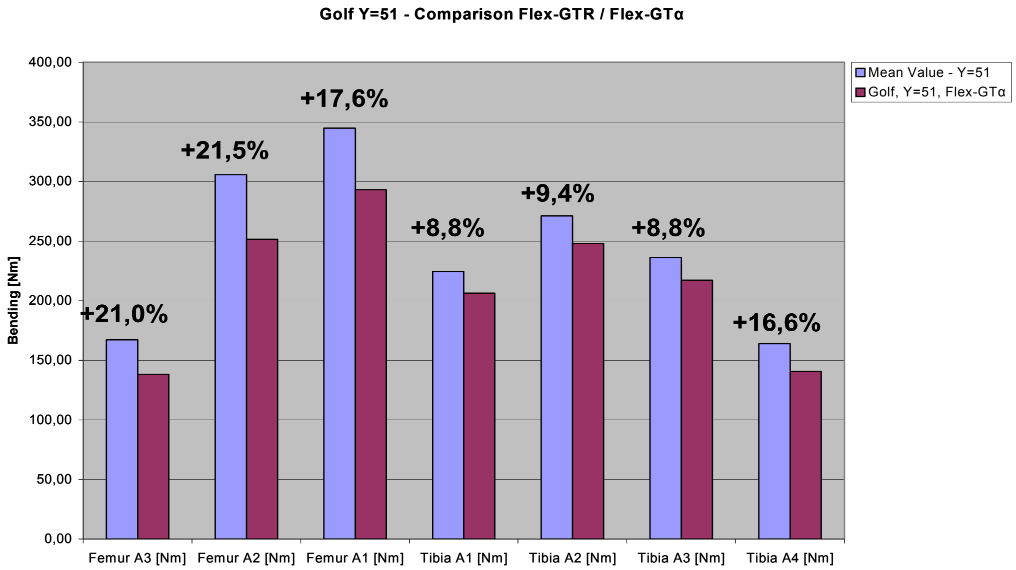

Figure 26: Comparison of Flex GTR and Flex GTα at Y = 51 mm: Bending moments

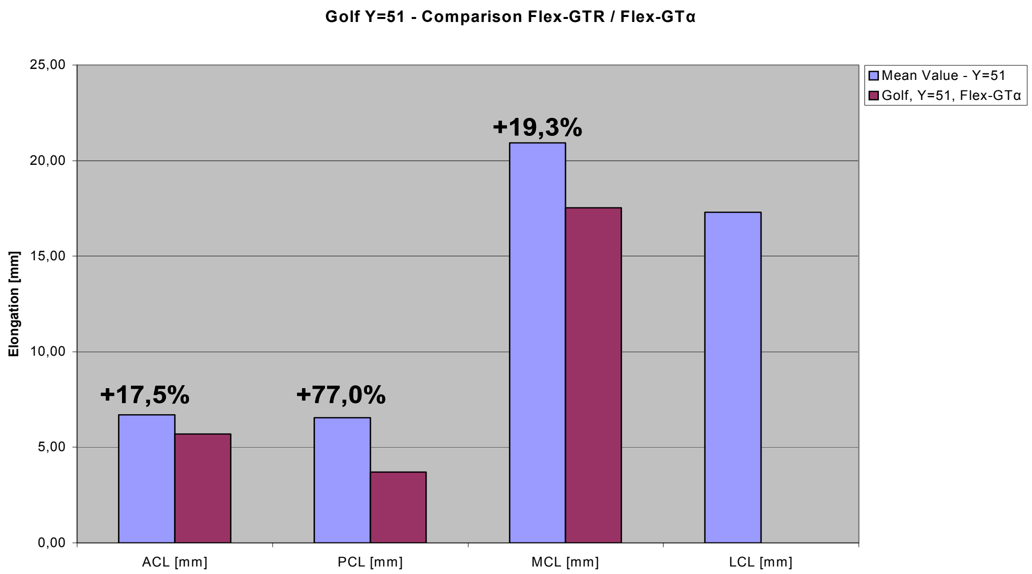

Figure 27: Comparison of Flex GTR and Flex GTα at Y = 51 mm: Elongations

The figures show clearly that also in these vehicle tests the results increase significantly: Between 8.8% and 21.5% for the bending moments and between 19.3% and 77% for the elongations.

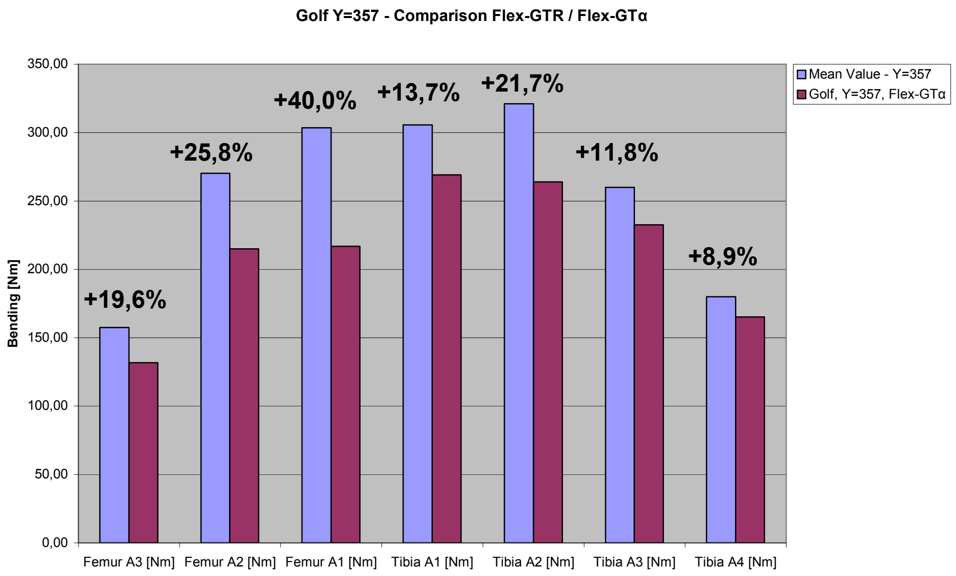

Figure 28: Comparison of Flex GTR and Flex GTα at Y = -357 mm: Bending moments

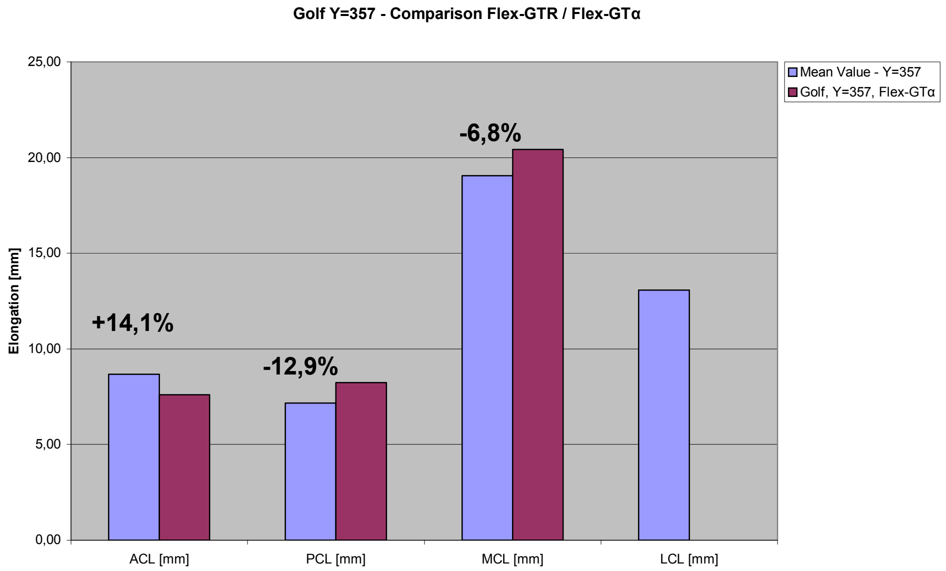

Figure 29: Comparison of Flex GTR and Flex GTα at Y = -357 mm: Elongations

In these tests the impact point was further outboard. Therefore the differences between the results with the Flex GTR and the Flex GT are only little comparable with the other impact location. There also is an increase of values for the bending moments and for ACL: Between 8.9% and 40%. But the results of MCL and PCL have decreased: 6.8% and 12.9%, respectively.

5.3 Vehicle tests with Mercedes A-Class

Also these test results were compared with results obtained during the 2007 project at the same impact locations on the A-Class using the Flex GT prototype (Flex GTα). Again, the comparison was made between the mean values of three tests each.

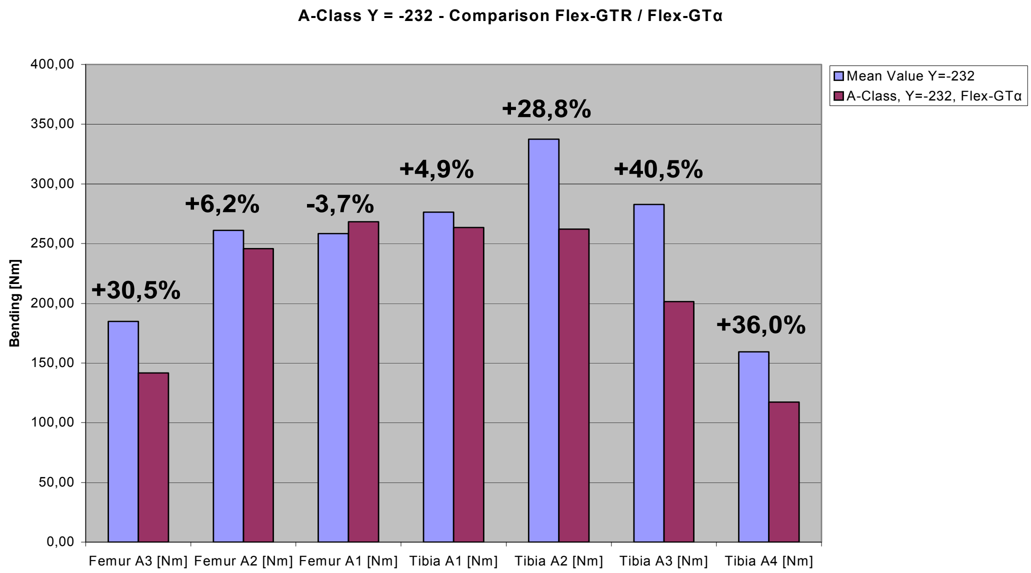

Figure 30: Comparison of Flex GTR and Flex GTα at Y = -232 mm: Bending moments

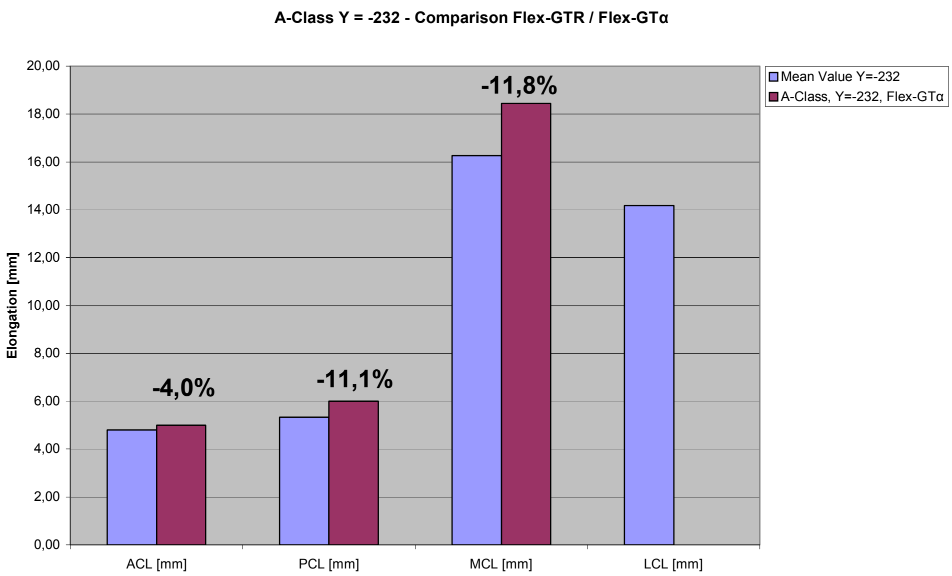

Figure 31: Comparison of Flex GTR and Flex GTα at Y = -232 mm: Elongations

In the figures 30 and 31 it can be seen that there again is an increase of values for most of the bending moments except Femur A1. The increase lies between 4.9% and 40.5%. The results of Femur A1 as well as all of the elongations decrease by 3.7% up to 11.8%.

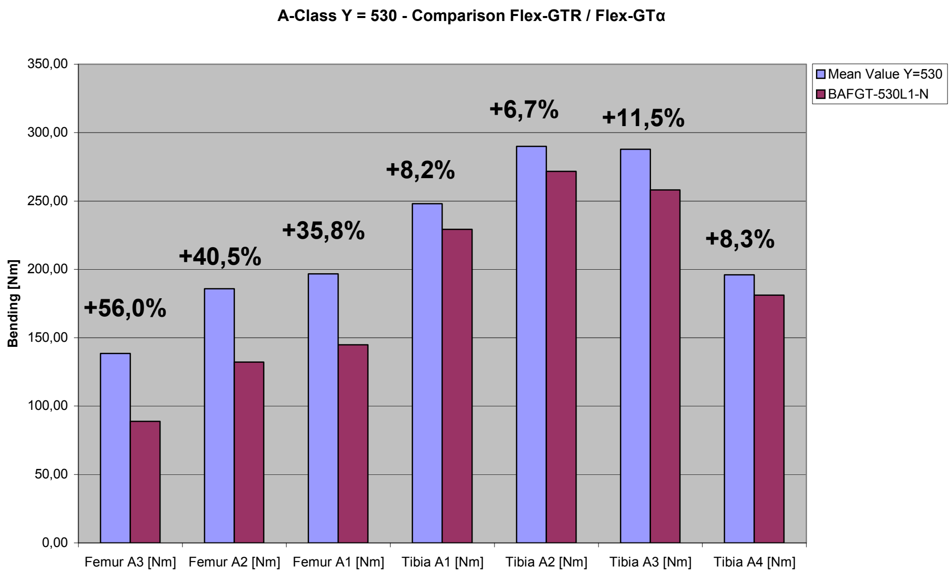

Figure 32: Comparison of Flex GTR and Flex GTα at Y = 530 mm: Bending moments

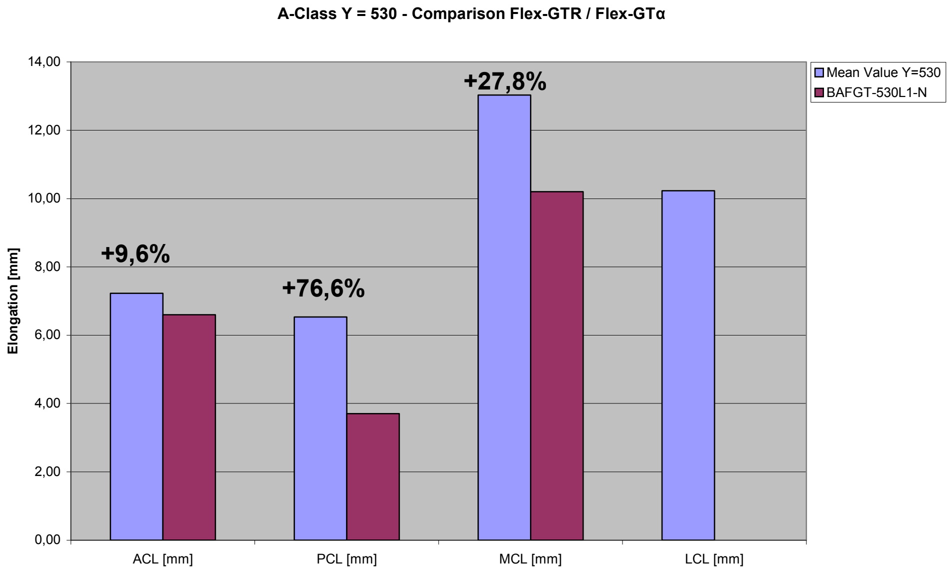

Figure 33: Comparison of Flex GTR and Flex GTα at Y = 530 mm: Elongations

Contrary to the other impact location of the A-Class, all of the results presented in the two figures above have increased. The difference lies between +8.2% and 76.6%.

5.4 Oblique Vehicle Impact Tests

During former studies and test series it became clear that the used legform versions produced different results when impacting the right or the left side of a vehicle front. The reason was the asymmetry of the knee sections of former Flex PLI versions. The Flex GTR was modified to become almost symmetrical. In this chapter, the mean values of two test series of oblique impacts on the A-Class are compared, three tests with an impact angle of +30° and three test with -30°.

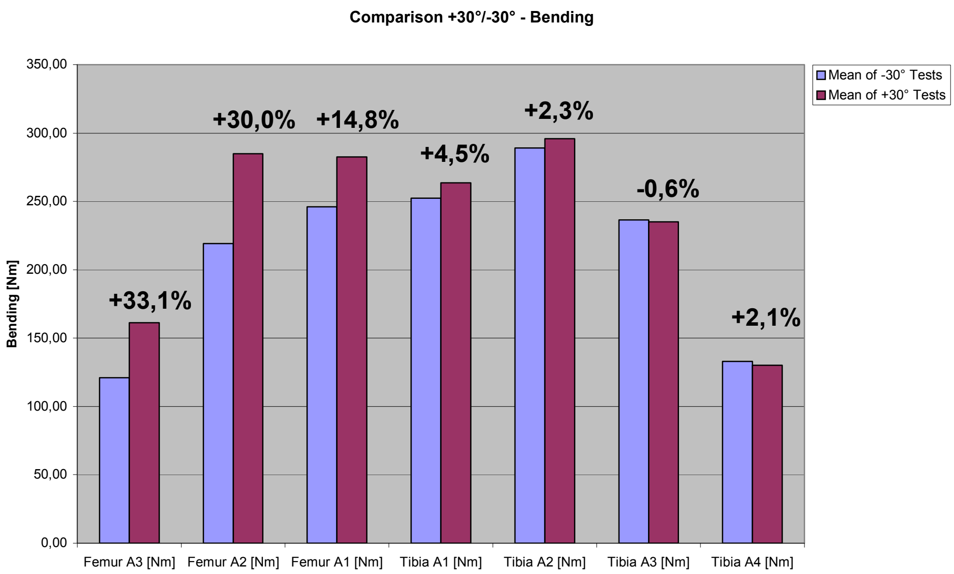

Figure 34: Comparison of +30° and -30° impact angle: Bending moments

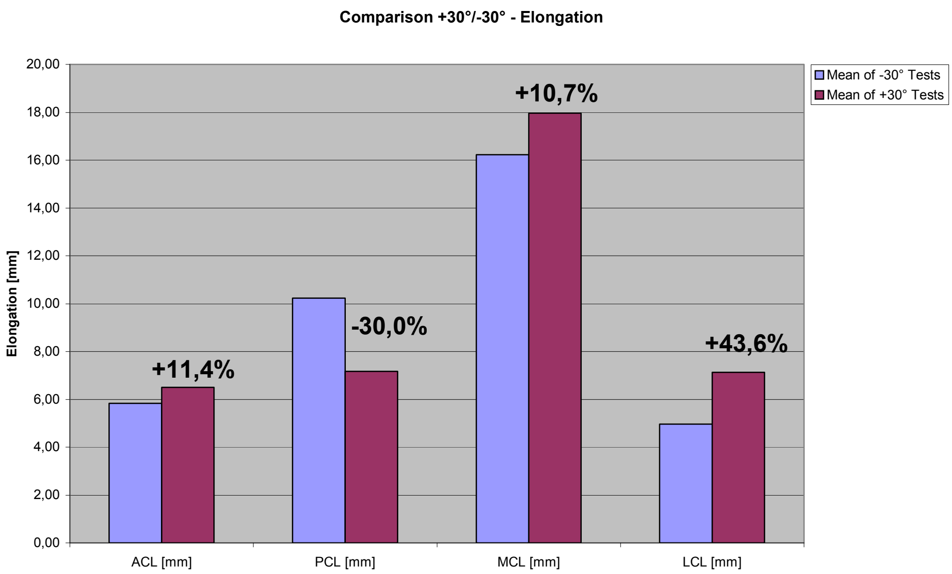

Figure 35: Comparison of +30° and -30° impact angle: Elongations

The results show that the impactor is not absolutely symmetrical because there are significant differences between the results of the tests with two different impact angles. Whereas the difference in the tibia bending moments is acceptable (up to 4.5%), the differences in the elongations and the femur bending moments are quite high: up to 33.1%. (LCL was not considered because the maxima usually occurred during the rebound of the impactor.)

In addition to the comparison of the mean values, the data signals were investigated. Fig. 36 and 37 show two examples of tests with -30° and +30°.

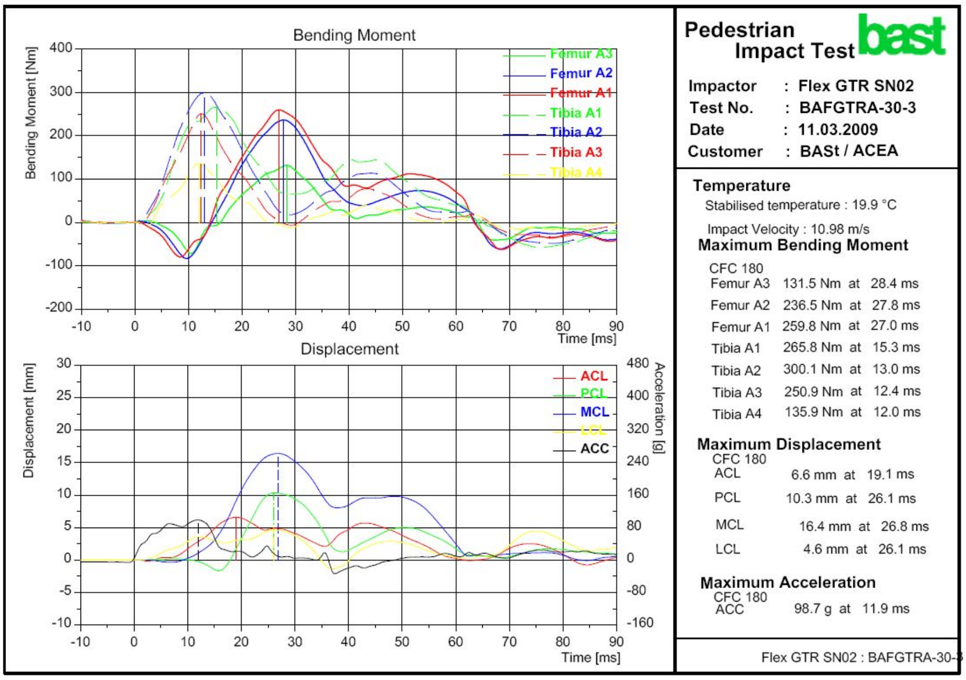

Fig. 36: Data signals of one test with an impact angle of -30°

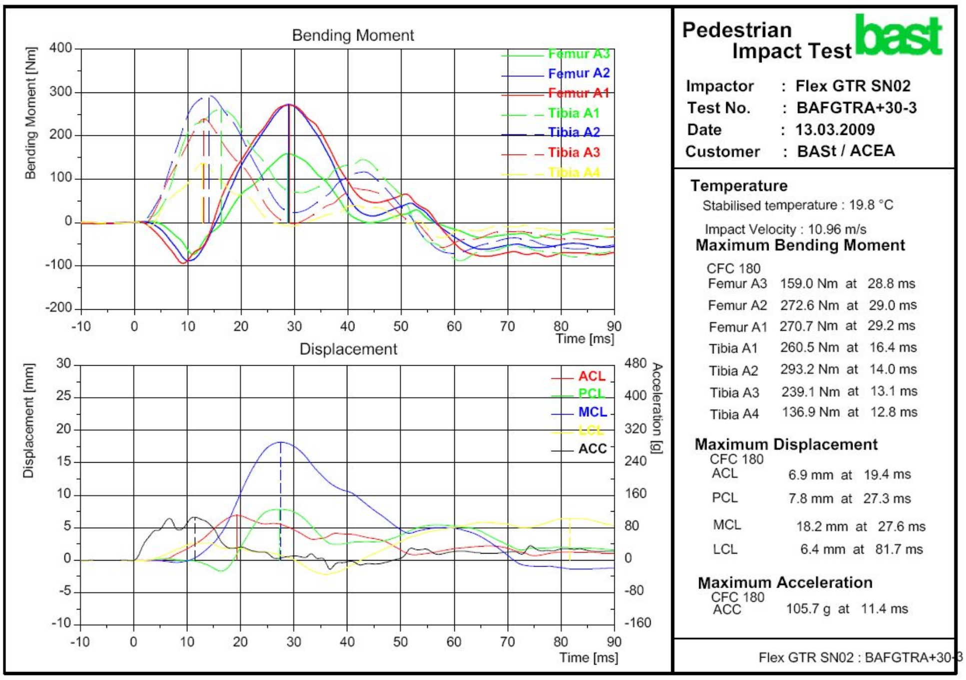

Fig. 37: Data signals of one test with an impact angle of +30°

In these plots there is hardly any difference visible in the signals of the femur and tibia bending moments. Only the maximum values vary to some extend. However, the signal curves of the elongation channels show some difference: In the +30° tests the ACL, PCL and MCL signals have only one major peak whereas in the -30° tests these signals have a second local maximum at about 45 ms. This observation is also an indication for the asymmetry of the legform.

5.5 Vehicle Tests with Ford Mondeo - Reproducibility

Similar to the inverse tests, also with the Ford Mondeo all three impactors were used with three tests each on the same impact location to assess the reproducibility of real vehicle impact tests. Table 6 shows the coefficient of variation of the results. The classification details are the same as in chapter 5.1.1, page 28.

Sensor	Femur A3	Femur A2	Femur A1	ACL	PCL
CV	12,5	8,4	5,3	7,6	13,0
Rating	Not acceptable	Marginal	Acceptable	Marginal	Not acceptable
Tibia A1	Tibia A2	Tibia A3	Tibia A4	MCL	LCL
5,5	8,2	12,9	5,9	5,8	2,7
Acceptable	Marginal	Not acceptable	Acceptable	Acceptable	Good

Table 6: Coefficients of variation of nine vehicle impact tests (in %)

In these vehicle tests, the reproducibility of only five sensor outputs was good or acceptable whereas six sensors have only a marginal or not acceptable reproducibility.

5.6 Vehicle Tests with Ford Mondeo - Rubber Issue

As described in chapter 3.4, longer rubber sheets were introduced to the impactor. Three impact tests with the Ford Mondeo were performed and the mean values of the tibia bending moment results were compared with the corresponding values of the nine impact tests on the same impact location but with the short rubber sheets.

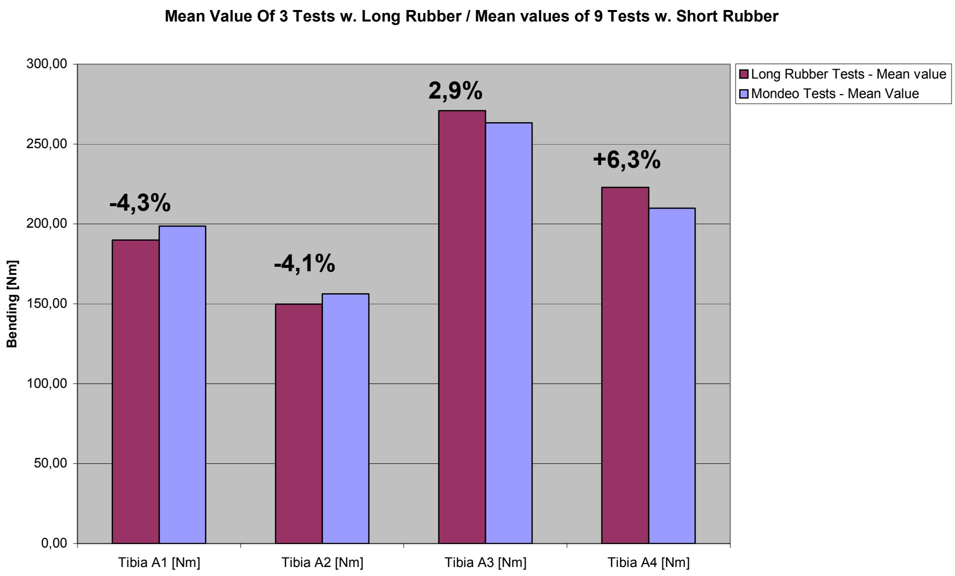

Figure 38: Comparison of short and long rubber sheets in vehicle impact tests

It is clear from figure 38 that the results differ only slightly between tests with short and long rubber sheets. The maximum difference is 6.3% at tibia A4.

5.7 Functionability Of The Impactors

During this extensive test program one potentiometer failed and had to be replaced. In four tests the crimping of string potentiometers loosened and had to be repaired. Several smaller issues had to be solved, especially in the initial phase. However, in the end all three impactors could be used as intended.

6 Summary and conclusions

6.1 Summary

To evaluate the final version of the Flex-PLI, a total of 63 tests with three similar legforms were performed at BASt. The legforms were equipped with two different on-board data acquisition systems and a cable-based system for off-board data acquisition systems.

In order to assess or ensure the functionality of the impactors, several pendulum function tests had to be carried out, especially during the early phase of the project when several initial issues had to be solved with the newly developed legforms. In addition, also after repairs or disassemblies of the impactor the function tests became necessary.

Twelve inverse tests were performed. Repeatability and reproducibility were investigated by using all three legforms. Furthermore, the results were compared with the results of tests with the previous version of the impactor. An additional set of three inverse tests was executed after the whole vehicle test series in order to assess the long-term repeatability.

With three vehicles, Volkswagen Golf, Mercedes A-Class and Ford Mondeo, impact tests were carried out on test locations that had already been tested in former projects with previous versions of the flexible legform in order to investigate the difference.

As the knee design had changed during the development of the Flex GTR, oblique impact tests were performed to assess the intended symmetry.

As a last minute change, the rubber part of the skin and flesh simulation was enlarged to cover the whole length of the impactor. Three vehicle tests with these longer rubber sheets were performed and compared to earlier tests with the shorter rubber sheets.

Only minor damages of the impactors were observed during the tests.

6.2 Conclusions

From the inverse tests it could be concluded that both repeatability and reproducibility are good or at least acceptable for all channels. (See page 21, no. 5.1.1)

A comparison with inverse test results obtained with the Flex GT version of the impactor in a previous project showed that some of the averaged measurement values were higher when using the Flex GTR: The tibia bending values increased up to 17% (A3), the MCL values by 11% and the PCL values by 26%, whereas the ACL values decreased by 5%. (See page 22, no. 5.1.2)

The long-term repeatability (reliability) was investigated by comparing results of inverse tests with the same legform impactor that were performed before and after 40 tests. Although two repairs with disassemblies of the knee area of the legform were necessary, the long-term repeatability can be denoted as very good. However, a slight tendency to higher values could be observed. (See page 23, no. 5.1.3)

During the vehicle tests the reproducibility of the results was partly not acceptable. (See page 30, no. 5.5)

As found during the inverse tests, the measurement values on vehicles were generally higher compared with former tests with the Flex GT version. E.g., the range of values for the tibia moments was from +8.8% to 40.5% and for MCL from -11.8% to +27.8%. (See page 24ff, no. 5.2 and 5.3)

In the oblique tests it was observed that the impactor responses were not exactly symmetrical in tests with the legform having the same amount of rotation around the z-axis to either the left or the right side. However, it has to be taken into account that these tests were only performed with one particular vehicle. (See page 28ff, no. 5.4)

The scatter that was observed in the output of the Tibia A3 sensor was assumed to be caused by the length of the rubber sheets in the impactor, which did not cover the lower end of the legform. The solution was found by introducing longer rubber sheets that cover the whole length of the impactor. Comparative tests did not show any significant difference in test results, but a possible cause for scatter was eliminated. (See page 30, no. 5.6)

During the first vehicle tests some vibrations were observed in the signals. The reason for this effect was found in the acceleration phase of the test execution when the legform was still supported by the launcher system. A solution was found by introducing an additional support pad for the knee area.

For the final assessment of the legform usability as an appropriate homologation tool the durability, handling and serviceability is of great importance. Because of the limited number of tests of the series documented in the present report further investigation of these issues is required.

Regarding these results and conclusions, especially concerning the reproducibility, it has to be taken into account that the impactors used for this project were the first three prototypes of the new version Flex GTR. Furthermore it has to be taken into consideration that the number of test repetitions was only three and the number of vehicles also was only three.

For a reliable investigation of repeatability, reproducibility and symmetry additional investigations are required based on further tests with more impactors, more vehicles and more repetitions per test configuration.

7 Annexes (DVD)

Annex 1: Photo documentation
Annex 2: Highspeed videos (AVI/MPG/JPG)
Annex 3: ASCII data of the tests
Annex 4: Measurement plots (PDF)
Annex 5: Datasheets of the sensors and honeycomb material used
Annex 6: Changes from Flex GTα to Flex GT