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Fibre Reinforced Plastic Concepts for Structural Chassis Parts

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Abstract

Fibre reinforced plastics (FRP) have a high potential for reducing masses of automotive parts, but are seldom used for structural parts in the chassis. If the whole chassis concept is adapted to the new material, then a high weight saving potential can be gained and new body concepts can result. DLR Institute of Vehicle Concepts designed and dimensioned a highly stressed structural part in FRP. A topology optimisation of a defined working space with the estimated loads was performed. The results were analysed and fibre reinforced part concepts derived, detailed and evaluated. Especially by the use of the new FRP material system in the chassis area, a weight saving of more than 30% compared to the steel reference was realised. With the help of those concepts it is shown, that there is also a great weight saving potential in the field of chassis design, if the design fits with the material properties. The existing concepts still have to be detailed further, simulated and validated to gain the full lightweight potential.

Keywords: Fibre Reinforced Plastics; Chassis Design; Lightweight Design Concepts; Finite Element Simulation; FEM.

Résumé

Plastiques renforcés de fibres (PRF) ont un fort potentiel de réduction des masses de pièces automobiles, mais sont rarement utilisés pour des pièces de structure du châssis. Si le concept de châssis est adapté au nouveau matériel, un potentiel élevé d'épargne de poids peut être acquis et de nouveaux concepts de construction peuvent en résulter. L'institut DLR des concepts de véhicule ont conçus et dimensionné une partie structurelle fortement sollicités en FRP. Une optimisation de la topologie d'un espace de travail défini par les charges a été réalisée. Les résultats ont été analysés et les concepts des pièces renforcées de fibres dérivées, détaillées et évaluées. En particulier grâce à l'utilisation de ce nouveau système de matériau FRP dans la zone du châssis, un gain de poids de plus de 30% par rapport à la référence de l'acier a été réalisé. Avec l'aide de ces concepts est démontré, qu'il ya aussi un grand potentiel d'économie de poids dans le domaine de la conception du châssis, si les ajustements de conception correspondent avec les propriétés du matériau. Les concepts existants doivent encore être détaillés, simulés et validés pour obtenir le potentiel total en termes d'économie de poids.

Mots-clé: Plastiques renforcés de fibres; conception du châssis, les concepts de design léger; simulation par éléments finis, éléments finis.

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Nomenclature

A	cross-sectional area
a	acceleration
c_d	drag coefficient
E	Young's modulus
F_a	acceleration forces
F_c	climbing forces
F_d	drag forces
F_f	friction forces
f_r	frictional resistance
g	gravitation acceleration
m_t	total mass
ρ_a	density of air
Ø	shape factor
ΣF_{dr}	sum of driving resistant forces
Σm_r	sum of rotating masses

1. Reasons for mass reduction

Driven by increasing political and market demands, automotive manufacturers must further reduce the CO_2 emissions of their products. To achieve CO_2 reduction, there are several possibilities. First of all is the increasing of the degree of efficiency primary of the drivetrain by hybridisation or even changing the drivetrain into an electric concept. Another way is the reduction of mass of the vehicle to reduce the running resistance.

1.1. Running resistance equation

As can be clearly recognised in the equation of motion, three out of the four terms are determined by mass in general. Within the Institute simulations have been made, that the reduction of mass is a key factor to reduce the driving resistance. The main result of our simulation is, that up to 75% of the drive resistance depends on the mass, if a middle class car, such as a VW Golf, is running on a New European Drive Cycle (NEDC).
The equation of motion is known as follows with the additional results of our simulation:

$$\Sigma F_{dr} = F_f + F_d + F_a + F_c \tag{1}$$

$$\Sigma F_{dr} = m_t \cdot g \cdot f_r \cdot \cos(\alpha) + \rho_a \cdot A \cdot c_d \cdot v^2/2 + a \cdot (m_t + \Sigma m_r) + m_t \cdot g \cdot \sin(\alpha) \tag{2}$$

$$\sim 35\% \quad + \quad \sim 25\% \quad + \quad \sim 40\%$$

⇨ ~75% of driving resistance of a middle class car in NEDC is dependent on mass

1.2. Increase in range by lightweight design

Mass therefore remains a key resistance factor at constant speed or on gradients, even if the acceleration energy, inevitably lost when braking, can in part be recuperated by hybridisation of the power train. A simple parametric calculation model was constructed to illustrate the basic parameters of the vehicle (table 1).

Table 1. vehicle parameters

Parameter	Value
Vehicle mass	1000kg
Rolling resistance coefficient	0.01
Drag coefficient	0.32
Front face	2.2m²
Useable battery capacity	28.2kWh
Efficiency of powertrain	70%

The useable battery capacity is determined by the parameter of the estimated vehicle range. In this case it was chosen to be 200km in the NEDC, which results in a total battery capacity of ~35kWh by an estimated value 80% of usable battery capacity.

Simple calculations on a hypothetical small electric car with the data from Table 1 show, that a 23% range increase (without recuperation), especially in urban traffic, is possible by reducing the weight by 20%. If the recuperation of brake energy is included, which is state of the art for electrified urban vehicles, then an increase in range of 21% can still be expected. In the following diagram the dependence of range increase on mass reduction in different driving cycles is shown. From this it can be seen, that the range of electric vehicles is heavily dependent on the field of use, but that in any case mass reduction always pays.

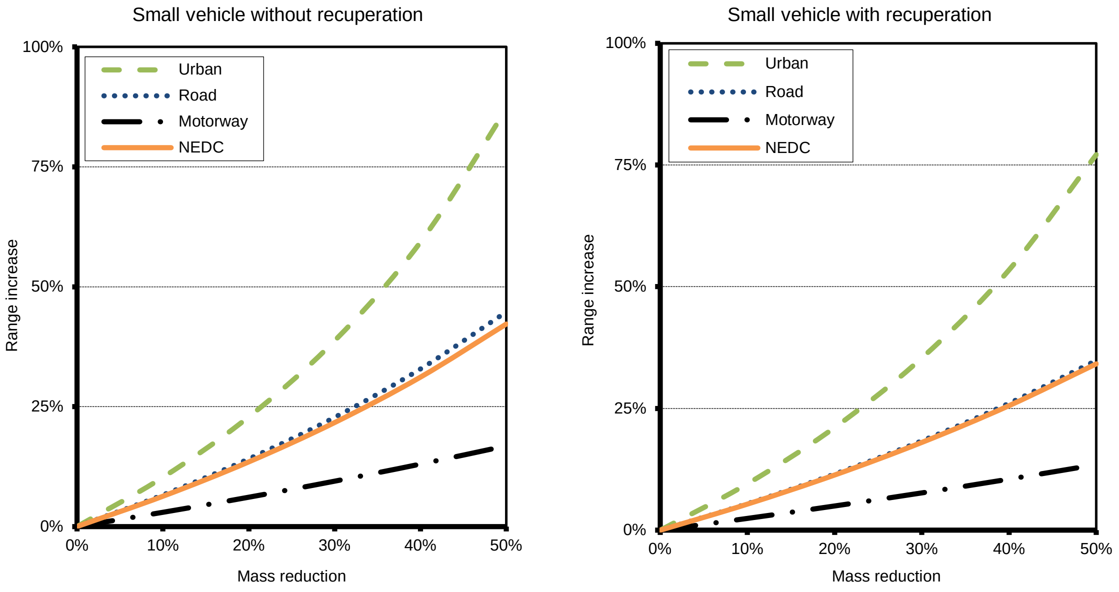

Fig. 1. (a) Increase of range for a small vehicle without recuperation;
(b) Increase of range for a small vehicle with recuperation.

1.3. Mass distribution in the vehicle

From the example of the study by Lotus Engineering in 2010 (“An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Program”) it is clear, that the chassis with brakes and wheels in its present form carries a similar part (24%) of the total weight, compared to body and drivetrain (each about 24% on the Toyota Venza). Lotus Engineering also assumes, that with the currently available lightweight approaches and materials, a weight reduction of more than 20% can be achieved by 2017 without difficulty. In doing so, the chassis will have increasing importance, as the conventional resources still yield little weight reduction, if the complexity of the requirements persists. A lighter vehicle also means, that the drive and the body can be built more simply and hence lighter (secondary lightweight construction factors).

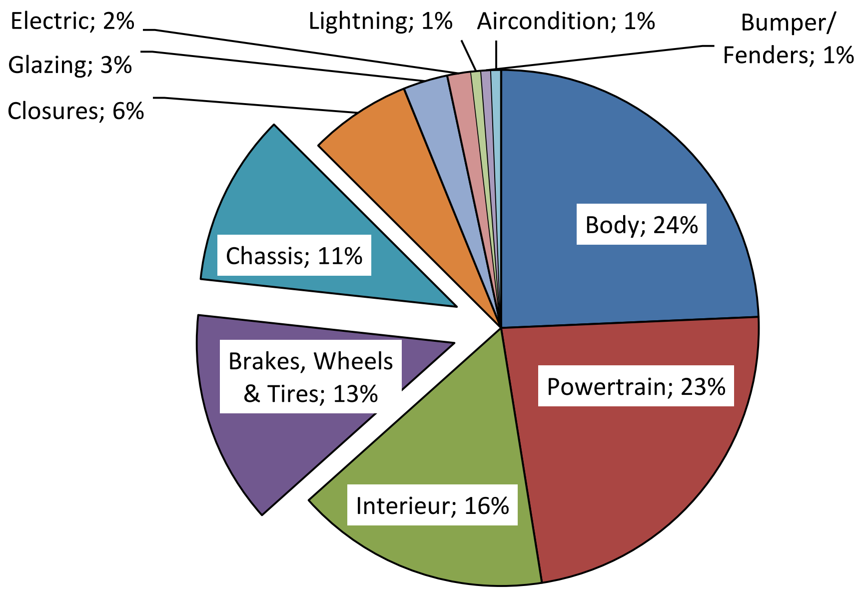

Fig. 2. Mass distribution in the Toyota Venza (Lotus, 2010)

Beyond reducing the weight of the chassis means less mass on the moving axle parts, a better engine response of the vehicle to road unevenness and better driving dynamics, hence greater comfort and increased safety. Comfort, possible load capacity and the handling has improved from generation to generation, as is shown by the example of the rear axle of the Mercedes S Class series W126, W140 and W220. There the weight increased from the first to the second generation by almost 20%. This was mainly due to the change in the chassis principle, from a semi-trailing arm axle to the well-known space link axle with five links, which has been highly praised by the press. During the course of this change, the permitted rear axle load increased by more than 20% and with it also the specific load capacity. In order to counteract the weight spiral, the axle concept for the next generation underwent lightweight design treatment. The weight was reduced by almost 25%, nearly without reducing the permitted rear axle load; the specific load capacity thus also increased by 25%. A detailed overview is given here in the table 2.

Table 2. Development process of the rear axle in the S-Class (Wallentowitz, 2003)

Daimler model	Principle	Weight [kg]	Permitted rear axle load [kg]	Specific load capacity [kg/kg]
MB W126 (1979-1991)	Semi-trailing arm axle	48.8	1120	23.0
MB W140 (1991-1998)	Multilink suspension	57.6	1380	24.0
MB W220 (1998-2005)	Multilink suspension	44.1	1325	30.0

2. Possibilities for lightweight design

2.1. Lightweight strategy

New designs and materials offer designers possibilities for reducing the mass of the vehicle, despite increasing comfort and safety requirements. Generally four basic types of lightweight design, which can combat the weight spiral, are significant (Haldenwanger, 1997).

1. Lightweight design linked to performance requirements
2. Lightweight design from new design concepts
3. Lightweight design from new materials
4. Lightweight design related to changes in body shape

The existing minimum requirements were checked in relation to the requirements for lightweight design, and if necessary modified and superfluous constraints dropped. This formed the basis for a reasonable and optimum lightweight design solution. Building on this, the conceptual lightweight design can exploit further weight saving potential, for example by parts/function integration, modularization or optimization of the package. The most common form of lightweight design to be used is lightweight material design. In the early years of automotive racing history, great store was set on the use of magnesium for car bodies or rims, in order to save weight compared to steel or aluminium. Thus a large part of the body of the Porsche Cisitalia-Monoposto of 1947, also called the Porsche 360, was of 1mm thick magnesium sheet, which was stretched over a tubular steel trellis frame (Ostmann, 2008). Lightweight material design is not limited to one material, which is used everywhere. Ideally the right material should be used in the right places, which leads to multi-material design. Great importance is attached to lightweight body shape design today by using modern FE calculation tools (topology optimization) and this is being used more and more. Here the ideal shape of a component at given loads can be calculated, so that a minimum of material needs to be used. If all four lightweight design types are consistently used in a sensible sequence a weight saving near to optimum can be achieved. To exploit the whole potential, all the parameters, such as material characteristic values, must be known exactly. Here particularly, there is still a need for research into high performance fibre composite plastics, so that these can be used to a greater extent by automotive manufacturers.

2.2. Fibre composite plastics

At a conceptual level, fibre composite plastics possess a high potential for reducing the mass of parts and components. The fibre orientation in the load direction, in combination with function integration, which reduces the number of parts, is a benefit, which has until now been used only seldom in the automotive sector. In addition holistic body concepts in particular, which contain parts designed to match the calculated load path, so that unidirectional fibres can optimally absorb the loads, are still lacking. The integration of plastics into existing production lines, especially if integration into the body structure has to be achieved before painting, is another critical point to look out for. Although there are plastics at the present time, which can survive the high temperatures in cathodic dip-paint coating without damage, these are normally expensive. Suitable joining concepts must also be developed and validated for multi-material design structures. The still high manufacturing costs, due to, among other things, insufficient automation, also make use in large production runs difficult. One reason for this is in comparison to metal working, that long cycle times are required due to the chemical processes in duroplastic resin systems, as used, for example, in resin transfer moulding (RTM). New development trends indicate a considerable reduction in injection times, so that this obstacle will not exist for much longer. A further hurdle in the use of new material systems is also the lack of ability to design parts and components in fibre composite plastics in such a way, as to quickly and accurately predict their failure behaviour. This is essential for the automotive sector. The developments in this material group are proceeding rapidly. The material types are so varied that there will probably not be a comprehensive materials database available in the near future, as there already is for aluminium or steel for example.

3. Alternative materials for the chassis with a methodical procedure for the use of fibre composite plastics

In order to simplify and shorten the development of fibre composite plastic parts, partners from industry and research have cooperated in the BMBF (German Federal Ministry of Education and Research) sponsored “Active Lightweight Construction Chassis project”, known in German by the initials “ALF" (Aktives Leichtbaufahrwerk, Förderkennzeichen: 03X3023C). Here tests were carried out on a generic component made from various fibre matrix combinations, in order to develop a novel integrated chassis using fibre composite plastic.

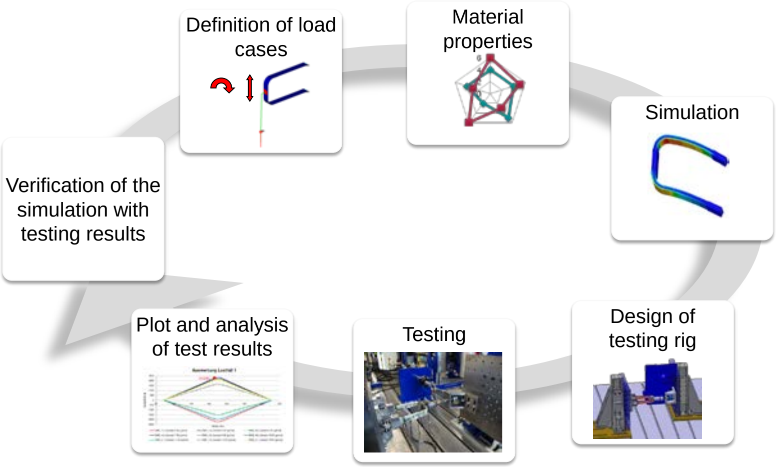

Fig. 3. Development methodology for fibre composite plastic components

A challenge in the numerical design of the chassis and flexural loaded chassis components is the fact, that non-linear states must also be considered, due to the elastic de-formation. To overcome this hurdle, a generic component was designed initially as it might theoretically be in a chassis. In this work a C-shaped bracket, based on a long-short arm rear axle and theoretical material characteristic values, was initially designed. Then load patterns were defined, which could each initiate a controlled failure. The material characteristics, based on test results of flat specimens, were used in a new calculation model. The relatively easy-to-calculate tray models were built up in the same way, as the complex volume models. Here the influence of the impact of component thickness on the calculation process was investigated. The expected maximum loads were then used to design a test rig. The test rig was built and the test pieces produced in a vacuum assisted resin injection (VARI) process. CT images of the critical range of the radius were made for quality control to exclude possible damaged areas, such as air bubbles, before the tests.

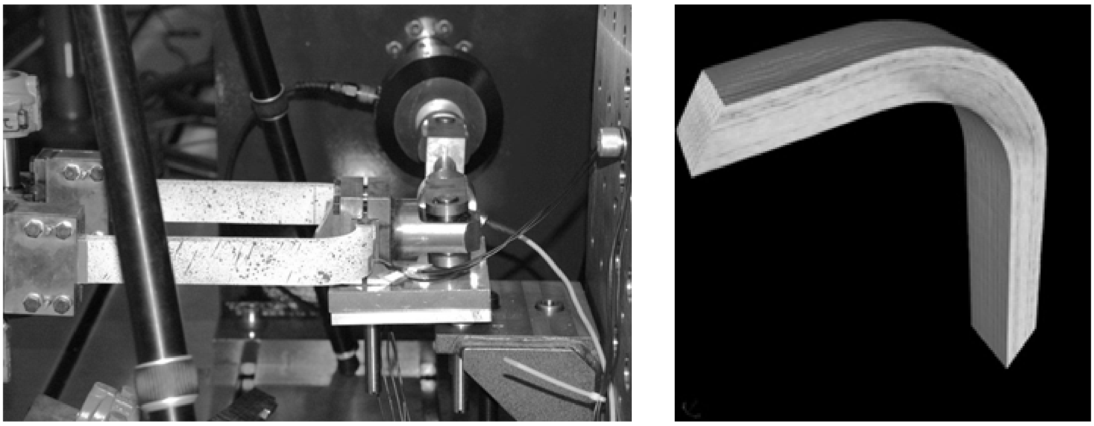

Fig. 4 (a) Test rig with C shaped bracket; (b) CT image of radius

The results were matched to the FE results after the tests had been carried out and are thus validated for the use in the further development of components with this material. Due to the particularly positive damage tolerance, confirmed in the test in which the maximum load was several times higher than for the first case of damage, the fibre composite plastic showed itself to be very well suited for flexural loaded and safety-relevant components. (ATZ, 2011)

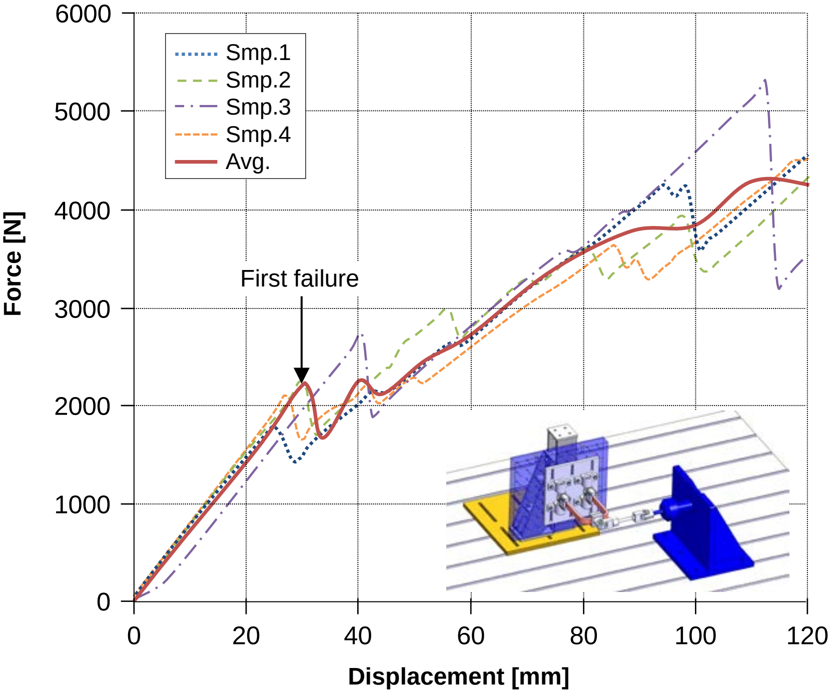

Fig. 5 Force/displacement diagram for load case 1 (ATZ, 2011)

4. Lightweight design concepts in fibre composite plastic

4.1. Concept: Long-short arm

In the development of the long-short arm (sword) concept in fibre composite plastic, all degrees of freedom were first defined. This included in particular the definition of the space available. The arm positions with their maximum movements, the position and dimension of the damper, as well as that of the arm bearing were specified from the driving dynamics simulation. The brake calliper was positioned according to the arm positions and subtracted from the overall model. This gave the maximum available design space, which was further prepared for topology optimisation using the Altair Hypershape/Catia plug-in for the numeric calculation. The three main load cases, available from the driving dynamics simulation, were introduced and weighted set on the bearing locations of the control arms, damper and the brake calliper. The calculation results with Altair Optistruct showed distinct load paths, which were then used for further conceptual design.

As the transfer moulding process of SMC, as well as the thermoforming of GMT are particularly economical and capable of short cycle times, the optimum materials to be used were ascertained, corresponding to their static material characteristic values. A single shell model with strengthening ribs was designed for such a press process and was given typical wall thicknesses, demoulding slopes and radii. For comparison, a two-part shell version was created, which had about the same volume and therefore, depending on the material used, had the same weight. To evaluate the concepts the models were set with different material cards for GMTex, SMC GF50 and SMC CF60 and calculated for the three most important load cases using CATIA V5 static analysis. Typical material characteristic values from semi-finished product producers served as material cards, which used as input for CATIA. The calculations did not serve to validate individual concepts, but only for their evaluation and as an aid to the selection of which concepts with which materials would be further pursued. As a maximum deformation of 0.5 mm in the y-direction, transverse to direction of travel, is permissible in the bearing locations to ensure safe handling, this was weighted as the main criterion for the analysis using a factor of 3. The other two criteria, weight and permitted tension, were allotted a factor of 1. After analysing all combination possibilities, the two-part shell SMC-CF60 concept was shown to be the most promising. The permitted tensions lay within the calculated maximum values except for some details, and the concept still offers optimisation potential for the final design. Only in load case 3 were the maximum displacements almost not maintained. This, however, can be solved by appropriate action in the following detailed design.

Table 3. Criteria for evaluation of concepts and materials

Criteria	Value smaller than			
Rating	1	2	3	4
Mass	▨			
Acceptable stress	100%	80%	50%	15%
Max. Displacement	2.0mm	1.00mm	0.7mm	0.5mm

Table 4. Rating of criteria

Ratings			
Mass	1		
Load case 2	1	Stress	1
		Displacement	3
Load case 3	1	Stress	1
		Displacement	3

Table 5. Comparison of sword designs

		Quality rating					
			Load case 2		Load case 3		
		Mass	Stress	Displacement	Stress	Displacement	total
One shell	GMTex	100%	0%	0%	0%	0%	33.3%
	SMC GF50	25%	50%	0%	50%	0%	16.7%
	SMC CF60	75%	75%	25%	75%	50%	56.3%
Two shells	GMTex	100%	50%	0%	25%	0%	39.6%
	SMC GF50	25%	75%	25%	50%	0%	25.0%
	SMC CF60	75%	75%	100%	75%	50%	75.0%

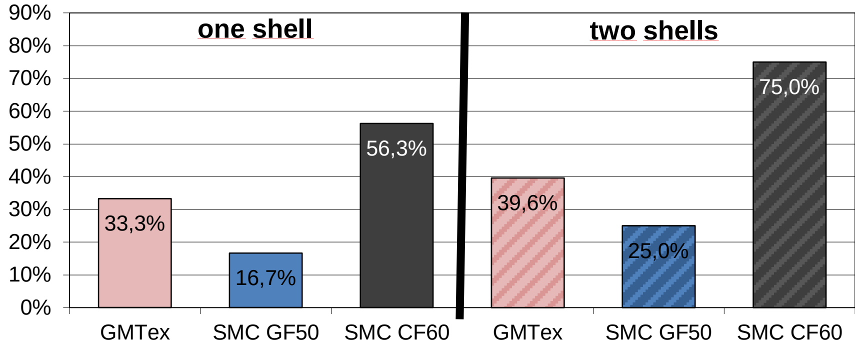

Fig. 6 Evaluation of sword concepts

4.2. Concept: front axle

The aim of this concept is the weight reduction of an existing front axle by function integration and the suitable choice of material. Based on the Renault patent (EP0436407, 1993), the lower wishbones of the suspension, to which the wheel mounts are attached, were joined together as a spring element. This transverse leaf spring assumes the role both of a spring and also provides wheel guiding properties, which means that the coil springs on the dampers can be dispensed with. Using a bearing, rotatable on both sides, the spring can also perform a stabiliser function, so that this is no longer required. For initial sizing of the transverse leaf spring a theoretical approach was chosen.

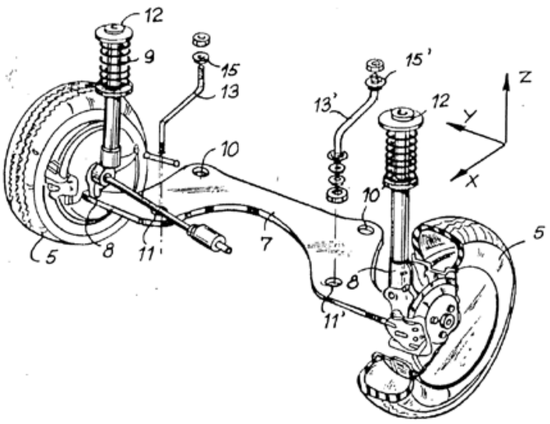

Fig. 7 Wheel guiding structure (EP0436407, 1993)

For this the synchronous (c_{ss}) and the reciprocal (roll rate, c_{rs}) spring constants were calculated using the following two formulas (Chang, 2006):

$$\frac{1}{c_{ss}} = \frac{L_1^2 \cdot L_2}{2E \cdot I_2} + \frac{\emptyset \cdot L_1^3}{3E \cdot I_1} \tag{3}$$

$$\frac{1}{c_{rs}} = \frac{L_1^2 \cdot L_2}{6E \cdot I_2} + \frac{\emptyset \cdot L_1^3}{3E \cdot I_1} \tag{4}$$

$\emptyset$ is a shape factor, that is defined by the ratio b_1 to b_0 for the trapezium shape of the arms. At a closer look it is obvious, that by an increase of the arm length L_1 spring rate as well as the roll rate decrease, although the roll rate decreases less fast due to the factor 6 instead of the factor 2 in the first term of the corresponding equation.
All geometrical parameters are described in the following sketch:

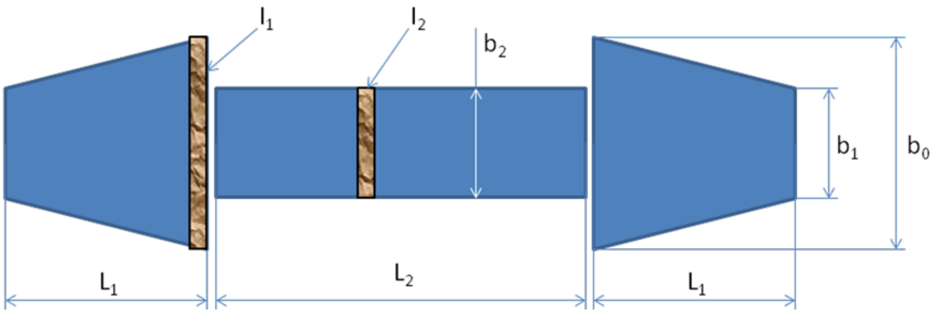

Fig. 8 Schematic diagram of transverse leaf spring

By specifying the space available based on the chassis geometry, spring characteristic values, the arm length and the track width, the remaining values can be generated. A fibre composite plastic with unidirectional fibre orientation was selected as the material for the leaf spring, as the expected main loads impact on the vehicle in the transverse and vertical directions. The material characteristic values for the pre-dimensioning were taken for generally accepted epoxy glass fibre composite (E-Glass, 60%vol) from trade literature. The values found were used in the different concepts and were then rated. After selecting the best concept, this was then detailed and the remaining components designed. As transverse forces are conducted through the leaf spring, the sub frame can be designed to be correspondingly lighter and simpler. The concept created was then finally tested using static FEM simulation in CATIA for its load bearing capacity.

5. Conclusion and outlook

In the development of drive and vehicle concepts for tomorrow’s vehicles considerable diversification will take place in comparison to today’s universal vehicles with ranges of up to 1000 km. In the process it can be expected, that three vehicle concepts will share a large part of the market. One is the universal vehicle as now with ranges of up to around 800 km with internal combustion engine hybrids and, for example, a ~50km pure electric range. Then a distinct long distance vehicle with ranges up to 1000 km, but unlike the universal vehicle, without zero emissions capability, unless it is as fuel cell vehicle with hydrogen as the energy source. Finally as a last group, the city vehicle with ranges up to ~200km, which will be completely electrically operated.

Especially with regards to the energy needs and the increase in range and the conservation of resources, all means available must be harnessed to make the vehicle lighter. In the chassis area substantial mass can still be saved without forfeiting safety. Fibre composite plastics with active systems offer themselves here to exploit the still available potential and to ensure sustainable mobility.

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