Safe Small Electric Vehicles through Advanced Simulation Methodologies

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EXECUTIVE SUMMARY

This document describes the results of SafeEV work package 5 subtask 1, in which a safety solution selected from WP4 is physically produced. A suitable test bench is then devised and used to evaluate the performance of the solution. As the selected component is a stiffness adaptable transversal beam for REVM2, testing is performed in both the reduced stiffness and the normal stiffness states for comparison. It is concluded that by reducing the stiffness of the material, a significant reduction in peak load transferred to the pedestrian can be achieved. Details of the development of the physical component and its test bench are described in this report.

Two virtual demonstrators are developed based on concepts previously discussed in WP4. These are an “O shaped” airbag that showed good potential for improving pedestrian safety, and the modelling of the restraint system configuration of REVM1.

An analysis of the REVM1 front structure updated in WP4 is performed to assess the influence of structural changes on the sensing system. A comparison is made between the design used in WP3, in which it was found the structure was too soft for state of the art sensor performance and the design from WP4. It is found that as well as increasing pedestrian safety (as shown in WP4.1), the time for activation of the pedestrian safety system is also improved.

APPROVAL STATUS

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Glossary

CRF  Centro Ricerche Fiat
CF   Carbon Fibre
CFRP Carbon Fibre Reinforced Plastics
EPP  Expanded polypropylene
EU   European Union
Euro NCAP European New Car Assessment Programme
FE   Finite Element
FS   Failure surface type
GMS  Strain at shear strength, ab plane
HBM  Human Body Model
IKA  Institut für Kraftfahrzeuge RWTH Aachen University
L-PET Low Melting poly(ethylene terephthalate)
REVM Reference Electric Vehicle Model
RTM  Resin Transfer Molding
SafeEV Safe Small Electric Vehicles through Advanced Simulation
SEVs Small Electric Vehicles
UD   Unidirectional
VIF  Virtual Vehicle Research Centre
1 Introduction

This SafeEV project deliverable documents all project activities related to the experimental manufacture and testing of a safety solution selected within the project. It also covers the further development of two concept solutions to the level of virtual demonstrators and analysis of the updated front structure.

For the physical manufacturing a component studied in WP4, a stiffness reducible transversal beam, is selected from a shortlist by the WP4 partners and then modified to allow for prototype manufacturing. As well as the manufacturing of two full size demonstrators, several small scale demonstrators are also manufactured to demonstrate experimentally that the material can be stiffness modified before a pedestrian collision. Additional test coupons are also produced to show the stiffness reduction.

A test bench is devised to allow for the testing of the small scale transversal beams in a dynamic impact test. The results of these tests are reported herein. All work related to the physical manufacturing and testing of the transversal beam can be found in Chapter 2.

An external windscreen airbag was previously considered in WP4.1 and was explored in two variants, i.e. an “U shaped” and an “O shaped” configuration. As the “O shaped” bag showed good potential for improving pedestrian safety, this external airbag concept solution was selected for the further development and refinement and is the first virtual demonstrator discussed in Chapter 4.

The restraint system configuration of REVM1 model was optimised in WP4.2. In Chapter 4, the modelling of such an optimized generic restraint system is improved through the introduction of more complex numerical methods for its main components. This is considered within the second virtual demonstrator.

In Chapter 4, the updated front structure of REVM1 is analysed with respect to signals using virtual demonstrators. An acceleration sensor is integrated into the new FE front bumper and an analysis is made on the influence of structural changes on the sensing system. This analysis allows for a conclusion to be drawn on whether or not structural improvements made on the bumper to increase pedestrian safety also produce a positive effect on the acceleration sensing.
2 Manufacture and testing of specimens

After discussions between the partners involved in WP4 a shortlist of possible components that were considered suitable for further development and manufacture was created. These were the transversal beam, the lower bumper and the lower windscreen frame. As detailed in D4.1, an improvement in pedestrian leg impact safety metrics can be attained by replacing the existing steel design with a stiffness adaptable material that reduces stiffness before a pedestrian impact.

2.1 Manufacturing

2.1.1 Creation of moulds

A 3D surface model of the original transversal beam was generated by Pininfarina based on the mesh used for simulations in WP4 and is shown in Fig. 2-1.

Fig. 2-1: Original transversal beam CAD file from WP4

Unfortunately this original model is of insufficient detail and did not contain all of the necessary surfaces to create a reasonable mould for manufacturing. Furthermore, as it is a
steel beam, it is not designed to be manufactured using composite manufacturing techniques. For this reason it is necessary to create a new geometry suitable for prototyping in CFRP in an open mould.

The overall shape and size of the original geometry is kept the same as the original steel design to ensure the parts are interchangeable, but some modifications are made to simplify the curvatures and allow for simple tooling. The model used for the manufacturing of the mould is shown in Fig. 2-2.

![Top view](image1)

![Side view](image2)

![Top view](image3)

Fig. 2-2: CAD file used for creation of the moulds used in manufacturing

A comparison between the two models is presented in Fig. 2-3.
The CFRP transversal beam design in WP4 has a thickness of 3mm, which was considered by Swerea to be too thin for such a large part manufactured in an open mould, as it would lack torsional stiffness. This is a problem as the beam will be created in an open mould and be handled manually, in which case it could be subject to torsion. This could cause damage to the beam. In more expensive methods such as resin transfer moulding (RTM), the beam would not be manually handled and this would not be a problem, but RTM is too costly for the production of low volume prototype parts. It is suggested that using a thicker beam would eliminate the problem of low torsional stiffness.

Two 3D finite element models are created in Ansys to show the difference in torsional stiffness. The models consist of 9390 layered shell elements (shell 181) each:

- First model: 8 +/- 45° layers, total thickness 3 mm
- Second model: 14 +/- 45° layers, total thickness 5 mm

The 0° fibre direction is aligned with the global x-axis. The boundary conditions are applied to cause a torsion (moment of 100 Nmm) on the beam and are shown in Fig. 2-4.

Fig. 2-3: Comparison between old (right) and new (left) geometries
Fig. 2-4: Boundary conditions imposed on the transversal beam model

The results of the 3 mm and 5 mm models are shown in Fig. 2-5 and Fig. 2-6, respectively.

Fig. 2-5: Result of simulation with a 3mm thickness transversal beam
Fig. 2-6: Result of simulation with a 5mm thickness transversal beam

The results indicate that under the applied moment of 100 Nmm the deflection of the beam decreases from 0.23 mm for the 3 mm beam to 0.06 mm for the 5 mm. This is a reduction of 74% and thus, a beam of 5 mm thickness is considered suitable for manufacture using an open mould technique based on the manufacturer’s experience of creating parts of similar size.

The aim of the work package is to demonstrate the behaviour of a selected safety component, in this case the transversal beam. Due to time and cost constraints it is not possible to produce a sufficient number of full size transversal beams in CFRP for testing. Instead, test specimens and further simplified small scale versions of the transversal beam are designed and manufactured as they are able to demonstrate the behaviour of the beam. The small scale beam is shown in Fig. 2-7 and this model is used to create an open mould used for specimen manufacturing.
2.1.2 Specimen manufacturing

The full size transversal beam demonstrators are made of 15 layers of L-PET and 14 layers of carbon fibre weave +/- 45° stacked together for a total thickness of about 5 mm. The demonstrators are manufactured in two steps in order to minimise dry spots on the bottom side. First only one layer of L-PET and one layer of carbon fibre are laid on the mould and heated (see results on Fig. 2-8). Subsequent layers are then added, until all 14 layers of carbon fibre and 15 layers of L-PET are laid in the mould.

Fig. 2-8: Application of the first layer of L-PET, followed by the first +45° layer
At this point the pinned release film, peel ply and the bleeder are placed (Fig. 2-9). Finally, the vacuum bag is applied.

The consolidation of the part is carried out at 220°C with a pressure of 45 mBar for a duration of 5 hours.

To investigate the effect of using a UD carbon fabric instead of a weave, which is expected to increase performance before stiffness modification, a single small scale demonstrator is made using UD carbon fabric laid +45° and -45° in separate layers with one L-PET layer in between. All other small scale demonstrators are manufactured using a weave (6 layers of CF and 7 layers of L-PET).

All layers were placed and fixed by hand one by one in the mould and fastened with tape. On top of the L-PET / carbon stack a pinned release film, release weave, bleeder and vacuum bag were placed. Vacuum is applied to pressurize the preform during melting. Consolidation takes place in an oven for 2 to 3h in 220°C.

Since the stiffness modification relies on the resistive heating of carbon fibres, a copper mesh is introduced in different configurations for the introduction of the current to see which, if any, is more efficient. An example of this is shown in Fig. 2-10.
Fig. 2-10: Copper mesh to apply current from the side of the specimen (left) or from above/below (right)

The finished specimens are shown in Fig. 2-11.

Fig. 2-11: Manufactured small scale demonstrators showing bottom (left) and top (right) side

In addition to the transversal beams, plates of the stiffness modifiable material are manufactured to attain the material properties during testing at TU Graz.

The materials used can be summarised as:

- **Carbon fibre UD fabric**: Sigmatex LC005, 264 g/m²
- **Carbon fibre weave**: Sigmatex T650, 380 g/m²
- **Pinned release film**: Aerovac I00344000
- **Release weave**: A100 PS
- **Bleeder**: Aerovac Airbleed 200
- **Vacuum bag**: WL600V
- **Seal**: Aerovac SM5142
- **Pipes**: PTFE 6/8 mm
2.2 **Design of test bench**

In WP 4 different safety solutions were developed and the lower transversal beam were selected for the WP 5 specimen (see D4.1 Nuss et al., 2015). A transversal beam has two different functions for safety; one is for frontal impacts (occupant safety) and the second for pedestrian safety. The transversal beam is mounted on the crash box. To represent the behaviour within a component test bench, it is necessary to have similar boundary conditions. In principle it is necessary to reduce the component range step by step and compare it with the full vehicle simulation as shown in [Marbler, 2009].

2.2.1 **Development process and test bench**

The development process is based on a full vehicle simulation model. First of all an analysis of this full vehicle simulation is necessary, followed by a component reduction. FE simulations are used for the comparison between full vehicle and reduced model simulation (Teibinger et al., 2010). This process is illustrated in Fig. 2-12.

![Development process for determination of structural system boundaries](image)

As mentioned above the transversal beam is mounted on the crash box. The aim is to have similar conditions in the test bench. Beside this it is also necessary to have a good reproducibility in order to have no influence from the test bench and the components for the test results. The usage of a crash box is therefore not seen as appropriate solution for the test bench. It was decided to use EPP foam (Expanded polypropylene) with a density of 140 g/l. EPP foam is easy to manufacture and flexible in compression direction, which means the EPP foam is a good candidate for the usage within the test bench. Furthermore the intention of the testing activities was to check the usability of the stiffness adaptable material from Swerea for this application.
It is necessary to test the specimens for both material conditions, hard and soft due to the hard condition is necessary for occupant protection and the soft one for pedestrian protection. A dynamic test bench with an impact in the middle of the specimen is selected for the test setup (Fig. 2-13) to assess the maximum deflection. The specimen (blue colour) is fixed on the test bench. On both ends the EPP foam is positioned. A rounded impactor is chosen for the force transmission. An energy input was selected, where for the stiff state of the material only small deflections should occur during the test. Therefore an impactor of weight 6.9 kg and velocity 4 m/s was selected, as this boundary condition would create the behaviour expected from the simulation (discussed in Chapter 2.4).

Fig. 2-13: Test bench for physical testing of the specimens

2.3 Experimental testing

The experimental crashworthiness pre-testing is performed by TU Graz. The manufactured specimens from Swerea were used for quasistatic and dynamic testing. Two different specimens were tested, a plate (3mm thickness) and a scaled transversal beam profile. All tests are defined as either static or dynamic bending tests using the bench designed by VIF for testing the profiles in a situation which reflects the original mounting position. The used material from Swerea is a stiffness adaptable CFRP with a LPET thermoplastic matrix material (described in D4.1) and following material characteristics (Table 1):
Table 1: Material data provided by Swerea

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<td>22 GPa</td>
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<tr>
<td>$E_{12}$ / $E_{13}$</td>
<td>5.6 GPa</td>
<td>0.1 GPa</td>
</tr>
<tr>
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<td>2.2 GPa</td>
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</tr>
<tr>
<td>$v_{12}$</td>
<td>0.28</td>
<td>-</td>
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<tr>
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<td>1600 MPa</td>
</tr>
<tr>
<td>XC</td>
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</tr>
<tr>
<td>SC</td>
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Due to the use of the thermoplastic as matrix-material, by heating of the specimen with an external power supply (direct heat or electric resistance) a loss of stiffness is expected. The testing in this case is important to have in first place validation data for the simulation results. Secondly, the effects of stiffness-reduction can be better assessed, failure modes detected and the influence of temperature evaluated.

The plates and small scale demonstrators which were manufactured and tested should give better input for simulation and validation as the reduced complexity of the model enhances the validation possibilities as well as the better reproducibility of results due to the specimen design.

The transversal beam (Fig. 2-14) was selected in D4.1 as the test component to be evaluated in WP5.

Fig. 2-14: Transversal beam selected as reference component for small scale testing

The specimens were manufactured using 7 layers of a +/-45° CF weave, T650. However, one specimen (no. 616) is manufactured using a trial process consisting of 10 UD layers of LC005 CF in a +/-45°(layer by layer) configuration. This is expected to result in a higher performance specimen. However, only one specimen was manufactured in this way so that a UD layer specimen could be benchmarked against the other weave specimens. With the specimens received at TU-Graz, the following test-matrix was defined shown in Table 2 and Table 3:
Table 2: Plate tests conducted at TU-Graz

<table>
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<tr>
<td>Quasistatic / T=~80°C</td>
<td>634.04 / 0.005  634.05 / 0.005  634.06 / 0.005</td>
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<tr>
<td>Dynamic-Pretest / T=22°C</td>
<td>634.04 / 2.5 - -</td>
</tr>
<tr>
<td>Dynamic / T=22°C</td>
<td>634.07 / 2.5  634.08 / 2.5  634.09 / 2.5</td>
</tr>
<tr>
<td>Dynamic / T=~80°C</td>
<td>634.10 / 2.5  634.11 / 2.5  634.12 / 2.5</td>
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Table 3: U-profile tests conducted at TU-Graz

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<td>Dynamic-Pretest / T=22°C</td>
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<tr>
<td>Dynamic / T=~80°C</td>
<td>628 / 4.0  630 / 4.0  631 / 4.0</td>
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As an example the specimens are shown in Fig. 2-15 and electrical connector positions are marked. In case of the plates no electrical connection was planned. For the u-shaped profiles different connections were manufactured in order to determine whether any method was significantly better than the others.

Fig. 2-15: Test specimens and different connection types

2.3.1 Test Bench at the TUGraz Laboratory

Two test benches were used for testing of the CFRP specimens. One was a quasi-static bench, a „Hydraulic Press“, where force-displacement curves can be measured. Three point bending cylinders were mounted for the testing in a lower axis distance of 125 mm. The test bench including one plate is shown in Fig. 2-16.
Fig. 2-16: Quasi-Static test bench for CFRP material testing

The dynamic test bench can cover speeds up to approximately 9 m/s and 30 kg of impactor weight. Like on the quasi-static bench also force-displacement curves were measured. Additionally, the sled and impactor acceleration-signals were recorded. To have a better understanding of the curves produced high speed cameras were installed for a top and side view of the impact. For reviewing the temperature level a thermo-cam was used, controlling the starting temperature of the specimens pre-heated in an oven. This decision was made because an electrical pre-heating device at the right output power level was not available. An overview of the bench is shown in Fig. 2-17.
2.3.2 Pre-Heating Tests

Before quasi-static and dynamic testing of the heated specimens pre-testing was conducted to ensure a temperature level which is near the specification for stiffness loss. Therefore pre-heating and cool-down tests were recorded with a thermo-cam to assess the temperature distribution and if the equipment is capable to activate the specimens as specified. A fast activation was not the target for testing activities. These additional tests were conducted to better understand the heating phase of the specimen. Heating was performed with two different power supply units:

- Supply unit up to 3 V, up to 20 A. (max. Power 60 W)
- Heating with a 12 V car battery: measured current ~200 A. (max. Power 2400 W)

Cool down was performed after a heating phase where a constant temperature distribution in the specimen was obtained:

- Cool down after a pre heating in an oven up to ~80 °C

The temperature distribution was recorded with a thermo-cam (VarionCam). With a power supply unit at ~2 V, it was not possible to reach 70-80 °C in an acceptable time (>1 min). Zones of > 100 °C were detected at the connectors, but temperature distribution figures showing areas with levels of 30-40 °C for both connection types (one side and diagonal). With the 12 V battery the minimum recommended temperature can be reached in the small scale demonstrator, but with an inhomogeneous temperature distribution. Limitations for an inhomogeneous distribution can be traced back to a non-ideal equipment for specimen heating and that the connections of the specimens were not optimized for crash testing. Improvements are expected for future solutions, therefore optimization of the electrical connection needs to be performed in future studies to achieve fast homogeneous activation.

Fig. 2-18 indicates from this small study into different connection placements, a copper mesh along the length with connectors placed in the centre results in an better distribution of temperature within the specimen.

![Fig. 2-18: Heating with a low-power supply unit and a 12V car battery](image)
2.3.3 Quasi-Static Tests: 634.01-06 (P), 632 (U-Profile)

The next step in testing was the quasi-static testing of six plates and one U-profile. The plates were tested with 5 mm/s speed of the hydraulic cylinder. For the profile 1 mm/s was selected as force level was expected to be quite different within the first deformation zone and therefore a more detailed curve is necessary. For all three plates and the one profile at room temperature fibre fracture was visible after the test and delamination occurred in the plates for specimen 634.01-03. For the heated specimens 634.04-06 no visible fracture was found. Delamination was seen at all three plates, mainly at the cylinder contact point where the highest shear forces are expected. From the difference in peak load between the heated plates (~200 N) and the unheated ones (~1300 N), a stiffness reduction of about 80 %–90 % can be achieved depending on temperature level (tested at~80 °C). The results are shown in Fig. 2-19.

![SafeEV 3-Point Bending, [634]01-06, [632]U1](image)

**Fig. 2-19:** Force-Displacement curves of the seven quasi-static tests

In Fig. 2-20 the post photos of one unheated and one heated plate are included. It can be seen that for 634.01 fractures occur along the cylinder contact zone. In case of the heated plate only thermoplastic matrix-material was pushed out of the woven fiber material. Due to the slow deformation and the cool down process of the material (hold position at max. deformation) the shape was like an L-profile. By heating it up again the original geometry can be recovered but with some delaminated areas at the contact zone but no apparent fibre breakage.
Fig. 2-20: Post-Test photos of two quasi-static tested plates

2.3.4 Dynamic Tests: 634.07-12, 634.04_pre-damaged

As a next step the dynamic test bench was built up and the remaining six plates as well as one plate from the heated quasi-static tests were tested at a speed of 2.5 m/s. The speed was selected to obtain a reasonable force-displacement curve for both unheated and heated specimens, absorbing all kinetic energy of the impactor with the CFRP material only. This was working well for six specimens, but one heated was contacting the “safety honeycomb” behind. In Fig. 2-21 the curves of the new specimens are shown whereas in Fig. 2-22 only the unheated ones and the pre_damaged heated quasi-static specimens are included. Clearly it can be seen that the stiffness reduction shows an advantage in dynamic testing, with a reduced effect compared to quasi-static testing (reduction @~30 %–40 %). For the unheated specimens fibre fracture and delamination occurs for all four cases, where the pre-damage had already delaminated which decreases the maximum force level reached by nearly 30% compared to the new ones. Compared to quasi-static testing the heated specimens were delaminated between the layers but no fractures were visible. Specimen 634.04 tested at 80°C in quasi-static test conditions shows good performance in a second dynamic test up to 10 mm. These results are shown in Fig. 2-21 and Fig. 2-22.
Fig. 2-21: Force-Displacement curves for six plates (unheated and heated)

Fig. 2-22: Force-Displacement curves for 4 unheated dynamic plate tests

In Fig. 2-23 two example post-test photos are shown. 634.07 is a unheated tested specimen. 634.10 was tested with a max. single point recorded temperature at the impact time of 90 °C. Between both specimens differences in deformation behaviour are clearly visible. As the unheated one tested has fractures at the impact location and complete delamination of some layers, whilst the heated specimen has no visible fractures and no visible delamination.
2.3.5 Dynamic Tests: 616 – 631

As a last point in CFRP testing the scaled transversal beam profiles were tested. As already known from the quasistatic testing there is a significant increase in stiffness due to the U-shaped geometry. Therefore the speed was increased to 4 m/s, the impactor mass of 6.9 kg was still the same. The test bench design and pre-calculation was done by ViF. The components were then mounted according to the layout to the baseline test bench. The foam material should in principle behave like a „Crash Box“ in a real vehicle environment. As seen in the test results this was fulfilled by the material selection made.

In Fig. 2-25 the force-displacement curves are shown. One stiff profile (616) had a much higher peak force and less deformation, as expected as it was manufactured in a different way. But for the other specimens good reproducibility of the results can be seen with the selected material. The heated specimens have some small deviations but this goes in line with the temperature at impact time. The stiffness reduced profiles seems to be mechanically stable.
with dynamic force reduction by half of the unheated specimens peak force. The test should in principle reflect a possible leg impact against a front vehicle structure where the transversal beam is one of the influencing boundaries in deformation space, or in case of pedestrian assessment, lower leg tibia acceleration.

![SafeEV 3-Point Bending, U-Profiles](image)

Fig. 2-25: Force-Displacement curves of 6 undamaged profiles, but 616 with a different material/manufacturing process

In Fig. 2-26 the post-test photos of one unheated and one heated profile is shown. It can be seen that again in the unheated test the material shows fracture at the impact point. But there was no visible delamination of the specimen. Differently to the unheated test, the heated specimen showed no fracture, no delamination and only a minimum of plastic deformation. With the original mould it should be possible to shape the profile once again and gain a similar stiffness. For the pedestrian of course the stiffness reduced transversal beam would be of advantage by reducing the injury risk. With respect to the test results, other components, critical for the pedestrian can also reduce the injury severity for child and adult heads, at least near the windscreen area (upper/lower).
2.3.6 Conclusions

Fig. 2-27 includes all test results done with the CFRP material. The results in general are showing good reproducibility for the different boundaries. Only the already mentioned specimen manufactured differently with a uni-directional fibre was stiffer. The activation of the material has the expected effect of stiffness reduction. In quasi-static testing the stiffness @ 80 °C is ~20 % of the reference specimen stiffness at room temp. (22 °C). In dynamic testing 40 % - 50 % of the reference stiffness was attained. The same was seen in the testing of the transversal beam profiles. A suggestion for the reduced stiffness loss in dynamic testing can be the inter-laminar shear forces of the viscoelastic matrix-material which are higher at higher strain rates, described also in Agirregomezkorta et al 2009. Optimization of the electrical connection needs to be performed in future studies to achieve fast activation. Further information regarding validated theoretically activation of the material can be found in Deliverable 3.6 of the ENLIGHT project.

As seen in the previous discussions of the test results the material used and scaled geometry can reduce injury risk by activation of the thermoplastic matrix for the pedestrian lower leg impact. If also used for other parts there might be a decrease of injury risk for head impacts as well.
Fig. 2-27: Force-Displacement curves - summary of all test results

2.4 Simulation

The test results are described in detail in chapter 2.3. In this chapter the simulation results in comparison with the test results are discussed. Force over displacement is recorded for the simulations, similar to the tests.

Fig. 2-28 shows the specimen in detail. The specimen and the selection of it are described in detail within chapter 2.1. The specimen is a small version of the transversal beam with the same properties (stiffness adaptable material). It is utilized for the component tests in the component test bench.
2.4.1 First simulation results

Starting point of the stiffness adaptable material was the material card described within D4.1 (Nuß et al., 2015). Fig. 2-29 shows the force over displacement for the stiff material. The blue lines are the test results (see chapter 2.3), the green line is the simulation result with the material card from D4.1.

![Stiffness graph](image)

Fig. 2-29: Comparison of component test with stiff material simulation vs. test results

The comparison of the simulation result with the test result shows some deviations. The main difference are the force maximum and the decrease of the force. This is mainly due to the lack of non-linear behaviour in the material card.
Fig. 2-30: Comparison of component test with soft material simulation vs. test results

Fig. 2-30 shows similar to Fig. 2-29 the comparison of the soft material. The difference between the simulation result (green line) and the test results (blue lines) is high for the force maximum as well as for the maximum displacement. Also for this material in the beginning there was no curve for the shear stress/strain behaviour included which is the main reason for the deviations.

2.4.2 Modified stiffness adaptable CFRP material card

In the next step the shear stress/strain behaviour were analyzed. Fig. 2-31 shows the shear stress – strain curve of the stiffness adaptable material at room temperature (20°C). Fig. 2-32 shows the shear stress – strain curve of the stiffness adaptable material at 80°C, as shown in ENLIGHT D3.7 (Bachinger et al., 2014). It can be seen that the stiffness adaptable material has a non-linear behaviour and must be integrated into the material model, so that the simulation results match better the testing results.
The material model *MAT_LAMINATED_COMPOSITE_FABRIC has a possibility to include a nonlinear stress strain curve for the shear part. This is included in both material cards (stiff and soft) and shown below. The changed parameters are described below and marked red in Fig. 2-33 for the stiff state of the stiffness adaptable material.

Gamma: Strain limit of the first slightly nonlinear part of the shear stress versus shear strain curve

Tau: Stress limit of the first slightly nonlinear part of the shear stress versus shear strain curve

FS: Failure surface type
GMS: Strain at shear strength, ab plane

SC: Shear strength at ab plane

Fig. 2-33: *MAT_LAMINATED_COMPOSITE_FABRIC card for modified stiff state of stiffness adaptable material

Fig. 2-34: Comparison of component test with the modified stiff material simulation vs. test results

Fig. 2-34 shows the comparison of the test results vs. the simulation with the modified stiff state of the stiffness adaptable CFRP material. The simulation result is now in the first part similar to the testing results. The maximum of the force is about 500 N higher in the simulation compared to the test results of specimens 623 and 627 (description of the specimen can be found in chapters 2.1 and 2.3. The maximum displacement is about 2.5 mm lesser in the simulation as in the test results of specimens 623 and 627.
In Fig. 2-35 the changed parameters marked red for the soft state of the stiffness adaptable material within the *MAT_LAMINATED_COMPOSITE_FABRIC.

*MAT_LAMINATED_COMPOSITE_FABRIC
Mat_Svereja_Soft
$:$ 0.1203 9.5E-6 23.0 0.1 0.1 1.0E-3 9.5E-3 5.7E-2
$: aeb qbc qce slint1 slint2 slimc2 slims
$: 1.0 0.1 0.1 1.0E-2 1.0 1.0E-2 1.0 0.0
$: scpt tsize crods soft is
$: 3.0 0.0 0.0 0.0 -1.0
$: v1 v2 v3 d1 d2 d3 beta
$: 0.0 0.0 1.0 0.0 0.0 0.0
$: e11 e12 e22 g12
$: 9.0E-2 2.35E-2 6.8E-3 12.0E-3

Fig. 2-35: *MAT_LAMINATED_COMPOSITE_FABRIC card for modified soft state of stiffness adaptable material

![Soft](image)

Fig. 2-36: Comparison of component test with the modified soft material simulation vs. test results

Fig. 2-36 shows the comparison of the test results vs. the simulation with the modified soft state of the stiffness adaptable CFRP material. The simulation result is now in the first part similar to the testing results, mainly the maximum of the force fits quite good to the results of the specimen 630 (description of the specimen can be found in chapters 2.1 and 2.3) and the
maximum displacement fits to the test results of specimen 630 as well, only the force decrease is in the simulation bigger as in the test results.

2.4.3 Conclusion

The results of the simulation fits with the modified material card as described in chapter 2.4.2 quite good to the test results. There are still some differences between the simulation results and test results. This is mainly due to some factors were neglected. For example the through thickness stress, the damage and the possible plasticity geometry, etc. are affecting the results. Nevertheless with the current simulation model the differences between stiff and soft state of the stiffness adaptable material could be assessed (with test validation). The solution with the stiffness adaptable material has a positive influence on pedestrian leg protection (which will be discussed within D5.2) and no negative influence to the occupant protection.
3 Virtual demonstrators

Within WP4.1, two promising pedestrian protective concept solutions were identified for the REVM1 vehicle: a new front bumper design and an external windscreen airbag. The latter solution was explored in two variants, i.e. an “U shaped” and an “O shaped” configuration. The “O-shaped” version showed a very large safety potential, because it addresses a very critical impact configuration (head impacts on the entire windscreen frame perimeter) and drastically reduces corresponding injury levels (HIC values). Consequently, this external airbag concept solution was selected for the further development and refinement work planned within WP5.1, then leading to a first virtual demonstrator.

Within WP4.2, the restraint system configuration of REVM1 model was improved through an optimization of its main components and the introduction of a retractable steering wheel column (RSWC) concept (then leading to the intelligent occupant protection system 1 described in deliverable D4.2). The modelling of such an optimized generic restraint system was then improved within WP5.1, by the introduction of more complex numerical methods for its main components (i.e. the airbags), then permitting a numerical simulation of the restraint system action during the impact closer to the physical behaviour observed in real testing. This refined REVM occupant compartment model represents the second virtual testing demonstrator planned within WP5.1.

In the following sub-chapters, the description of these two improved numerical models or virtual demonstrators is provided.

3.1.1 External Airbag for Pedestrian Safety

In order to improve the pedestrian head protection, w.r.t. the early concept examined in WP4.1, in the most critical areas of the windscreen frame of REVM1, the “O” shaped windscreen airbag concept model was refined. The numerical simulation conducted within WP4 on the early bag model showed in fact that the higher HIC values were observed in the lateral windscreen areas, where the bag covers the A-pillar. As a consequence, in order to reduce these values, the bag was modified by introducing an enlarged section (see Fig. 3-1) in the A-pillar zones, so that the projected area of the inflated bag can better cover this area.

The final bag shape, with the increased dimensions, was built in the F.E. environment in its unfolded configuration first and later verified through some inflation simulation to check its capability to sufficiently cover the selected portion of windscreen frame; subsequently, head impact simulations were conducted, too, in order to verify the effective reduction of the HIC values.

The final windscreen airbag concept keeps the chambers layout of the “O” shaped bag early designed in WP4; the dimensions of the circular transversal chambers, the central “hole” on
the windscreen and the seams position haven’t changed, while the external chambers were enlarged by about 17 cm.

Fig. 3-1: “O” enlarged shaped windscreen airbag concept for REVM1

In addition to that, the bag concept design was improved with the introduction of a bag folding pattern (see Fig. 3-2) and the simulation of its deployment phase before the head impact.

Fig. 3-2: “O” enlarged shaped windscreen airbag concept for REVM1

The approach followed in this phase consisted of the following steps:
3.1.1.1 Airbag folding

Several airbag folding patterns were investigated, with more than 20 folding process simulations performed that led to the selection of a final solution in which the bag is first rolled up (around Y axis) and then folded at its extremities.

The realization of the selected folding pattern required the following steps: first, the specific tools for the rolling and the bending process were modeled in the F.E. pre-processing environment and subsequently applied within Ls-Dyna code, where the tools movements were set in order to obtain the final bag packed configuration. All the tools that participate in the folding process simulation are built in a simplified manner by using properly dimensioned rigid planes.

The folding process simulations started from the un-folded bag and continued up to the obtainment of the completely folded bag.

The final choice of the rolled folding scheme took into account also the similarity between this external bag and the window air bags (used for occupant protection in side impacts) in terms of overall shape (wide surface vs. thickness ratio). The fact that the windscreen bag, for the practical implementation on the car, should be inserted in a case positioned in the area below the windshield base, makes it similar also from the point of view of the case solution (i.e. long and narrow).

In the first phase of the folding process simulation, the bag flows between two planes to avoid that it curls up and it is folded in 10 consecutive rolling up steps (see Fig. 3-3), in the second phase of the process, the bag packed in the above mentioned way is further folded at its extremities, along the seam path (Fig. 3-4).
3.1.1.2 **Head Impact**

The head impact simulations were then performed by considering the bag inflation before the arrival of the headform impactor on the targeted windscreen frame impact locations: each simulation started from the folded bag initial condition up to the fully inflated and in–position bag, considering the transitory phase of deployment and correct positioning on the interested car zones (again, the windscreen surrounding frame).

The main characteristics of the final “O” shaped enlarged windscreen airbag module considered in this study are illustrated in the following list:

- Airbag volume: approx. 130 litres
- Airbag fabric with very low porosity and sealed seams
Inflator: hybrid gas generator

Time needed for full inflation & stabilization: 50 ms

In order to drive a bag of this size during the deployment and even to ensure a good positioning in the car zones to be covered, a virtual tethering system was introduced, too. This simplified solution consisted of numerical one-dimensional elements connecting the bag extremities to the upper corners of the windscreen frame: during the bag deployment, their tensioning generates a stabilizing force that guides the bag extremities along the windscreen pillars, up to the completion of the deployment phase. The engineering of the corresponding real tethering solution generating such an effect was not considered because it was out of the scope of the work planned within this task.

The bag deployment and inflation is presented in Fig. 3-5

Fig. 3-5: “O” shaped enlarged airbag concept deployment and inflation

The impact tests on the “O” shaped enlarged bag were mainly conducted with the adult headform, in order to verify the effect of the design interventions introduced in the upper part of the bag, where the impacted points were critical in the early bag version from WP4 (like for example points A7, A8 located along the windscreen pillar (see Deliverable D4.1)); such an assessment included also the points not interested by the size enlargement (like for
example points A3 and A9, located on the upper transversal bag chamber (see Deliverable D4.1)) to confirm the previous good results obtained in WP4.

The simulation results of the enlarged and refined external windscreen airbag were compared with the previous ones (from WP4) in the same impact points and the reduction trend in monitored outputs (HIC values) was demonstrated.

The improved windscreen airbag concept design explored in this study has in fact confirmed its great potential in improving the head protection level for the impacts interesting the critical windscreen frame area.

In the following, the details about such results are presented. Pictures from Fig. 3-6 to Fig. 3-9 show the results obtained on the “O” shaped enlarged bag compared with the first “O” shaped bag concept developed in WP4 and the reference results without bag, i.e. referred to the REVM1 with the original generic windscreen model (called OLD in the figures).

<table>
<thead>
<tr>
<th>POINT</th>
<th>HIC 15 - OLD WINDSCREEN</th>
<th>HIC 15 - EXT. O_SHAPE BAG</th>
<th>HIC 15 - EXT. O_SHAPE ENLARGED BAG</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>1548</td>
<td>491</td>
<td>329</td>
</tr>
</tbody>
</table>

Fig. 3-6: “O” shaped enlarged airbag concept for REVM1: adult headform results for impact point A3
Fig. 3-7: “O” shaped enlarged airbag concept for REVM1: adult headform results for impact point A9

Fig. 3-8: “O” shaped enlarged airbag concept for REVM1: adult headform results for impact point A7
Fig. 3-9: “O” shaped enlarged airbag concept for REVM1: adult headform results for impact point A8

The enlarged airbag improves the head protection in the critical zone (points A7, A8), that are better covered and softened by its new configuration. Thanks to the higher gas flow rate and therefore to a better inflation of the bag, the numerical simulations show a reduction in HIC values in the impact point of upper part of the windscreen (points A3, A9), too.

The analysis of the numerical simulations performed in this task permitted also to highlight some points/recommendations for future improvements of this type of external bag concept, recalled in the following list:

- improvement of bag folding pattern/process: a further bending step of the extremities could be added in order to obtain a shorter bag package that it may be inserted in the area close to the lower windshield rail, under the bonnet upper edge;

- a detailed study of the tethering system to drive the airbag during the transitory phase of deployment and its correct positioning over the windscreen frame. A first possibility could be a thin cable that comes out of the windshield seal area along the A-pillars and that connect the bag extremities with an appropriate point of the A-pillar itself (i.e. a refinement of the simplified mechanism/principle used in the numerical simulations, that presents similarities with the tethers used in the window bags used for occupant protection in side impacts); another solution could be a sliding system along the A-pillars (in which the bag extremities are engaged and run during the
inflation), consisting of a guiding element anchored to and/or integrated in the car frame and of a slider fixed to the bag extremities (ensuring to them the possibility to translate upwards and rotate simultaneously during the deployment phase);

✓ use of more complex numerical simulation methods during the further phases needed to develop a detailed design for a practical solution/application (i.e. adoption of the particle method in place of the simple model airbags).
3.1.2 Intelligent occupant protection system 1 improved modelling

As already mentioned, the objective of this part of WP5.1 was the improvement of the restraint system numerical model of REVM1; in particular the activity was addressed towards the two following main lines:

✓ implementation of the air bag particle modelling approach for the two frontal airbags (i.e. Driver Airbag and Knee Airbag);
✓ integration of the two new bag models using the particle method on the full car REVM1 model to be used for the reference frontal impact simulations (FWDB frontal impact at 50 km/h), including the upgrade of this car model to the complete v4 status (i.e. implementation of the new front bumper developed in WP4.1 in addition to the retractable steering wheel column concept).

3.1.2.1 Airbag particle model

Starting from the simple airbag model used in the occupant compartment of REVM1 up to the end of WP4, a more detailed and complex airbag model was implemented to generate the second virtual demonstrator planned in WP5.1. This activity was conducted for both the inflatable devices existing in the REVM1 occupant protection system, i.e. the Driver Airbag and the Knee Airbag (see Fig. 3-10: Driver and Knee Airbags particle modelling).

The Ls_Dyna option *AIRBAG_SIMPLE_AIRBAG_MODEL, based on a uniform pressure method with no pressure variation on bag surface and location, was used in the previous WPs to simulate airbags deployment and their interaction with the occupant (dummy model).

In this WP the CPM option (Corpuscular Particle Methodology) was instead adopted and implemented for the airbags modelling; this option considers the effects of transient gas dynamics and thermodynamics by using a set of particles to represent a blend of gas molecules.

The corresponding Ls-Dyna card used in the model is called *AIRBAG_PARTICLE.

In practice the corpuscular method is based on the kinetic molecular theory, where the gas molecules are treated like rigid particles following the Newton’s laws of mechanics: the collisions among molecules and between molecules and airbag fabric are managed by the code as perfectly elastic impacts. In the formulation adopted by the code, the molecules of the gas are represented by reduced number of particles, so that their evolution can be managed with acceptable computational times (even if the use of this refined approach typically is more expensive in terms of CPU time).

The implementation of an airbag model based on this computational approach passes through a series of steps that can be summarized in the following list:
a) Definition/identification of the specific airbag parts present in the model (external and internal parts, vent holes)
b) Definition of the external air properties;
c) Definition of the inflator gas properties, mass flow rates and inlet temperature curves characterizing the specific pyrotechnical device to be simulated;
d) Specification of the characteristics of the vent holes (through specific functions of pressure and time);
e) Definition of the inflator position and geometry, together with the specification of nozzle directions;
f) Definition of the porosity characteristics of the airbag fabric.

All these inputs are given to the code through the proper fields of specific cards: in the following part of this paragraph, the keyword structure of such cards will be briefly presented and the meaning of the main fields/parameters recalled.

The complexity of this modelling approach requires typically a preliminary phase in which each airbag model is assembled and its deployment checked in a standalone configuration: here the selection of the proper parameters leading to the desired final behaviour is operated through the execution of several numerical simulations. When the isolated bags behaviour reaches the satisfactory level, they can be implemented within the occupant compartment of the full vehicle model and the reference impact configuration simulation executed. Usually some full car simulations are still needed for the last overall model adjustment/refinement before obtaining the run suitable for the final analysis of the results.

From the analysis of bag deployment animation results, the usage of the corpuscular method for the airbag models is immediately identifiable, as the particles flow is clearly visible within the airbag chambers and through the vent holes (see Fig. 3-10).
A description of the *AIRBAG_PARTICLE keywords referred to the Driver Airbag is presented below. For the Knee Airbag component the description is similar and then will be not repeated.

The card is organised like in Fig. 3-11

![AIRBAG_PARTICLE card for Drive Airbag](image)

Fig. 3-11: *AIRBAG_PARTICLE card for Drive Airbag

In the following, the meaning of main parameters involved in the definition of the card is shortly described.

- **AIRBAG PARTS**

  **SID1** defines the complete airbag (internal and external parts), **SID2** defines only the internal parts of the airbag (Fig. 3-12). The internal parts are represented by the inflator, the internal vent holes and the diffuser.
Fig. 3-12: Airbag parts

✓ **VENT HOLES**

The number of the vent hole parts is defined in the field *NVENT* (see Fig. 3-13). This number is linked to the fields *SID3*, where the vent hole parameters are defined. All nodes of the vent hole must belong to the surrounding fabric parts, too.

The material assigned to the vent holes is *MAT_NULL*; the material assigned to all the other bag parts is *MAT_FABRIC.*
**AIR PROPERTIES, INITIAL AIR**

This chart collects all the initial air properties inside and outside the bag (Fig. 3-14).

<table>
<thead>
<tr>
<th>*AIRBAG_PARTICLE_ID</th>
<th>ID</th>
<th>DAB</th>
<th>SID1</th>
<th>STYPE1</th>
<th>SID2</th>
<th>STYPE2</th>
<th>BLOCK</th>
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**Fig. 3-13**: Vent holes

**Fig. 3-14**: Air properties

*TATM* and *PATM* refer to air pressure outside the bag: the first is the atmospheric temperature (default = 293 K), the second the atmospheric pressure (default = 1 atm).

*IAIR* refers to the presence of initial gas inside bag (EQ. 0: No air, EQ. 1: Yes, using control volume method; EQ. 2: Yes, using particle method).

The other highlighted values refer to air gas parameters: *PAIR* and *TAIR* are respectively the initial pressure (default PAIR= PATM) and the initial temperature (default T AIR=TATM) inside bag.

*XMAIR* is the molar mass of gas initially inside bag.
AAIR-CAIR Constant, linear and quadratic heat capacity parameters;

NAIR Number of particle for air;

NPRLX Number of cycles to reach thermal equilibrium;

**INFLATOR CURVES AND GAS PROPERTIES**

![Inflator curves and gas properties](image)

Fig. 3-15: Inflator curves and gas properties

This card part (Fig. 3-15) describes the gas properties in term of number of particles and gas characteristics.

**NP** is the number of particle for air (the larger the volume the larger the number of particles).

**NGAS** is the number of gas components of the mixture from the inflator: this data is linked to LCMi data. For every gas component some data should be defined. **LCMi** and **LCTi** are respectively the mass flow rate and the temperature curves. **XMi** is the molar mass and the values from **Ai** to **Ci** are the constant, linear and quadratic heat capacity parameter for each gas component.
In Fig. 3-16 an example of the temperature and the mass flow rate curves for the four gas components of the gas mixture is shown. The temperature should be in Kelvin and the massflow should be in kg/ms.

The offset in time in the temperature and massflow curves correspond to the time to fire. This is controlled also by the OFFA parameter in *DEFINE_CURVE card.

**NOZZLE PROPERTIES**

The last part of the card refers to the gas nozzles characteristics (Fig. 3-17).
In detail:

**NORIF** is the number of orifices, that is linked to the **NIDI** card, where for each nozzle the node ID defining the location (**NIDI**) , the area (**ANi**) , the vector of the initial direction of gas inflow (**VDi**) , the cone angle in degree (**CAi**) and the chamber ID where the inflator node resides (**CHM_ID**).

Chamber are defined using the card *DEFINE_CPM_CHAMBER*. In Fig. 3-18 the card for the Drive Airbag chambers definition is shown.

![Chambers definition for Drive Airbag](image)

The aim of this card is to define the airbag chambers number (**NCHM**) and the chambers interaction. Indeed each chamber definition card set consists of a Chamber Definition Card followed by **NINTER** Interaction Cards.

**SID1** is the part set defining all parts that constitute the chamber volume. Each chamber's volume is calculated based on the part normals pointed inwards. So SID1 should have parts with their shell normals pointing inwards and and for this reason exists the field **SID2**, that can be used to flip the shell-normal.

The set **SID3** defines the interaction between chambers and **TOCHM** is the chamber ID of the connected chamber.

In the specific case there are three chambers, the inflator (CHM 998), the bag (CHM997) and the diffuser (CHM996). The first two chambers have just one interaction with the atmosphere, while the central chamber (CHM 996) interacts with the other two.
The already mentioned preliminary phase, in which each airbag model is assembled and its deployment checked in a standalone configuration, lead for the specific REVM1 airbags to the results visible in the following pictures.

More precisely, for what concerns the Driver Airbag, the deployment and inflation process operated through the particles is visualized in Fig. 3-19, where the animation sequence from the standalone configuration simulation is reported (one frame each 10 milliseconds). The comparison of this sequence with the one resulting from the simpler driver airbag model, used up to the end of WP4 (see Fig. 3-20), clearly highlights the more physical behavior obtained with the adoption of the more complex simulation approach. In fact the transient phase of the bag model using the uniform pressure approach presents a series of oscillations, along the steering wheel normal direction, before the final inflated shape is achieved and stabilized: this can be noticed from Fig. 3-20, where the bag is initially projected mainly forward (see the 20 ms animation frame), then comes back towards the steering wheel and acquires volume in the radial direction, too (time 30 ms); subsequently, it goes forward again (time 40 ms), before reaching its final inflated shape at time 50 ms. This final shape is characterized by a bag “thickness” along the normal direction that is lower than the maximum excursion experienced during the deployment process. Such a behavior is not observed in the real airbags and in the corresponding numerical models based on the corpuscular method, as the presence of a variable pressure inside the bag produces instead a progressive bag volume growth up to its fully inflated configuration, like shown by the inflation sequence reported in Fig. 3-19.
Fig. 3-19: *AIRBAG_PARTICLE Driver Airbag deployment and inflation
The activity carried out on the Driver Airbag for the implementation of the corpuscular method was conducted on the Knee Airbag, too.

The deployment and inflation of this other type of bag is shown in Fig. 3-21.
Fig. 3-21: *AIRBAG_PARTICLE Knee Airbag deployment and inflation
3.1.2.2 Integration of the new bag models within intelligent occupant protection system 1

This part of WP5 activity is focused on the evaluation of the results from the frontal impact simulation (FWDB 50 km/h configuration), after the introduction of the new corpuscular airbags into the REVM1 full car model and its complete upgrade to the version v4 status.

The frontal impact model was in fact upgraded with the integration of the front bumper concept developed in WP4 and the retractable steering wheel column was equipped with the Driver Airbag with corpuscular definition described in the previous task. The corpuscular Knee Airbag was included, too (see Fig. 3-22).

Fig. 3-22: REVM1 bumper, restraint system and corpuscular model refinement/improvement

The numerical simulations of the reference front impact configuration were then performed and after some refinement/adjustment actions the run suitable for the final analysis of the biomechanical results on the occupant (driver represented by an Hybrid III 50th percentile dummy model) was obtained.

The corresponding results are reported in Table 4, where the monitored dummy outputs obtained at the end of this WP5 activity are indicated together with the same indicators obtained in the previous phases of the project, i.e. at the end of WP3 and WP4 respectively. The status at the end of WP3 reflects the fact that the REVM1 restraint system was at that time still not completely optimized, with three dummy injury indicators still over the ECE R94 threshold values; within WP4, the restraint system was improved and optimized, so that the complete compliance w.r.t. the threshold values was achieved for all the dummy outputs.
Table 4: REVM1 bumper, restraint system and corpuscular model refinement/improvement: driver dummy outputs corresponding to the main evolutionary steps implemented in the model

| DELIVERABLE D 5.1 | SafeEV Project – Grant Agreement # 314265
|------------------|--------------------------------------------------
| Page 57 of 70    | SafeEV received research funding from the Community’s 7th FP

<table>
<thead>
<tr>
<th>REM1 to FWDB (frontal impact at 50 km/h)</th>
<th>Head acceleration [g]</th>
<th>Neck Shear Forces [kN]</th>
<th>Neck Tension Forces [kN]</th>
<th>Neck Bending Moment [Nm]</th>
<th>Thorax Compression [mm]</th>
<th>Thorax Viscosity Creation [m/s]</th>
<th>Femur Forces [kN]</th>
<th>Tibia Compression Forces [kN]</th>
<th>Tibia Index [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITUATION AT THE END OF WP4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) 2D+3D restraint system (from WP3)</td>
<td>Reference starting point</td>
<td>589.3</td>
<td>203.1</td>
<td>1.8</td>
<td>2.4</td>
<td>-15.2</td>
<td>60</td>
<td>1.04</td>
<td>0.89</td>
</tr>
<tr>
<td>2) 3D+4D+5D=ABE1+5E1+5E2 (e.g., configuration satisfying the target, i.e., REVM1 v4)</td>
<td>Reference starting point</td>
<td>631</td>
<td>75.6</td>
<td>1.4</td>
<td>2.2</td>
<td>-14.5</td>
<td>44</td>
<td>0.41</td>
<td>0.86</td>
</tr>
<tr>
<td>3) 3D+4D+5D+5E1=ABE1+5E1+5E2 (final configuration satisfying the target, i.e., REVM1 v4)</td>
<td>Bag deployment with corpuscular method</td>
<td>663</td>
<td>77.7</td>
<td>1.6</td>
<td>2.3</td>
<td>-14.8</td>
<td>45</td>
<td>0.43</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The last row of Table 4 shows that the introduction of the more complex corpuscular method for both REVM1 v4 Airbags confirms the biomechanical data obtained in previous WP4.

In fact, even if differences between the same indicators exist, these are very little and in practice negligible: the fact that in the frontal crash configuration used in this study the interaction between the dummy and the bags happens when such inflatable devices are already in the fully extended position explains the small differences detected with the new bag models.

The more physical behavior of the improved restraint system model implemented on this version of REVM1 (the second virtual demonstrator), other than permitting a further verification of the good performance of this occupant protection solution in a standard crash configuration like the FWDB, introduces also the possibility to analyze different non standard full car crash configurations where out-of-position like situations can appear and where the more accurate simulation of the transient phase of the bag deployment can give more realistic results, for what concerns the occupant response.
4 Analysis of signals in REVM1 front structure

The purpose of WP5 is to elaborate a use case for an advanced safety solution for dedicated SEVs. Therefore one solution elaborated within WP4 should be selected for further demonstration. In March 2015, at the last physical SafeEV meeting in Turin, Italy the project partners agreed on the use of an enhancement of the REVM2’s cross beam as best solution for pedestrian safety elaborated in WP4.

This component is manufactured by the project partner Swerea using its own intelligent material (change of material stiffness when electric voltage is applied). This exemplary component should be further evaluated within WP5 using the advanced simulation methods for pedestrian and occupant safety in SEVs developed in WP3. The Bosch contribution comprises the implementation and application of sensor systems in the selected solution.

Since the selected solution from WP4 (front transversal beam) requires pre-crash sensing (stiffness of transversal beam must be switched prior to leg impact to reach lower injury severity) it does not make any sense to include in-crash acceleration sensors into the selected component. Furthermore only the transversal beam was manufactured as test component and not the front bumper which is necessary for the implementation and incorporation of the acceleration sensors (acceleration sensors are mounted with a sensor holder on the front bumper). In addition, it was not planned within the SafeEV project to integrate environment sensing into the test setup and Bosch can’t cover this part within its planned contribution.

As a productive alternative to the original task (communicated to the PO), it was considered to analyse the redesigned REVM1 vehicle model. Within WP4.1 the front structure of the REVM1 FEM model was redesigned in a way to achieve a more pedestrian friendly front bumper. Within the alternative task in WP5 we will analyze the changed front structure of REVM1 (V4) regarding crash signals based on virtual methods. Thus, we will integrate our acceleration sensor models into the new FEM front bumper delivered by CRF from WP4.1 redesign (structural changes on bumper of REVM1 conducted within WP4 by CRF) and analyze the influence of structural changes on the sensing system. As in WP3 and WP4 the focus of WP5 analysis lies on acceleration-based sensing (for other sensing principles see D2 Wismans et al., 2013). This analysis enables us to make a statement if the structural improvement of the bumper w.r.t. pedestrian safety also has a positive effect on the required acceleration sensing. Based on the work already carried out in WP3 and WP4 this new task describes a logical step forward within the SafeEV project.

The sensor signal analysis in WP3 has shown that the structure of the vehicle front of the REVM1_V2 simulation model is too soft for a state of the art sensor performance. As a result no sensor calibration to determine triggering times for activation of in crash pedestrian safety system could be carried out even with adequate choice of sensor positions (sensor position was defined according to Bosch internal sensor installation guideline).
Within WP4 a new sensor position within REVM_V2 was defined to achieve better sensor signals, i.e. stiffer position within the front bumper. Although the new sensor position was not proper according to the installation guideline the underlying simulation methodology yielded adequate sensor signals. In this case a lower distance between the incorporated sensors and the cross beam was realized. Since the sensors could be damaged during the impact the contact between sensor and cross beam was adjusted by switching it off, so that no damage of the sensor is possible.

In the course of WP4 the front structure of REVM1 was redesigned by CRF to reduce the pedestrian leg injury as for leg impactor models according to the defined pedestrian safety tool chain, cf. Chapter 4.1.2 in D4.1 (Nuß et al., 2015). In the new design (REVM1_V4) the lower area of the bumper has been extended in X-direction and two foams (red in Fig. 4-1, left side) have been added in front of the lower and upper crash structure (brown in Fig. 4-1).

![Fig. 4-1: Comparison of REVM1 front design from work package 5 and 4](image)

Due to the redesigned front bumper of REVM1 and according to the elaborated virtual tool chain in WP3 in order to conduct our new task in WP5 the sensor position is moved in X-direction, while the sensors’ Y- and Z-position is kept constant. The three sensor positions throughout the evolution of REVM1 during the SafeEV project and the adapted methodology are shown in Fig. 4-2.
Fig. 4-2: Sensor positions in cross section of REVM1 bumper zone as elaborated in WP3 (left), WP4 (middle) and WP5 (right). WP5: Sensor at same Y- and Z-position as in WP4. Sensor has been moved in X-direction due to changed front bumper.

In the next step simulations with different impactors, impact positions and impact velocities are performed according to our introduced virtual tool chain approach considering sensor signals from WP3. For detailed sensor configurations and boundary conditions see D3.5 (Weber et al., 2015) chapter 6. The simulation results show that the point of rotation of the lower leg impactor has changed (compare Fig. 4-3) and is shifted from the upper crash structure path to the lower crash structure part. This represents a common way to cover pedestrian safety in larger vehicles and has been successfully transferred to SEV designs within WP4.

Fig. 4-3: Comparison of simulation results from work package 4 and 5 (impact position at Y=0mm, same sensor position, changed front design)
That means the first contact between leg impactor and bumper has been shifted downwards (Z-direction) and thus away from the sensor. After the first impact of the impactor on the lower area of the bumper the leg impactor is rotated around this area while reducing the knee bending. As primarily aimed by the redesign of the front structure the overall pedestrian safety of the bumper front was improved, since the injury levels could be reduced. However, the new structure yields a later impact of the impactor on the in-crash sensors if only the leg is considered. This fact is also highlighted by the measured acceleration signals at the impact positions (compare Fig. 4-4, lower graph).

![Sensor Position WP4](image1)

![Sensor Position WP5](image2)

Fig. 4-4: Comparison of simulation results from work package 4 and 5 (impact position at Y=0mm, same sensor position, changed front design)

With an impact velocity of e.g. 45kph an adequate sensor signal feature is first measured after 3ms if only a leg impactor is considered. However for triggering of the Pedestrian safety system the time difference between the first sensor impact and the first head impact as defined in Chapter 2.2.1 of D2 (Wismans et al) is the most important and relevant feature. Since in our case no overall pedestrian model was available the upper edge of the lower leg impactor was assumed as head impact reference. With the WP4 front design structure the first contact between the upper edge of the lower leg and the hood occurs after 13ms and with the redesigned WP5 structure after 18ms (compare Fig. 4-5).
If the contact time of the lower leg with the sensor is considered (WP4 with 45kph at 0.3ms and WP5 with 45kph at 3ms) than a total of 12.7ms (WP4) and 15ms (WP5) would remain for triggering of the pedestrian safety system. That means that with the new front structure more time (2.3ms) for the activation of the safety system would be available. A comparison of the use (lower leg impact) and misuse (basket ball impact) signals shows that a separation of the signals could be possible at least after 10ms (compare Fig. 4-6). That means with the new structure a triggering of an in-crash pedestrian safety system within 10ms to 15ms is still possible.

The focus of the REVM1 front structure redesign was to design a more pedestrian friendly bumper. In deliverable D4.1 (Nuß et al., 2015), it was shown that the new design has significantly reduced the pedestrian injury level. From the point of view of sensing, the new front structure has changed the measured acceleration signals but the time for activation of the pedestrian safety system was improved and could be possible within 10 to 15ms. Although in
the redesign of the REVM1 front structure the aspects of sensing were not explicitly considered (no available guideline for sensor friendly front bumper design) a good result from the sensing point of view was obtained. As a result of this study it should be always considered that a redesign of the front structure also influences (positive or negative) the contact sensing and thus triggering of pedestrian safety systems. As a guideline for virtual modelling in an early stage of a product development process we can state that structural changes e.g. in order to enhance primary safety shall be aligned to the sensing of secondary safety measures.
5 Conclusions

Within this task it has been shown experimentally that the use of a stiffness adaptable material can be beneficial for the protection of pedestrians in an impact. In quasi-static testing the stiffness drops to ~20% of the reference specimen stiffness at room temperature. In dynamic testing 40% - 50% of the reference stiffness was attained. The same was seen both the coupon tests and in the testing of the transversal beam profiles.

Although the simulations made using the current material card show a good overall agreement with the experimental results, some differences remain. These can be attributed to the omission of factors such as damage accumulation, through thickness stress and viscous effects.

The enlarged “O shaped” airbag was found to increase the head protection in the critical zone. The higher gas flow rate leads to a better inflation of the bag, resulting in a reduction in HIC values in the impact point of upper part of the windscreen. Recommendations have also been made for future improvements for this type of external airbag.

The improved modelling of the restraint system for REVM1 allows for the possibility to analyze different non-standard full car crash configurations. in which out-of-position like situations can appear and where the more accurate simulation of the transient phase of the bag deployment can give a more realistic occupant response.

The new front structure for REVM1 in WP4 altered the measured acceleration signals, but the time for activation of the pedestrian safety system was improved and could be possible within 10 to 15ms. It should be always considered that a redesign of the front structure also influences sensing capabilities and therefore any subsequent activation of safety systems. This should also be taken into consideration when redesigning structures.
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