Crashworthiness of an Electric Prototype Vehicle Series

Schluckspecht Project Collaboration for Crashworthiness

F. Huberth[*], S. Sinz[*+], S. Herb[*+], J. Lienhard[*+], M. Jung[*], K. Thoma[*], K. Hochberg[+], C. J. Fleig[+]
*Fraunhofer EMI, Freiburg; +University of Applied Sciences Offenburg

Contact: Frank Huberth, Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Germany, frank.huberth@emi.fraunhofer.de

The Shell Eco-marathon (SEM) is a challenge for student teams to develop energy-efficient vehicles and demonstrate the fuel efficiency of their prototypes. In Europe, this takes place at the Lausitz Ring in Germany.

Since 2009, the Schluckspecht team has taken part in the Urban Concept category of the SEM. The specification of the vehicles which start in the *Urban Concept Group* requires resemblance to roadworthy cars.

In the last quarter of 2009, the University of Applied Sciences Offenburg (FHO) where the team is located and the Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI, Freiburg, set up a cooperation to improve safety of the prototype Schluckspecht City.

Fraunhofer EMI deals with physical-technical aspects of high-speed, mechanical, and fluid-dynamic processes. This includes experimental and numerical analyses of crash, impact and penetration processes in a broad range of speeds from 10 m/s to 10,000 m/s, the response of structures to shock loads, dynamic material response and vehicle safety.

Figure 1: Schluckspecht City at SEM 2009

Figure 2:Schluckspecht E South Africa 2010

This cooperation included three versions of the Schluckspecht City, the improved Schluckspecht City based on the concept used at SEM 2009 (Figure 1), an adapted structure under the modified skin, called Schluckspecht E for an electric range record at Solar Challenge 2010 in South Africa (Figure 2). The actual prototype is a new battery electric version, the Schluckspecht City E2-light for the new class "Plug-In" Electric at SEM 2011. This concept is developed regarding maximum weight reduction with a small battery pack compared to the Schluckspecht E.

The first step in this work at Fraunhofer EMI was building a model of the space frame structure of the Schluckspecht City as used at SEM 2009 (Figure 3). This model was built using HyperMesh, based on an updated CAD-model built in Inventor 3D. The space frame was modeled with shell elements (Figure 4) using material model MAT_PICEWISE_LINEAR_PLASTICITY (MAT 24) [1, 2] and public reference data for the used aluminum profiles.

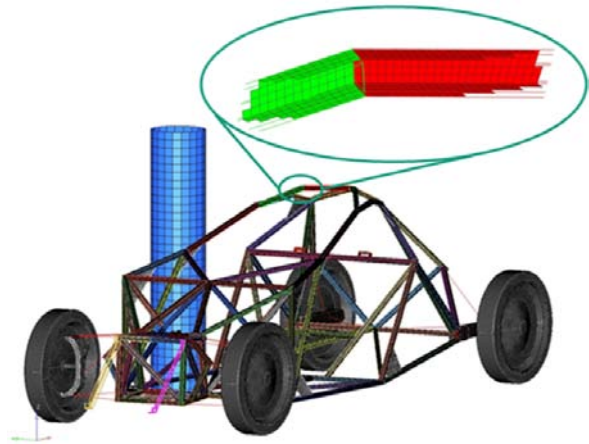**Figure 3: Schluckspecht City 2009 aluminum space frame**

Figure 4: Space frame model with pole for side impact simulation with LS-DYNA

To verify the modeling technique and the material data, 3-point-bending tests were performed (Figure 5) and simulated (Figure 6). This load case was used as it represents the most likely loading situation for the structure.
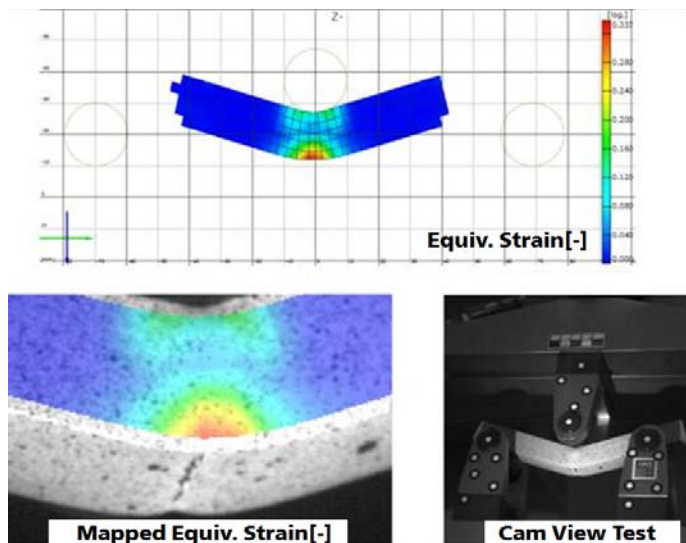

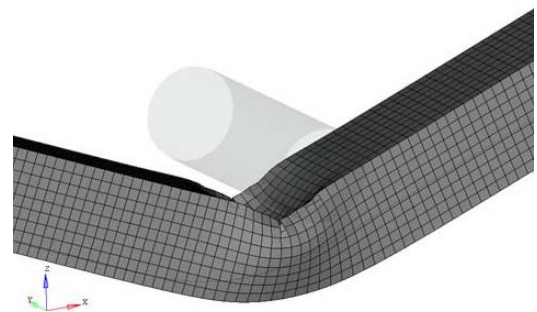**Figure 5: 3-point-bending test with optical strain field analysis**

Figure 6: LS_DYNA simulation of the 3-point-bending test

The simulation of the bending test was used to adapt the material data for the space frame profiles. These results were imported in the space frame model and a side pole test according to Euro NCAP[1] regulations was simulated. This load case was assumed as the most critical situation for the structure. The impact position of the pole was varied to find the weakest points (Figure 7).

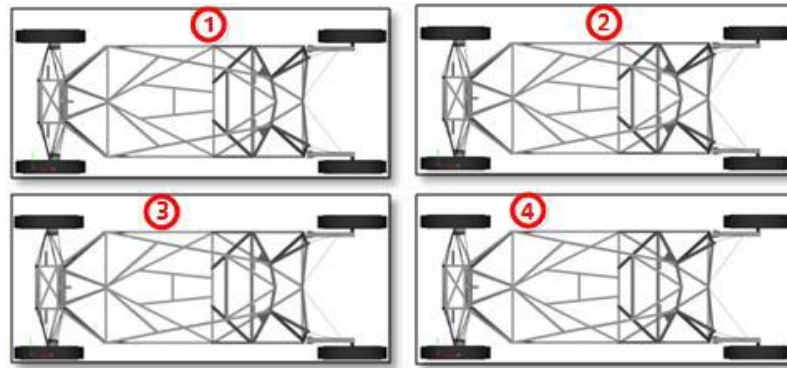[1] Euro NCAP: European New Car Assessment Program

Figure 7: Pole test simulations with different impact locations

Position 2 and 3 were identified as most critical. For position 2 of the pole (Figure 7), the lower side bar failed after impact. This result leads to a change in the cross bar configuration of the structure. A tube with a larger cross section was added in the state of the profile (Figure 8). The tube had nearly the same weight as the profile. The simulations showed, that the tube allowed the structure to absorb more energy as the failure occurred at a later state of deformation (Figure 9). Comparing the deformation, the tube shows folding, not buckling as the profile before.
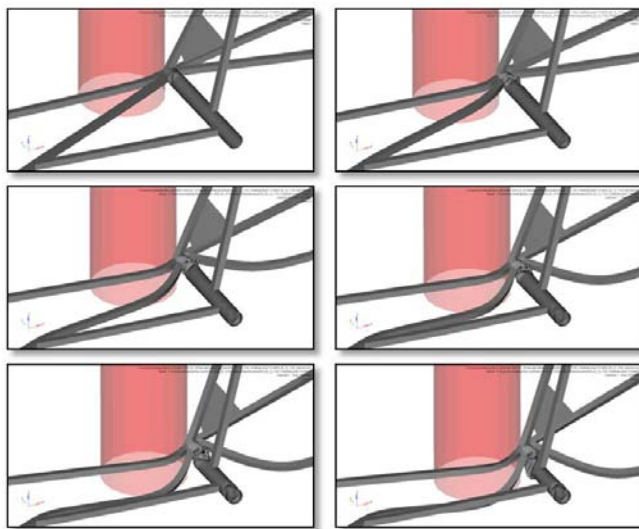

Figure 8: Side impact simulation for the improved structure with folding in the introduced tube cross beam
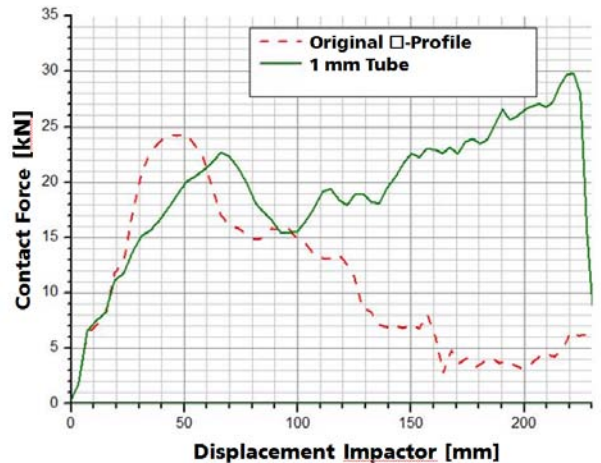

Figure 9: Diagram comparing impactor contact forces and impactor intrusion for the original (red dotted line) and the improved cross bar (green line)

In a second step, the crash model of the Schluckspecht City was extended with a body shell. The outer shell skin consists of a high-performance film sandwich composite, aramid honeycomb, and woven glass fabric laminated with synthetic resin (GFRP). Some areas are reinforced by additional woven carbon fiber laminates (CFRP). For surface finishing, a PVC film used for automobile body is used (Figure 10).
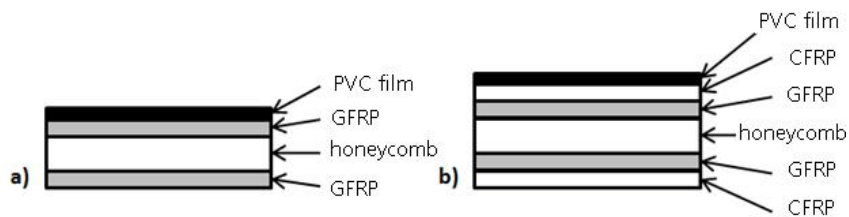
Figure 10: Sandwich composite setup with GFRP only (left) and additional CFRP (right)

Material parameters required for the simulation are calculated by iterative adjustment to experimental data. The experimental data were derived from dynamic tensile tests and 3-point-bending tests. The tensile tests were performed at layers of the GFRP and CFRP with comparable thickness to the layers in the sandwich composite (Figure 11 and Figure 12). As the sandwich composite has a structural and material behavior, the 3-point-bending tests were performed at the two different laminates with GFRP only and with additional CFRP layers.
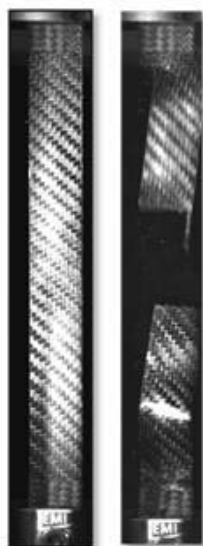

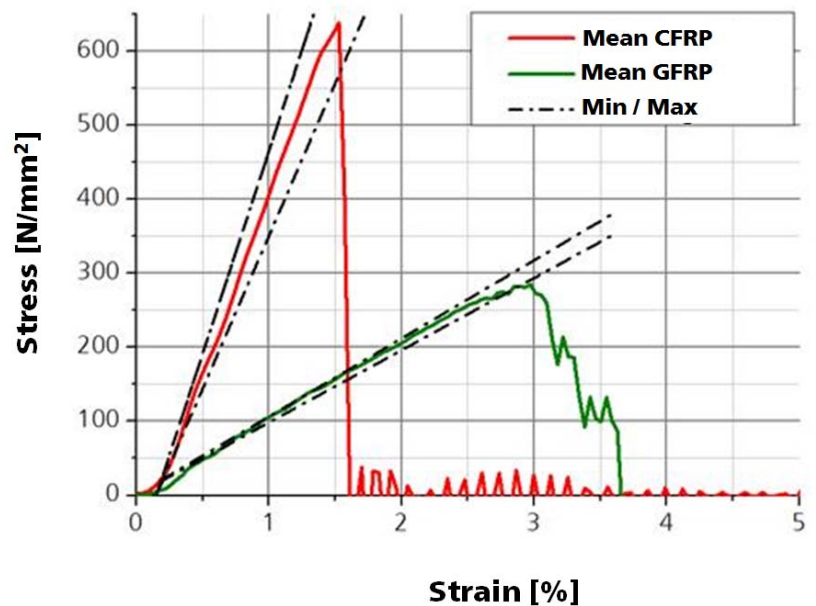**Figure 11: Dynamic tensile tests for characterization of the GFRP and CFRP fabric materials**

Figure 12: Stress strain tensile test results for GFRP (red) and CFRP (green) with marked variance

The outer skin is modeled using shell elements and adjusted to deliver quality reproducibility of the structural behavior of the sandwich composite. Body shell and structural frame are merged into one model (Figure 13). For the mesh quality, the default values of HyperMesh mesh quality functions were used, neglecting the element size (Figure 14).
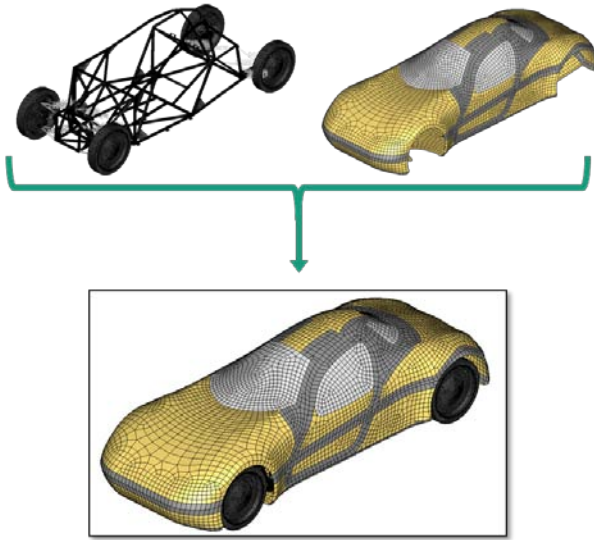
Figure 13: Combination of the developed models for the structure and the body shell
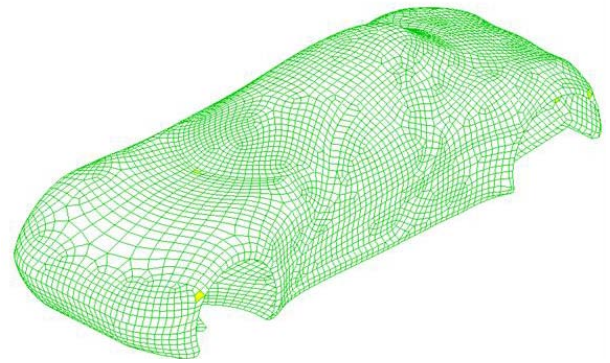

Figure 14: Quality check of the body shell FE-Model with HyperMesh default settings neglecting element size

As for the space frame described before, pole test simulations were performed. The results showed the potential of additional side protection by introducing stiffer parts in the body shell. The skin was modified in some areas (Figure 15) to improve the side impact behavior. This was achieved by changing the materal parameters in selected areas, marked blue. Increasing the stiffness of the side flange by a factor of five, the impactor was stopped after less than 125 mm intrusion (green graph, Figure 16) compared to the side impact simulation of the body shell without structure and additional reenforcement (blue graph).

Some stringer designs were investiated to achieve a five times stiffer structural response at very low weigth and with the applicability kept in mind.
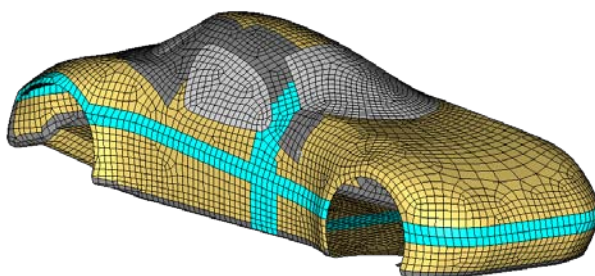

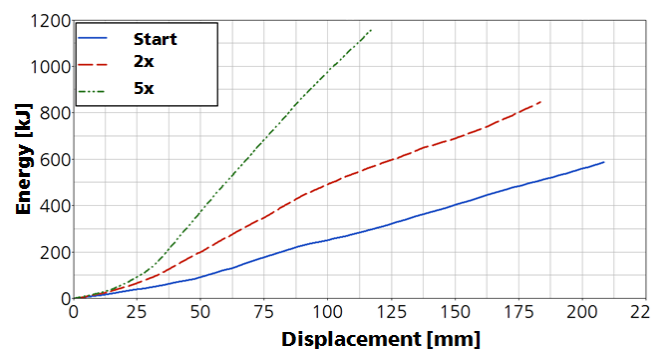**Figure 15: Body shell model with marked regions of reinforcement (blue)**

Figure 16: Energy absorption over pole intrusion for the initial state side protection (blue) and improved stiffness by reinforcement, twice (red dotted line) and five times stiffer (green dotted line)

Based on this work, FHO and Fraunhofer EMI developed and built a concept for a new approach, the Schluckspecht E. This prototype was constructed for real road tests with a battery electric vehicle (BEV) for an attempt to set a new range record for electric cars, powered by batteries. In September 2010, this concept reached a distance of 626.6 km without charging the batteries, supervised by the FEA.

The structure was designed and resulted in a concept named BatteryBowStringStructure (BBSS) according to the concept of a bow string bridge. The two batteries housings at the sides with a battery weight of 126 kg and a total capacity of 5640 Ah were mainly carried by two crossbows, mounted at the longitudinal bows and the central structural connector (Figure 17) comparable to a bow string bridge.

Here again the side protection was investigated using simulations of a pole test. The results showed the necessity of additional side protection for driver and battery safety. This measure was needed as the wall thickness of the housing of the two battery strings had to be reduced caused by restrictions in bending ability during forming. An additional profile and energy-absorbing polymer foam material were added. The simulation showed still a deformation but the housing showed no failure. Tests performed at cell blocks that constituted the modules showed the deformation ability of these modules as cells have space to avoid hard contact.

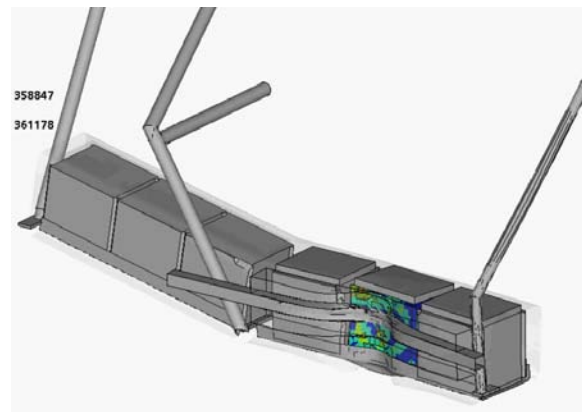**Figure 17: CAD-model of the Schluckspecht E structure with two battery packs**

Figure 18: Side pole simulation for the battery packs and the side structure of Schluckspecht E

Actual work in the collaboration is the new extreme lightweight structure for the SEM 2011 in May. Due to this target, the new concept is named Schluckspecht CityE2light (Figure 19). The realization is shown in Figure 20. This structural concept is built with intensive use of adhesive bonding. This avoids a thermal softening influence to the aluminum material and provides a better durability, as has been shown in some vibration tests at FHO. An additional effect is the use of smaller wall thickness.

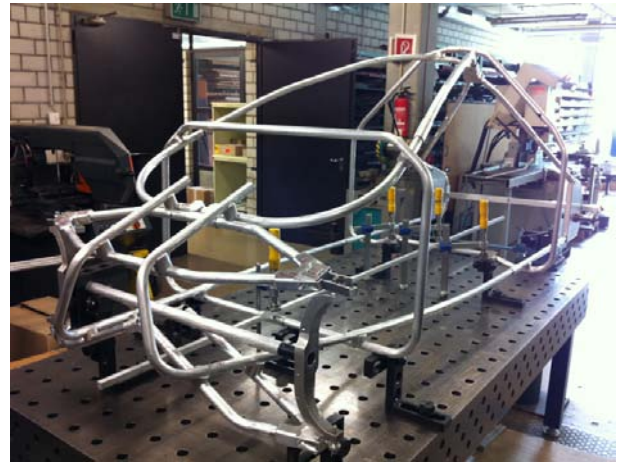**Figure 19: FE-Model of the Schluckspecht CityE2light**

Figure 20: State of the frame, 2011-05-02, Schluckspecht CityE2light

For the welding structure, the manual welding needed a certain wall thickness. As far as possible, the bow string concept was adapted here, too. The driver represents the main single mass. To follow the concept, the seat and thus the driver's mass is hung up by wire cables at crossing points of the longitudinal bows and the second cross bow. The bows are connected by wrapped CFRP-fibers and epoxy resin. The wire cable approach is used in the vehicle back for stabilization of the rear structure and to avoid track changes.

The structure was analyzed as the types before by pole test simulations (Figure 21 to Figure 29). The simulations already included an additional head protection. The dummy that was used is provided by DYNAmore[2] and was positioned using LS-PrePost. The vehicle hits the pole with an initial velocity of 29 km/h. This is a very high lateral velocity as the maximum speed for this concept is assumed as about 50 km/h. The driven speeds for SEM are about 30 km/h as not the time but energy consumption is the main criterion at SEM.

As shown for earlier states of the structure, the side protection of the vehicle has to be improved. To ensure the maximum lightweight approach, this side protection is included in the body shell, comparably to Figure 14. A first CAD-realization is illustrated in Figure 30 and Figure 31. The figures show the reinforcements in the upper and the lower ski shell. The final realization is in progress and will be done by lightweight cores that are laminated in the surrounding inner flanges of the two body shell parts. In the door region, the doorway is reinforced and to the door itself, a side protection bar will be added.

These measures and the additional integral helmet, mandatory by SEM-regulations, will assure the driver's safety at realistic collision speeds.

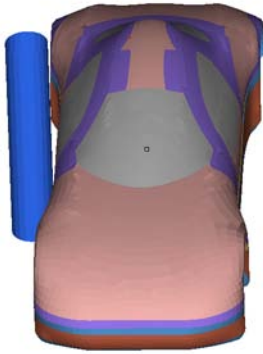[2] LSTC.H3.103008_V1.0_RigidFE.05th female dummy

Figure 21: Simulation pole test

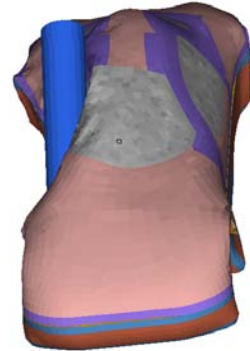**Figure 22: Pole intrusion 1**

Figure 23: Max. pole intrusion
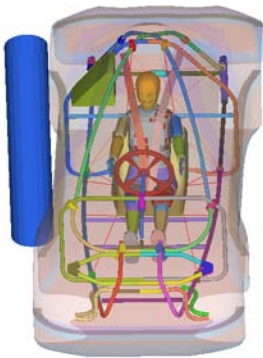

Figure 24: Dummy movement pole test
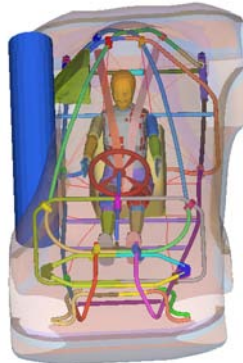

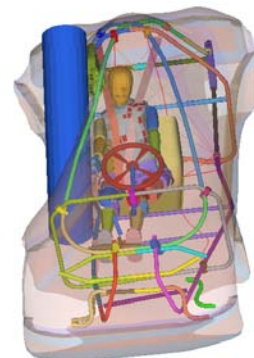**Figure 25: First dummy movement**

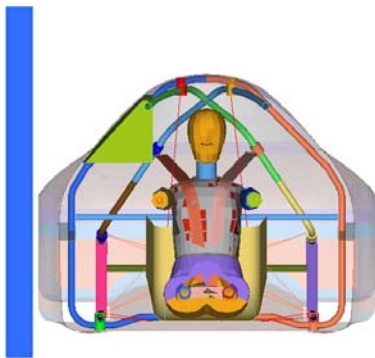

Figure 26: Max. dummy movement

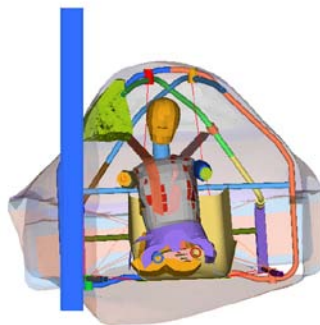
Figure 27: Frontal view simulation pole test

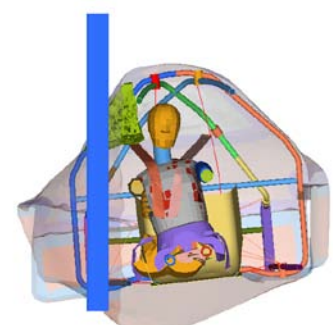**Figure 28: Frontal view simulation pole intrusion 1**

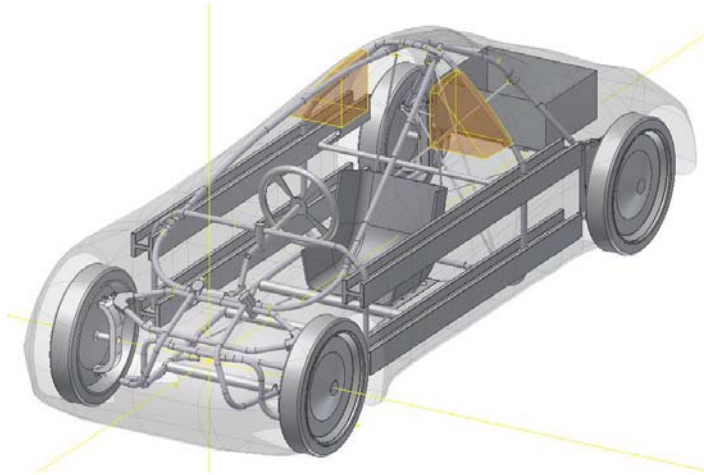**Figure 29: Frontal view simulation max. pole intrusion**

Figure 30: CAD-model of the Schluckspecht CityE2light with side protection system
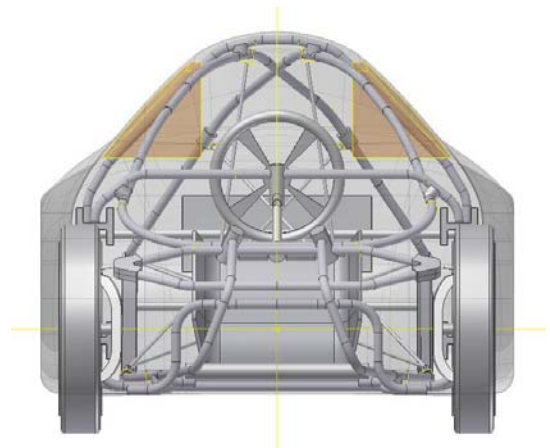

Figure 31: Frontal view CAD-model of the Schluckspecht CityE2light with side protection system

Conclusions

The collaboration of Fraunhofer EMI and the Schluckspecht team at the FHO has increased the crash safety of the Schluckspecht City concepts significantly. The process of CAE was introduced from CAD to FEM with iterative optimization for weak points.

Different models of structures and the body shell are available in CAD Inventor 3D and LS-DYNA input files. This allows fast improvements with small changes based on existing models for further work.

Acknowledgments

For supporting this work, we have to thank DYNAmore GmbH in Stuttgart, Germany, and Altair Engineering GmbH in Böblingen, Germany. The companies provided quick and straightforward support in many cases during the work at this project.

References

[1]   LS-DYNA KEYWORD USER'S MANUAL VOLUME I May 2007 Version 971
[2]   LS-DYNA KEYWORD USER'S MANUAL VOLUME II Material Models May 2007 Version 971