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New Lightweight Structures for Advanced Automotive Vehicles – Safe and Modular

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Abstract

The discussion around climate change and the responsible use of resources has pushed the topic of alternative drive technologies into the focus of the politics, the society and the industry – many even talk of a paradigm change.

The specific requirements of new vehicles grow as a consequence of the different drive train technologies, influenced for example by the storage technologies of electric vehicles. The challenge of lightweight design depends on the boundary conditions of each alternative drive train, which is expressed in new packages and load paths. For example, the absence of load bearing drive structures in the front end of the vehicle completely changes the crash performance and so solutions and answers for these problems must be found by a modified construction.

Beside these requirements lightweight design is a main topic in the development of automotive structures, because the mass influences the energy consumption of conventional petrol driven vehicles and the distance range of electric vehicles.

The Institute of Vehicle Concepts has developed different new lightweight concepts which are modular and safe to fulfil such requirements. An example is a circular carbon fibre reinforced plastic (CFRP) rib construction at the position of the b-pillar that creates a light, safe passenger compartment to assure the safety of the passengers as well as the components of a alternative drive train in case of a side crash. Another example is a new light front end structure which resembles current configurations in the package, but simultaneously reveals a clearly improved structural performance. This development is based on an efficient energy absorption mechanism in which the outer skin of cylindrical longitudinal members is peeled off in a crash. The new configuration permits a structure that can be adapted to different standards without the need for interventions in the overall concept.

Keywords: Lightweight structure; modular; CFRP, crash, multi-material design, vehicle concept

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1. Introduction and objective

The next generations of vehicle designs should be developed aiming for individual mobility whilst also retaining safety, environmental friendliness, and affordability. An essential step for increasing the body's performance in terms of safety and weight is the combination of high-performance materials such as new steel grades or high-performance fibre composite materials with a vehicle architecture optimised for these materials. This is oriented towards the packaging and safety requirements of modularly structured alternative power train systems. The basis of the work is the unique synthesis of research fields at the institute, which enables findings from research on alternative power trains to flow directly into novel lightweight and hybrid constructions.

Driving-resistance reduction using an economically sensible, lightweight approach is being prioritised due to the lower energy densities of alternative power train systems and a consequently smaller range. In this connection, the vehicle structure must feature simple scaling and modularisation due to steadily declining per-model unit counts. For this reason, special significance underlies the definition of the exact interface between the body and power train. This ensures that, depending on the characteristics of the vehicle's derivative, different energy storage and converters are safely integrated in the vehicle (see Fig. 1).

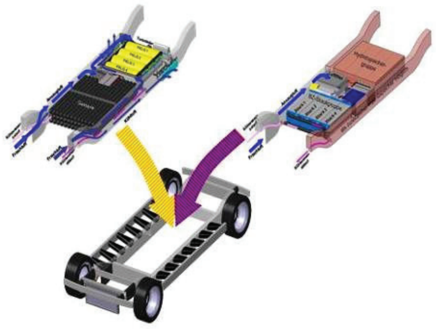

Fig. 1. Integration of alternative power trains in the vehicle's base

1.1. Lightweight structures

The Institute has developed different new lightweight concepts which are modular and safe to fulfill such requirements. [1]

An example is a circular CFRP rib construction at the position of the b-pillar that creates a light, safe passenger compartment to assure the safety of the passengers as well as the components of an alternative drive train in case of a side crash. Another example is a new light front end structure which resembles current configurations in the package, but simultaneously reveals a clearly improved structural performance. This development is based on an efficient energy absorption mechanism in which the outer skin of cylindrical longitudinal members is peeled off in a crash. The configuration permits a structure that can be adapted to different standards without the need for interventions in the overall concept.

1.2. Innovative vehicle structure in rib and space frame construction

The rib and space frame construction was developed under the previously-mentioned objectives in line with other areas of technology, such as aeronautics (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). Here, alternative power train components are located centrally in the vehicle's floor. Two end-to-end side members, which simultaneously receive the power train system's media supply, flank this area laterally. The area between the side members and the outer rocker panels incorporates energy absorbers for side impact and pole collision.

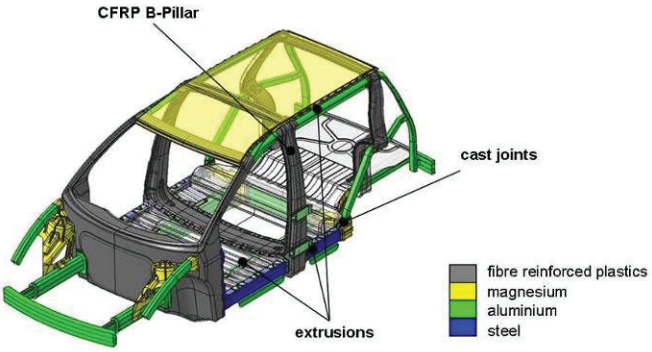

Fig. 2. Material overview in the rib and space frame model

This has the advantage that alternative energy storage for natural gas or hydrogen can be arranged in an intrusion-resistant, modular area with standardised dimensions; the centre of gravity can be lowered and weight distribution can be optimised.The vehicle's structure is formed by three ribs where the A-, B-, and C-pillars and the two roof crossbars are located today. Here, the ribs contribute primarily to maintaining the passenger compartment during an accident and thus to the passengers' safety. For this reason, the ribs are manufactured from the high-performance material CFRP. Connection of the highly stressed fibre-composite ribs with the geometrically simple metal profiles occurs via highly integrated cast components. This is how what we call the CFRP-intensive multi-material design, or 'Stuttgart model', is created. This construction increases safety and reduces weight, and the cost-intensive use of CFRP is restricted to the necessary places.

1.3. The rib's layout design and active principle

The b-pillar has a major effect on vehicle safety for the passenger in side impacts. To achieve good crash performance the common strategy is to design a b-pillar with an almost rigid structure in the upper area of the pillar to avoid an intrusion in the survival space. The forces are distributed in the vehicle underbody and roof structure and partly absorbed in deformation of the B- pillar and especially in deformation in the attachment points of the pillar. [3]

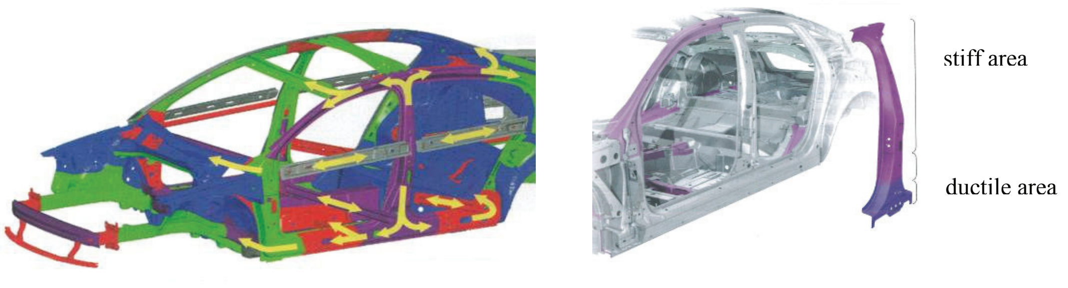

Fig. 3. (a) load paths at a sidecrash [2]; (b) different areas of a B-pillar from an Audi A6 [3]

Our B-rib was identified as the rib and space frame construction's central element, and its complex dimensions were intensively examined. The starting point of the development was a mechanical basic principle in automotive construction (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**). In the event of a side impact, the rib's ring structure in the base breaks open above a pre-defined force level, and the intact lateral section of the B rib rotates around a hinge joint in the roof-crossbar area. This measure shifts energy absorption into an area of the vehicle's structure that is non-critical for the passenger. At head and torso height, only minor intrusions into the passenger compartment occur via the system's kinematics, and the space for the deployment of additional safety systems remains intact. [1]

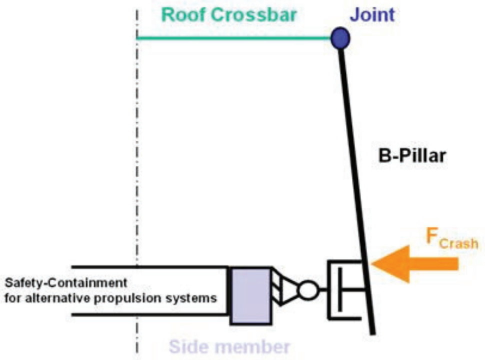

Fig. 4. The rib's active mechanical principle

In preparation for the topology optimization, which was conducted on a generic specimen, equivalent static loads meeting Euro NCAP side-impact requirements had to be extracted from existing dynamic simulations. Besides different load directions from the side impact, the generic specimen's eigenfrequency was taken into consideration to obtain a finer structure in the topology optimization.

The cross section design from the specimen was reviewed with a view to stiffness, resistance and the mass. The simulation's results were transformed into manufacturable cross sections taking various combinations of materials into consideration (see Figure 5).

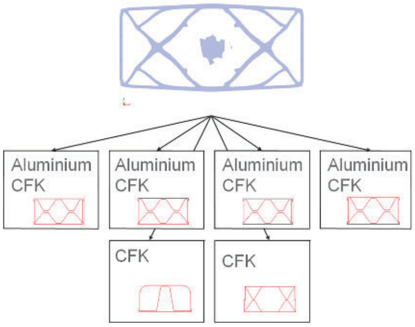

Fig. 5. Topology optimization of the b-rib structure

Subsequent benchmarking of the various combinations led to a three-layered structure (see Figure 6) comprising an inner and an outer shell as well as an “omega” shaped profile for stabilizing the structure. In addition, reinforcements and energy absorbers (crash cones) are located in the rib's lower area. Individual parts are connected with the help of a structural adhesive suitable for the dynamic load.

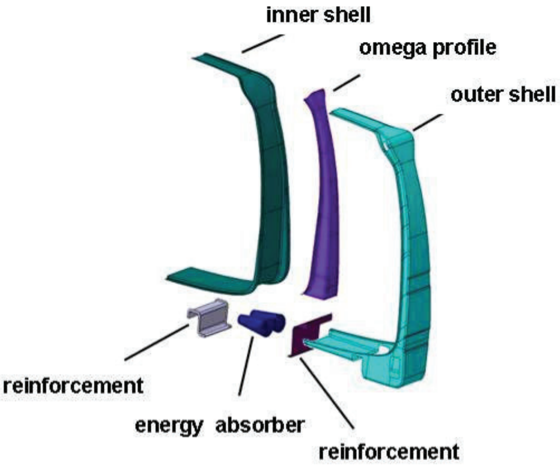

Fig. 6. The rib's structure

In pre-tests, dimensioning of fibre-composite energy absorbers for installation both within the rib and also between side members and rocker panels has been studied in drop-tower tests (see Figure 7). The weight-specific absorption capacity of high-performance carbon-fibre material is between 60 kJ/kg and 100 kJ/kg, which is about twice as large as for metallic materials. A cloverleaf-shaped base surface turned out to be the best cross section under the given conditions in the experiments performed at the DLR institute of structures and design.

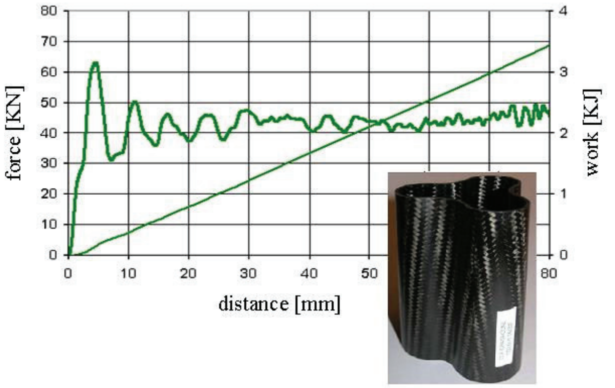

Fig. 7. Results of drop-tower tests conducted at the partner Institute of structures and design

The tested crash tube had no trigger. This is why the force-deformation curve shows relatively high oscillations at the beginning. The overall system's dynamic layout design was carried out in accordance with the Euro NCAP's side-impact requirements. The barrier (950 kg) impacts the standing structure at 50 km/h. The structure is impacted at a height of 300 mm measured from the vehicle's base. Thus the energy absorption zone and force transmission point of the barrier are not at this height. The rib's lateral structure, the area of today's B-pillar, is thus exposed to a high bending load. Pre-dimensioning in different rib sections followed from the static equivalent loads. Wall thicknesses were then continuously adapted to the respectively occurring loads.

The test results show that it was possible to fulfil the specifications imposed on the rib. Compared to the reference structure, which is a typical B-pillar from a medium-class vehicle, the weight of the rib construction within the section under consideration was reduced by 35% to 29 kg. The weight reduction is limited to about one-third of the initial value because the rib space frame takes additional functions into consideration, especially the integration of alternative power trains in the vehicle's base.

1.4. Development of the second generation

The second-generation rib was developed to meet ever-increasing safety requirements. This rib should meet not only Euro NCAP side-impact criteria but should also bear up under the American IIHS's side-impact requirements. The barrier's mass increases from 950 kg to 1,500 kg with the same impact speed. Moreover, the force application point moves further in the z direction (vertical vehicle axis) due to the barrier's greater ground clearance, which increases by 79 mm to 379 mm. The consequence of this is that greater crash energy has to be absorbed and dissipated in an unstable area of the vehicle's structure, above the rocker panels. Improvements in this connection versus the first generation lie, among other things, in improved integration of the rib on the space frame's adjacent support structure. The roof-crossbar /rib interface received special attention in this connection. Test-environment changes, corresponding even more closely to today's vehicle structures, also contributed to a more realistic picture of component behaviour in the component test.

The development of second-generation frames took place in the 'Novel Vehicle Concepts and Structures' project at the Institute for composite structures and adaptive systems. The prototype fabrication of the rib at the Institute was conducted using a single-shell tool concept and the vacuum infusion process (VARI) in the autoclave.

1.5. Validation of the rib prototype

After completion of the prototype, the Institute investigated the production quality of the assembled rib in the computer tomography (CT). This ensures that the exact cause can be identified when premature failure occurs during the test. A preliminary static investigation of the component was subsequently conducted at the Institute. Here, before the actual crash, the structure's stiffness should be reconciled with the simulation and any weaknesses possibly showing up should be checked. Furthermore, positions identified in the simulation for the application of the strain gauge were checked.

For this purpose, different static load cases were examined. The rib's critical area was subsequently investigated in detail using optical strain measurement (see Figure 8). This measurement system's advantage is that the displacements, which the system converts into strains, are recorded over a large area. That way it is subsequently possible to apply the strain gauges necessary for the dynamic test at the locations of greatest strain.

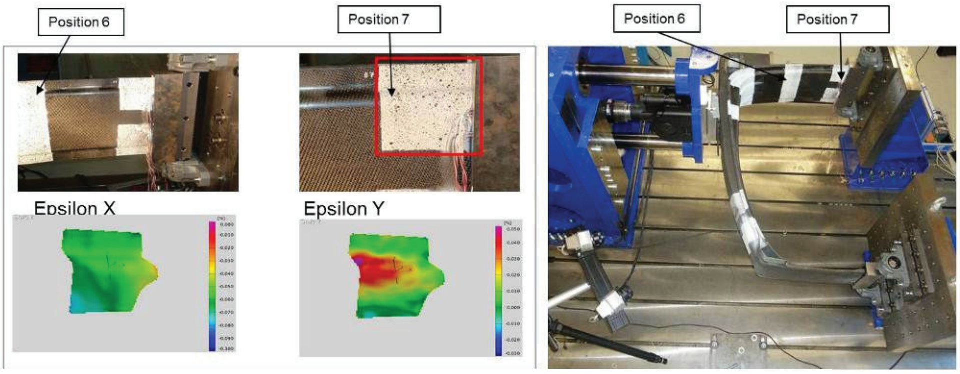

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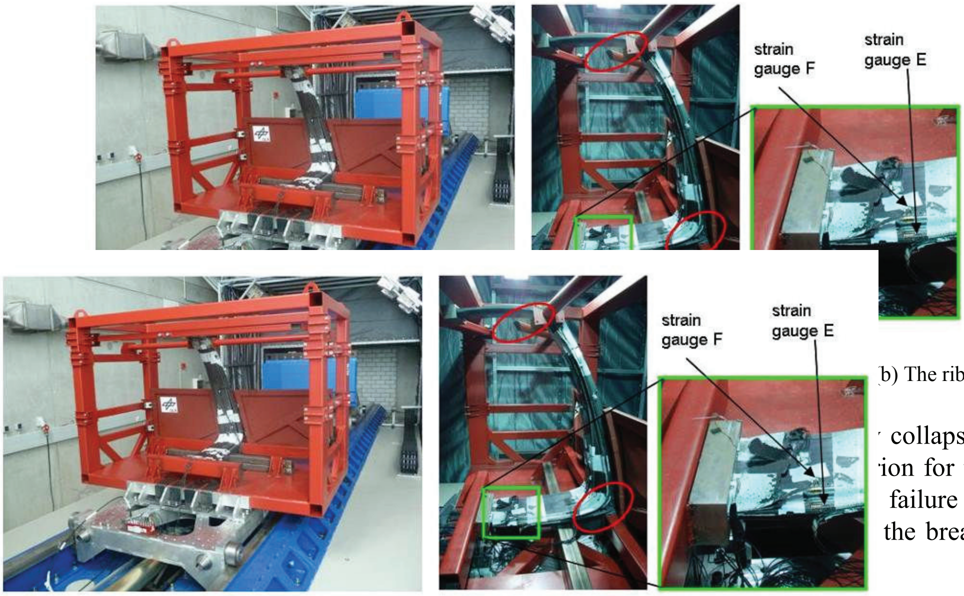
Fig. 9. (a) The crash test's test structure on the dynamic-component test facility at the Institute; (b) The rib's failure mode

): one on the adhesive flange, because the simulation indicated the greatest tensions here, and one just behind the radial area above the flange, because the static investigations showed the greatest strain there (see Figure 8).

After conducting the static tests and application of the strain gauges, the rib was installed in a substitute structure representing a mid-sized vehicle. A structure representing the roof crossbar, rocker panel, side member, and doors in abstract form was developed accordingly. Then the crash test was conducted in accordance with the previously mentioned American IIHS side impact. At the test facility, the crash sled with the barrier is accelerated to 50 km/h within 1.5 m using compressed air. It strikes the free-standing test sled on which the substitute structure is mounted (see Figure 9 a). The collision accelerates the free-standing test sled somewhat and it can give way backward, which simulates a passenger vehicle's behaviour during a side impact.



b) The rib's failure mode

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Fig. 9. (a) The crash test's test structure on the dynamic-component test facility at the Institute; (b) The rib's failure mode

b). The inner shell was displaced by about 70 mm during failure.

As the analysis of the strain gauges from the dynamic test shows, the area between positions 6 and 7 was the most heavily loaded, as was previously the case in the static investigation (see strain gauge F2 in Figure 10).

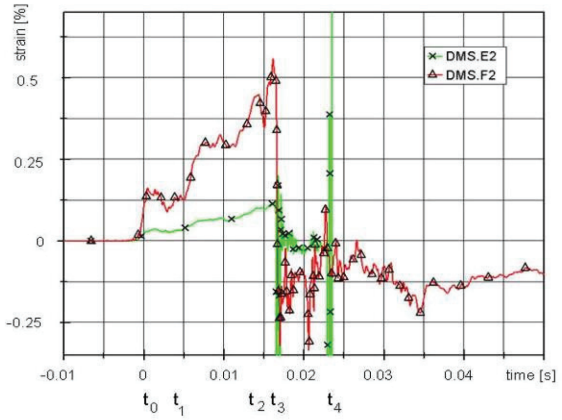

Fig. 10. Selected strain gauge signals during the dynamic test

The side-impact process can be divided into four phases here. At time t_0=0, the barrier impacts the doors causing the initial deformations and accelerations of the free-standing test sled:

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- t_1: deformation of the rib.
- t_2: adhesive seam failure, which is why a slight strain-gauge relief occurs.
- t_3: breakage of the inner shell, which is why strain gauges E and F are briefly relieved.
- t_4: wedging of the broken shell and shearing off of strain gauge E.

2. Safe and easy adaptable front end structure

Due to their modified package, alternative driven vehicle concepts increase the requirements on the design of vehicle front ends. State-of-the-art passenger cars using a front structure design which is dominated from two longitudinal rails (see Figure 11). Typically in an accident, a significant part of the kinetic energy of the vehicle will be absorbed by buckling of the longitudinal rails. Safety-relevant crash load cases are decisive for the design of front end structures. The front located propulsion units are integrated tightly into the structural behavior [4].

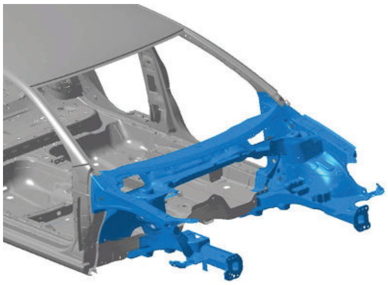

Fig. 11. Front end structure of a front-wheel drive [5]

Future vehicles will in essence offer more different propulsion options so that layout design of safety structures in the front end must be more sophisticated. In conventional front structures, power-train changes would lead to increased development effort and to many cost-intensive structural variants.

The development objective in the front-end area is therefore the creation of body structures exhibiting favourable front-end structure behaviour through suitable construction and modified crash management. A good structural behaviour independent of the particular type of propulsion would be beneficial. A further objective is simple adjustment of the required energy absorption without major interventions into the basic structure.

A new type of energy-absorption mechanism in which energy is absorbed by the peeling of the outer skin of a telescopic tube has been developed to achieve the objectives above (see Fig12). High specific energy absorption of more than 40 KJ/kg [6] and near-ideal force-paths and trajectories characterise this mechanism. This principle was then integrated into a novel vehicle structure.

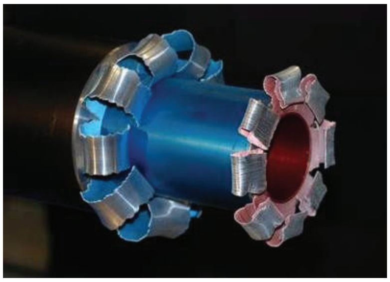

Fig. 12. Generic test component of a side member as peeling tube

2.1. The front end concept's layout design

Depending on their design, side member structures react sensitively to non-axial forces in crash cases. In today's vehicles, propulsion components support side-member structures during an accident. Structural integration of the power train is becoming ever more complex in the face of increasing power train variance. So the general requirements for a front-wheel drive, combustion-engine vehicle and an electric vehicle equipped with wheel-hub motors are very different. Also, the need for heavy battery modules in the vehicle significantly changes the mass distribution important for crash management in the front end. So the task of a safe front end structure is to assume the power train's structural functions thus reducing the influence of changes in the power train's architecture. This is achieved by the surrounding structure supporting shoring side members against oblique forces.

A front end structure was therefore developed in which three overlapping longitudinal structures mutually support, and thus stabilise each other through spatial connection. The side member structures are connected to one another in the transverse direction via a forward front-end member so that non-axial forces are absorbed by a total of six side member structures (see **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**3) [6]. For instance, essential installation spaces for different power-train components are retained here.

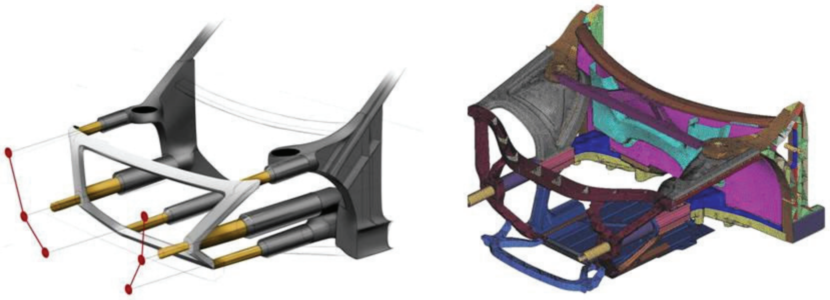

Fig. 93. Design sketch and detailed design of the new front end

The main side member consists of a double telescope tube in which energy is absorbed by metal cutting at two load levels. The first level fulfils AZT insurance requirements. An advantage of this structural design is that the retracting front tube increasingly stiffens the tube structure behind it. The connection of the six load paths should be maintained throughout the entire crash. The use of peel tubes in the developed vehicle structure enables easy adjustment of the longitudinal front-end forces required for energy absorption. For instance, if the mass distribution changes due to the selection of a different propulsion system, the side member force can be adapted by choosing a different cutting depth (modified cutting component) [4].

2.2. Validation of the structural concept using simulation

Besides a possible lightweight construction potential, this mutual stiffening of the structures can mainly achieve significantly improved structural properties. Simulation of a frontal crash against a 30° inclined wall with half vehicle offset (see Fig. 104) impressively shows the novel structure's potential.

Fig. 104. Comparison of the reference's crash properties (left) with those of the developed front end (right)

Here the newly developed design offers not only structural advantages but also weight savings of around 25 percent [7] compared to a conventional steel-body front end construction. The structure enables a construction with considerably improved safety versus conventional structures. This property can be used to advantage in vehicles with alternative power trains to circumvent cost-intensive adaptive developments and structural variations. The developed front end structure opens the possibility of equipping both conventional vehicles, and those with alternative power trains, without fundamental structural changes.

3. Summary and outlook

Vehicle development will always remain closely associated with the development of new materials, the requirements and by the architectural concept, with an apparent trend towards multi-material design – the right material for each use and each place in the vehicle. This method of construction still presents major challenges, e.g. with regard to joining components or recycling. Another change in vehicle architecture is initiated by alternative power trains. This allows deviation from a classical system configuration - such as today’s internal combustion engine, and implementation of new solutions. The objective of these measures remains the reduction of climate-damaging CO2 emissions.

The examples shown illustrate that economically attractive lightweight structures can be developed by the application of comprehensive lightweight construction strategies in conjunction with multi-material design. A major potential particularly lies in the application of concept-oriented lightweight design. New innovative lightweight design solutions can however only be developed on the basis of an understanding of the requirements, the ability to derive new methods of construction from this, broad material-related knowledge and competent application of construction and calculation tools for optimal component design.

The task of the Institute is to utilize these abilities to provide technologies for more efficient vehicles.

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