LIGHT-WEIGHT DESIGN CHANCES USING HIGH-STRENGTH STEELS

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ABSTRACT

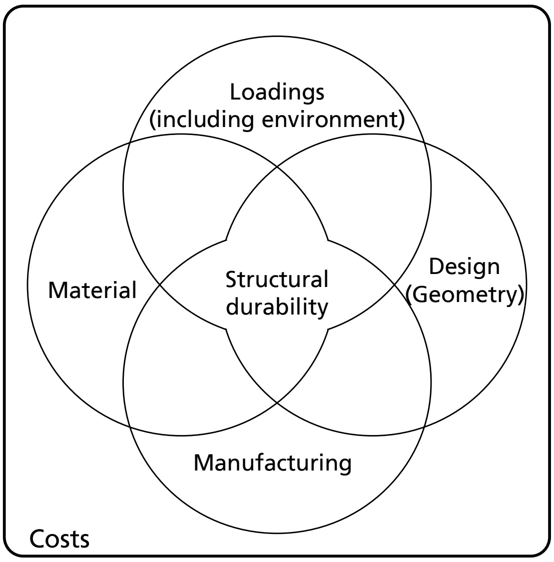
In order to make effective use of high-strength steels for designing light-weight structures, it is necessary to consider the interaction between the service loading, material properties, geometry and manufacturing technology. This interaction determines durability. The fatigue performance of high-strength steels can be better exploited if high stress concentrations are reduced through geometry improvement and manufacturing process control. With regard to their capability for high energy absorption, high-strength steels offer the best solutions for designing against impact loads and crash. These advantages of high-strength steels are realised in modern vehicle structures through the multi-material concept, where materials selection is made according to expected service loads and locally required strengths.

KEYWORDS

Structural durability light-weight design, high-strength steels, multi-material design, material substitution

INTRODUCTION

Light-weight design is not only a question of the strength level of materials to be used, but is more an interaction of material properties together with the loading, geometry, manufacturing technology and, last but not least, the costs. Fig. 1 identifies that these factors interact to influence the structural durability of components [1].



Ref.: V. Grubisic and C. M. Sonsino

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Fig. 1: Parameters influencing the structural durability of components

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Within this interaction, different light-weight design concepts, Fig. 2, may be generated by selection as well as combination of geometry, manufacturing technology and material

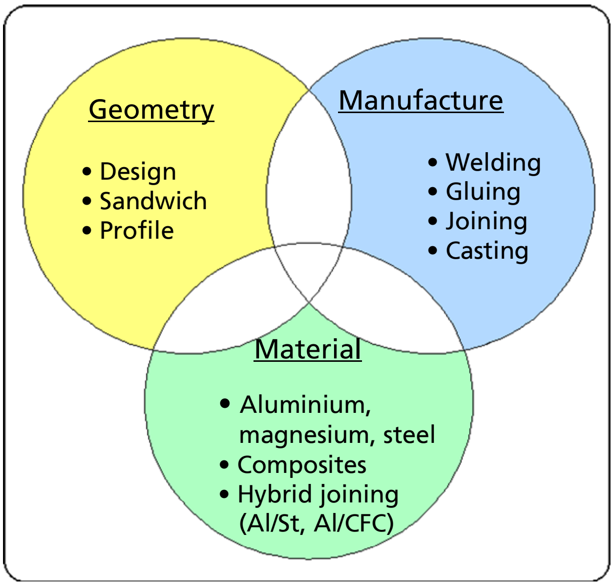

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Fig. 2: Light-weight design concepts

This paper will discuss the importance of these parameters, will show the criteria for material substitution, will present modern light-weight design concepts of the vehicle, especially of the automotive industry, and will close with future perspectives with regard to material selection.

1. INTERACTING PARAMETERS OF LIGHT-WEIGHT DESIGN

1.1. Comparison of materials with regard to stiffness, stability and costs

Stiffness and buckling are important criteria for the design of frames, crane booms, telescopes, Figs. 3 and 4.

DIA 7453e

Fig. 3: Applications in advanced high-strength steels

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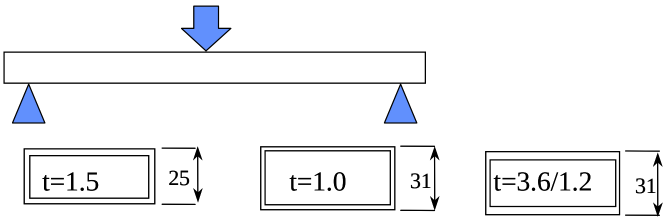
Ref: J.-O. Sperle

DIA 7455e

Fig. 4: Design of compression flange for increased buckling load in extra high-strength steel

A comparison of rectangular profiles of three different materials but with equal stiffness (here deflection), Fig. 5, reveals a higher loading capacity for aluminium, due to the larger length and thickness, and a lower weight, due to the lower density, but almost four times higher material costs compared with mild and high-strength steel profiles. Thus, by using a high-strength steel, through an increase of height and reduction of thickness, both weight and costs are reduced.



Section
Width 45 mm

Steel grade	Mild Steel	HS Steel	Aluminium (Extr.)
Yield strength	220 MPa	350 MPa	170 MPa
Stiffness	**1**	**1**	**1**
Loading capacity*	1	1.02	2.0
Weight	1	0.73	0.65
Material cost	1	0.88	3.7

****) Buckling considered***

Ref: J.-O. Sperle

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Fig. 5: Weight and cost comparison for equal stiffness under bending

A significant weight reduction can always be obtained, if the thickness is reduced, but to keep the same stiffness, an increase of the outer dimensions is necessary. In Fig. 6 this is demonstrated in the example of tubes of mild and high-strength steels. The increase of the outer diameter at reduced thickness also improves the bending loading capacity.

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	Mild	High	High
Yield Strength MPa	220	500	500
Diameter mm	80	80	100
Thickness mm	2,0	1,0	1,0
Loading Capacity in Bending*	1	1	1,42
Relative Stiffness	1	0,52	1
Relative Weight	1	0,5	0,6

*) Buckling considered

Ref: J.-O. Sperle

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Fig. 6: Structural tubes - loading capacity and stiffness comparison between mild steel and high-strength steel

The cost issue is always an important argument in materials selection and was already addressed in the example of the rectangular profiles in Fig. 5. Fig. 7 compares material costs related to weight for high- and higher-strength steels with aluminium, magnesium and fibre-reinforced composites. Steels have competitive advantages over light-weight alloys and composites not only with regard to material costs, but also in terms of manufacturing costs.

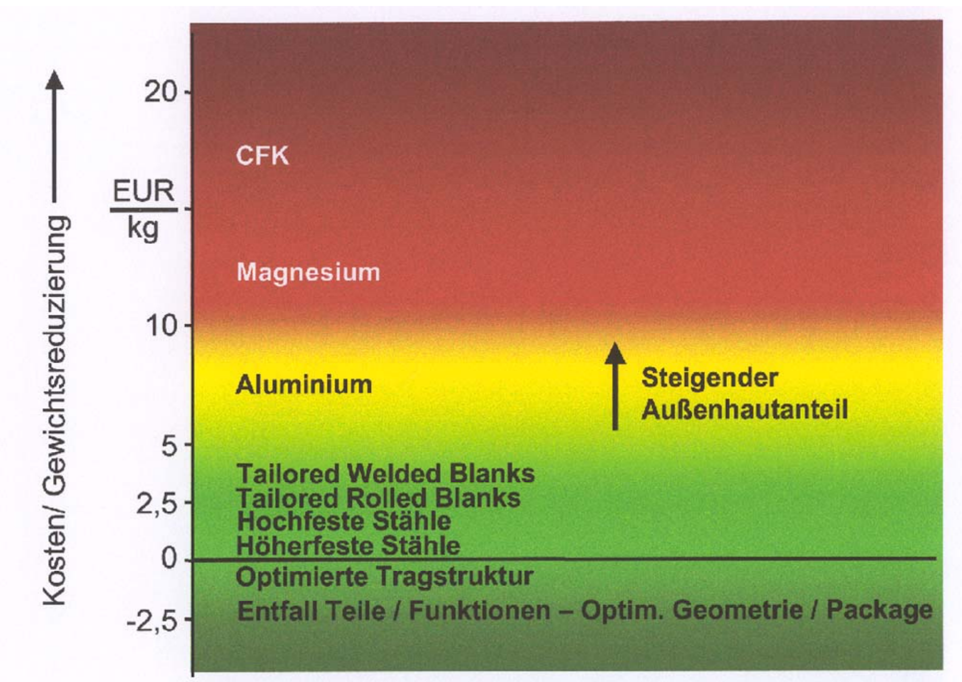

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Fig. 7: Material costs for weight reduction

The resulting question is how much extra costs can be afforded in order to reduce weight, Fig. 8. This question can be answered only by the market using life-cycle considerations.

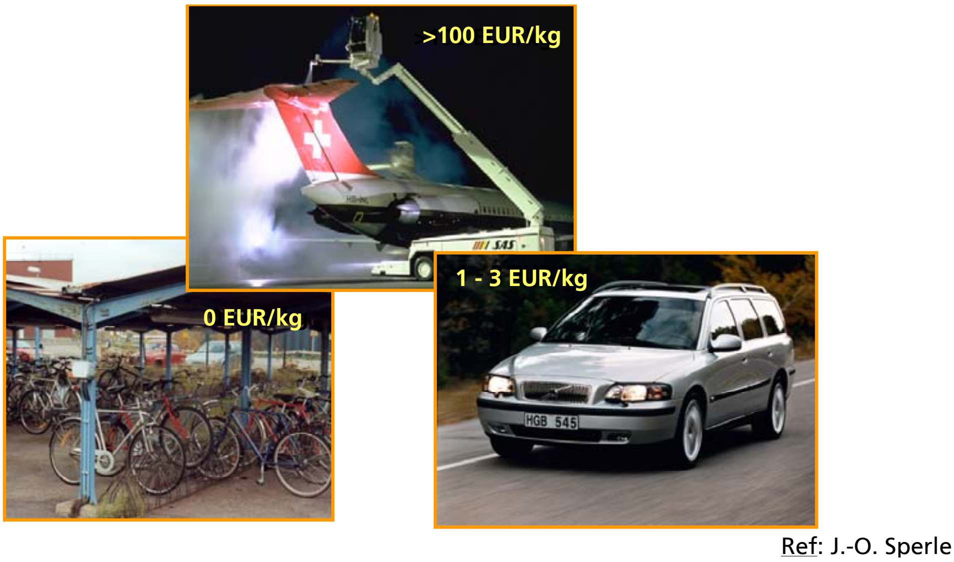

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Fig. 8: How much can we afford to reduce weight?

1.2. Consideration of Loads

1.2.1. Impact

According to the partition of structural durability, Fig. 9, materials have to be assessed on the basis of the anticipated loading.

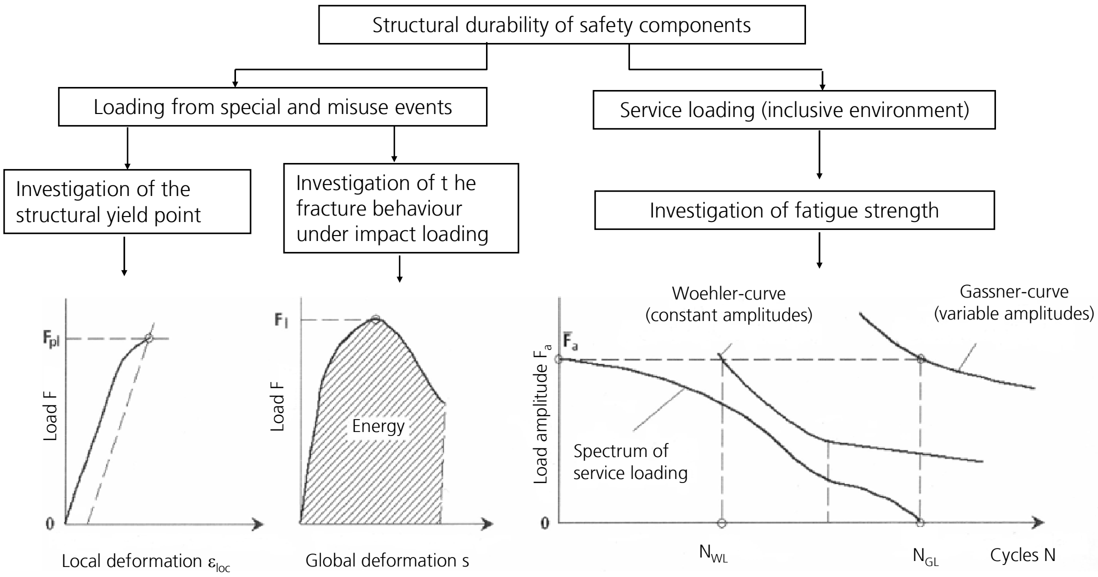

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Fig. 9: Partition of the structural durability of safety components

Sufficient ductility to provide the required energy absorption against impact loading and, in the extreme, against crash can be achieved only with high-strength steels. Fig. 10 shows the relationship between the impact load required for total rupture of artificially cracked stub axles of commercial vehicles as a function of the relative crack depth. The higher the material strength,

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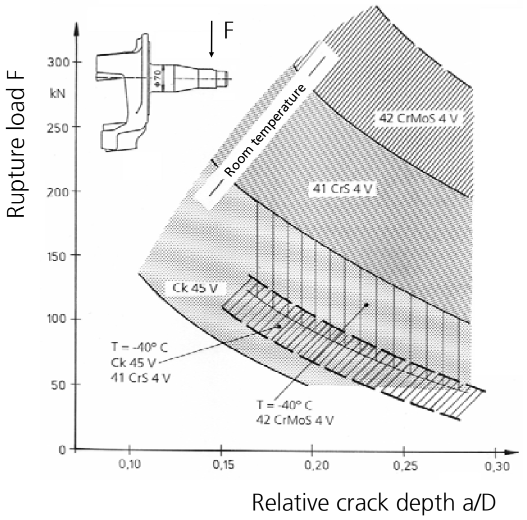
especially with regard to the yield strength, the higher is the rupture load [1, 2]. However, low temperatures reduce the impact resistance significantly [2].



Material \ Data	R_m in MPa	$R_{p0.2}$ in MPa	A_5 in %
Ck45V (SAE1045)	840	540	> 20
41CrS4V (SAE 1041)	920	700	13
42 CrMoS4V (SAE1042)	930	770	14

Load velocity: v = 7 m/s

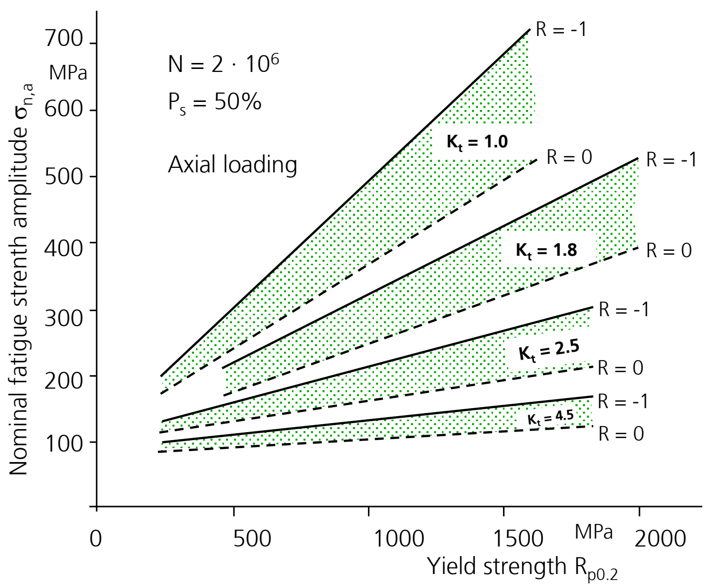
DIA 4508e

Fig. 10: Rupture load as a function of crack depth and temperature

1.2.2. Fatigue

As far as fatigue behaviour is concerned, under constant as well as under variable amplitude loading for unwelded material states, benefits of high-strength steels can be taken only in the case of low stress concentrations [1].

Fig. 11 displays the fatigue behaviour of different steel grades for plates and forgings and Fig. 12 the behaviour of thin automotive sheets as a function of material strength and stress concentration for constant amplitude loading. The knowledge from these figures is also valid for spectrum loading. If the stress concentration is too high, the design cannot be improved by selecting a higher grade.



Material	$R_{p0.2}$ [MPa]	R_m [MPa]
St 37	255	390
C 45	334	576
St 52	400	560
42 SiMnVS 3	478	777
49 MnVS 3	520	790
50 CrV 4	675	865
41 CrS 4	680	845
30 CrNiMo 8	740	840
42 CrMo 4	840	910
1.6604.5	1020	1150
42 CrMo 4	1029	1097
70 Si 7	1162	1294
1.7704.6	1190	1315
38 NiCrMoV 7 3	1504	2026
X 2 NiCoMo 18 7 5	1785	1885
60 SiCr 7	1990	2227

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Fig. 11: Fatigue strength of different forged or rolled steels as a function of the notch factor K_t

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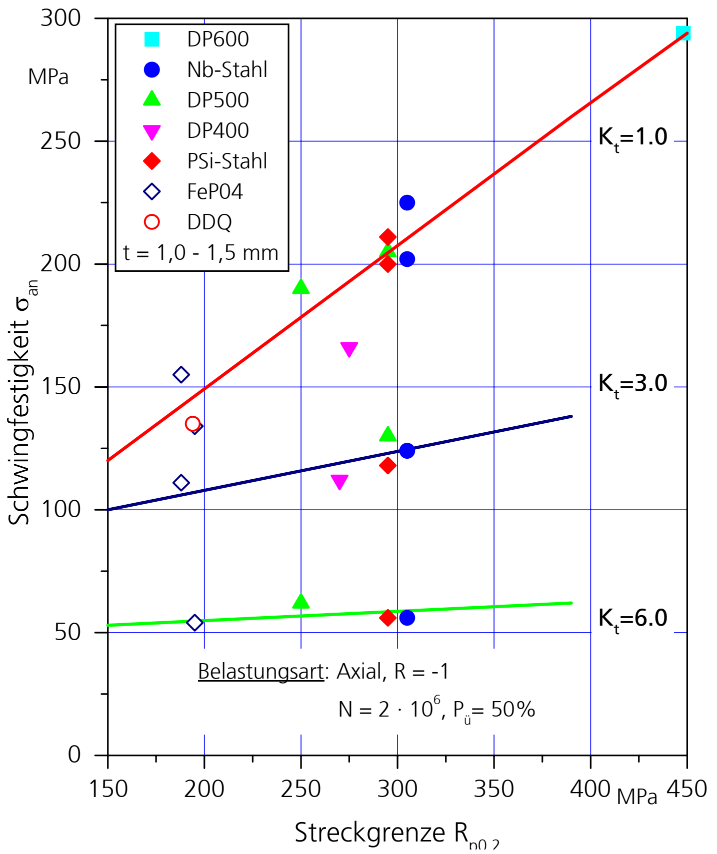

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Fig. 12: Fatigue strength of thin steel sheets for automotive applications as a function of the notch factor K_t

Also in the as-welded state no benefit of higher steel grades can be observed [3], Fig. 13. Therefore, fatigue design codes for welded structures do not distinguish between steel grades. An improvement may be expected if the weld toe radius can be improved.

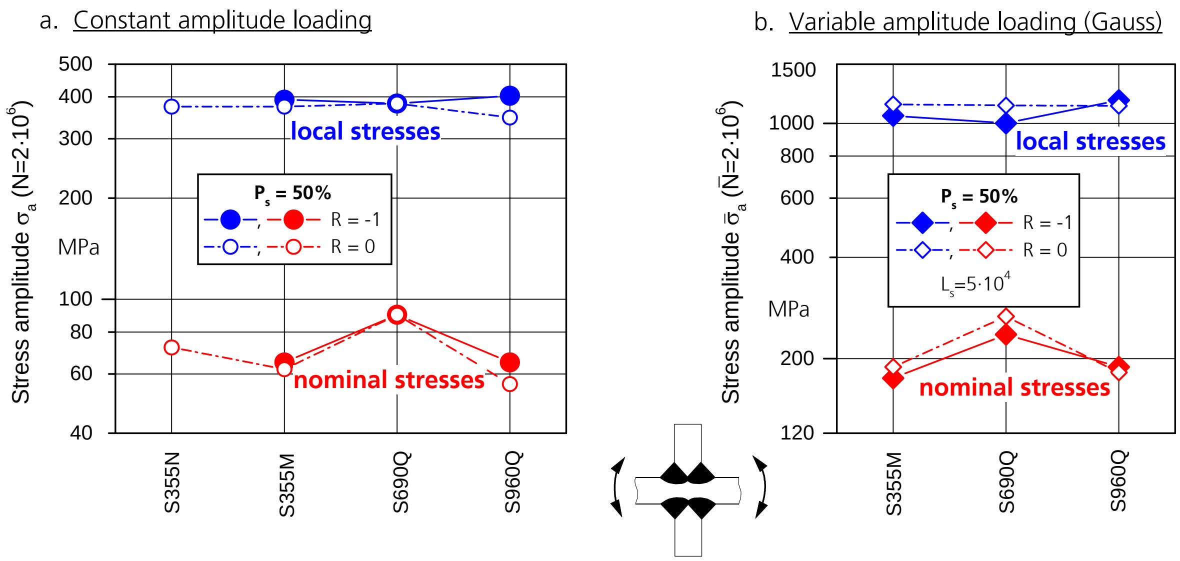

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Fig. 13: Fatigue strength of transverse stiffeners with a thickness of 30 mm

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In addition to the notch sensitivity of high-strength steels,an increased mean-stress sensitivity, i.e. the grade of decrease of endurable stress amplitude in the presence of a tensile mean stress, with increased strength is also observed [1], Fig. 14. This increased mean-stress sensitivity is related not only to the material's strength, but also to its ductility. The mean-stress sensitivity is defined for tensile loading, but, in the case of compressive mean stresses, high-strength steels reveal a larger increase of endurable stress amplitude than mild steels due to the higher mean-stress sensitivity.

In comparison to light-weight alloys, steels generally possess a lower mean-stress sensitivity [1].

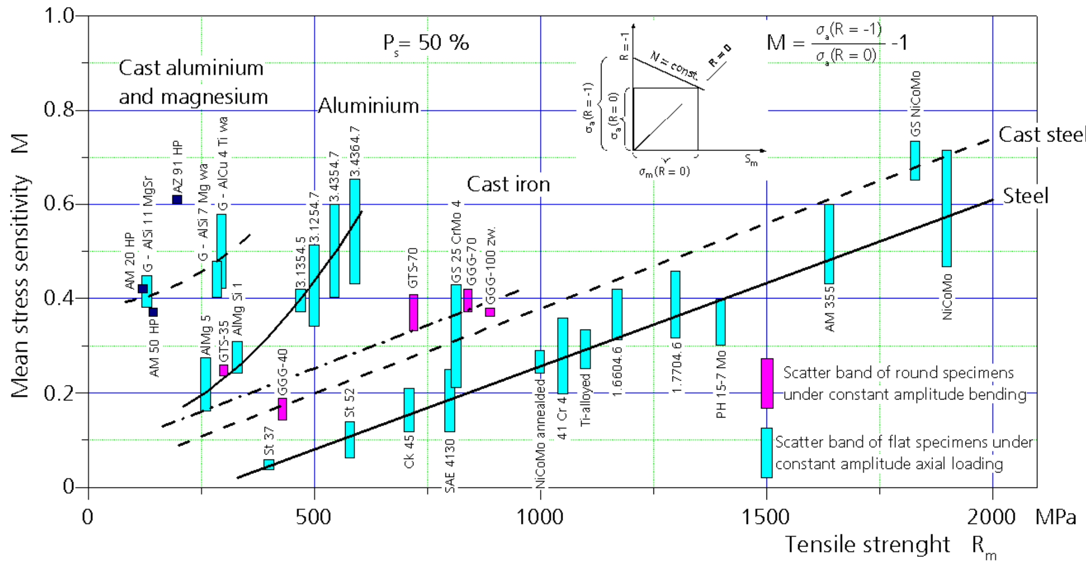

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Fig. 14: Mean stress sensitivity of some metallic materials

Despite these restrictions with regard to the higher notch and mean-stress sensitivities of high-strength steels, there are different design and manufacturing possibilities, which can be used to take advantage of the higher strength. These possibilities will be presented in the following sections.

1.2.3. Spectrum loading

In addition to the material aspects discussed above, a peculiarity should be mentioned of spectrum loading as it occurs on vehicles, Fig. 15, aircrafts, ships, plant components, with regard to light-weight design.

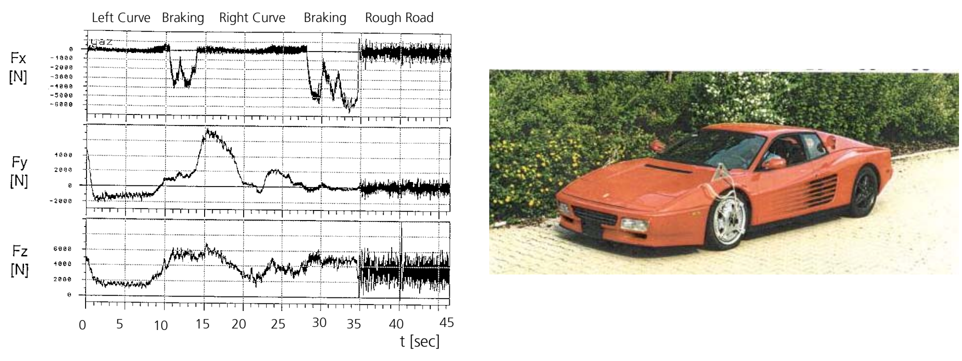

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Fig. 15: Wheel forces under different maneuvers sensed with velos 8J x 18 – Ferrari Testarossa

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A knowledge of the spectrum shape and the position of the resulting Gassner-line is the most important information for light-weight design [4]. Fig. 16 displays that at a required fatigue life of e.g. 10^8 cycles for a given maximum load, the constant amplitude fatigue strength is exceeded by a factor of 1.5 under the Gaussian spectrum and by a factor of 1.9 under the straight-line spectrum. This allowance of higher stresses than constant amplitude data enables the reduction of cross-sections and consequently of weight [4].

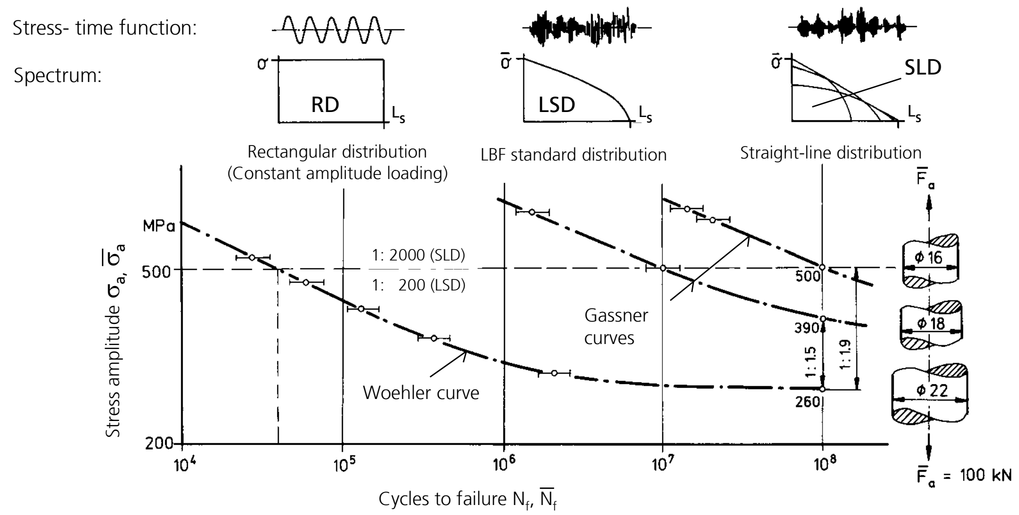

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Fig. 16: Influence of spectrum shape on fatigue life and component dimensions

The straight-line spectrum observed for steering rods , Fig. 17, halves the component weight compared with a constant amplitude design.

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Fig. 17: Chassis and steering rod

This knowledge is also applicable to welded structures. In Fig. 18 it is shown how the plate dimensions of a high-strength transversal steel stiffener can be reduced on the basis of the spectrum shape.

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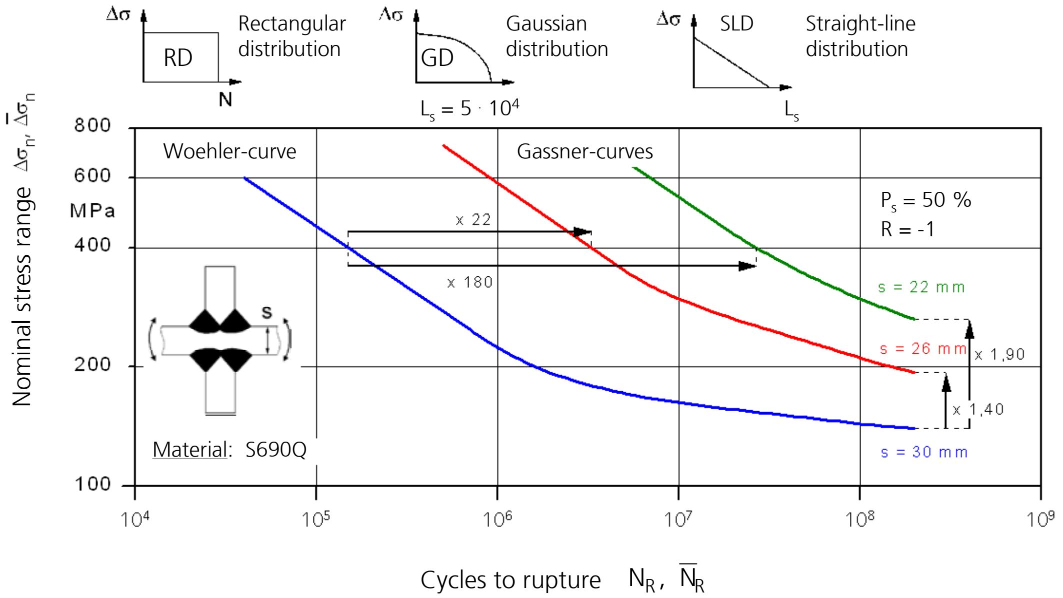

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Fig. 18: Influence of spectrum shape on fatigue life of a transversal stiffener

1.2. Light-weight design by geometry

The influence of geometry, especially notches, has been discussed already in terms of its interaction with material strength, Figs. 11 und 12. It was pointed out that the only way to exploite material strength better is through geometrical improvement. In addition to a local geometrical improvement, i.e. increase of notch radius, an effective method is to move critical stress concentrations from highly stressed areas into lower stressed ones by design. This can be achieved, e.g. in the case of offshore K-nodes, by introducing high-strength cast steel inserts with sufficiently large radii into the critical area and moving the V-butt weld to a lower stressed area, Figs. 19 and 20 [5].

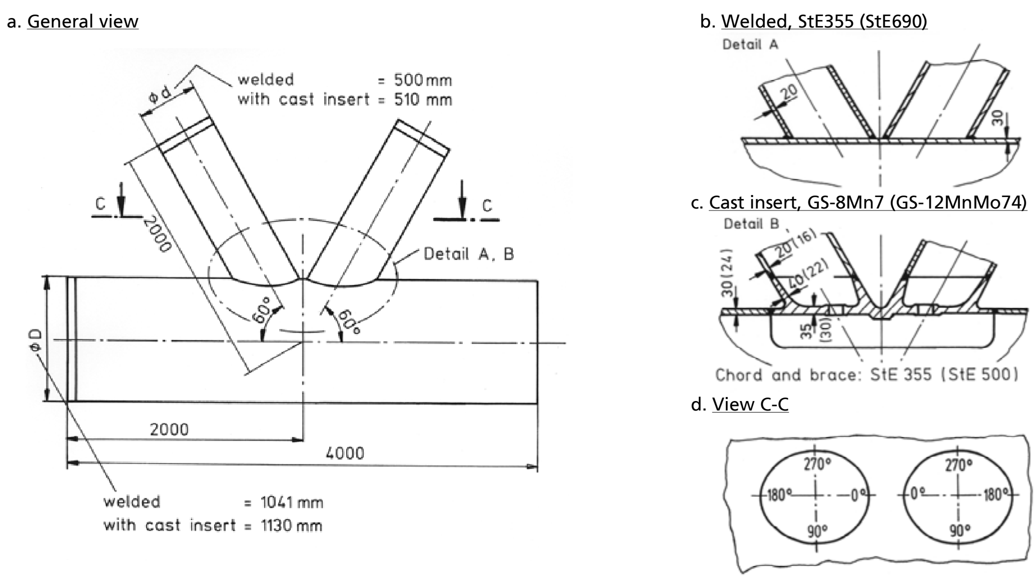

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Fig. 19: K-nodes

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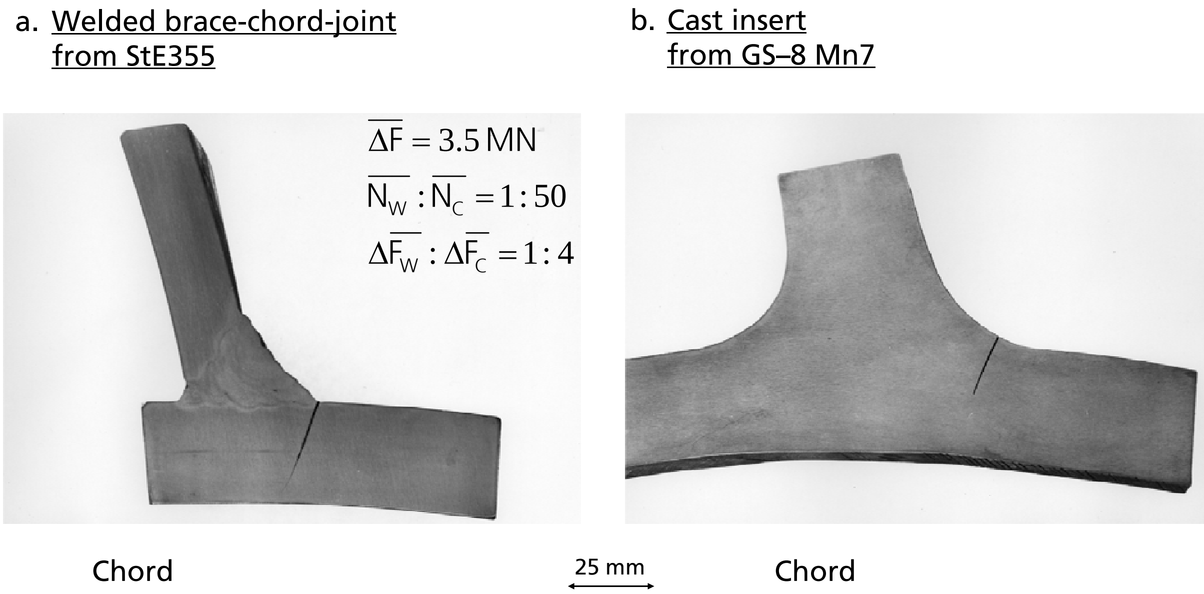

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Fig. 20: Cracks in the critical area of K-nodes

The increase of the loading capacity under variable amplitude seawave loading by about a factor of four for 25 years service, Fig. 21, also enables the construction of hybrid offshore rigs for higher bending moments at deeper waters, Fig. 22, without increasing the thickness and therefore benefiting from the high tensile strength of high-strength steels [5].

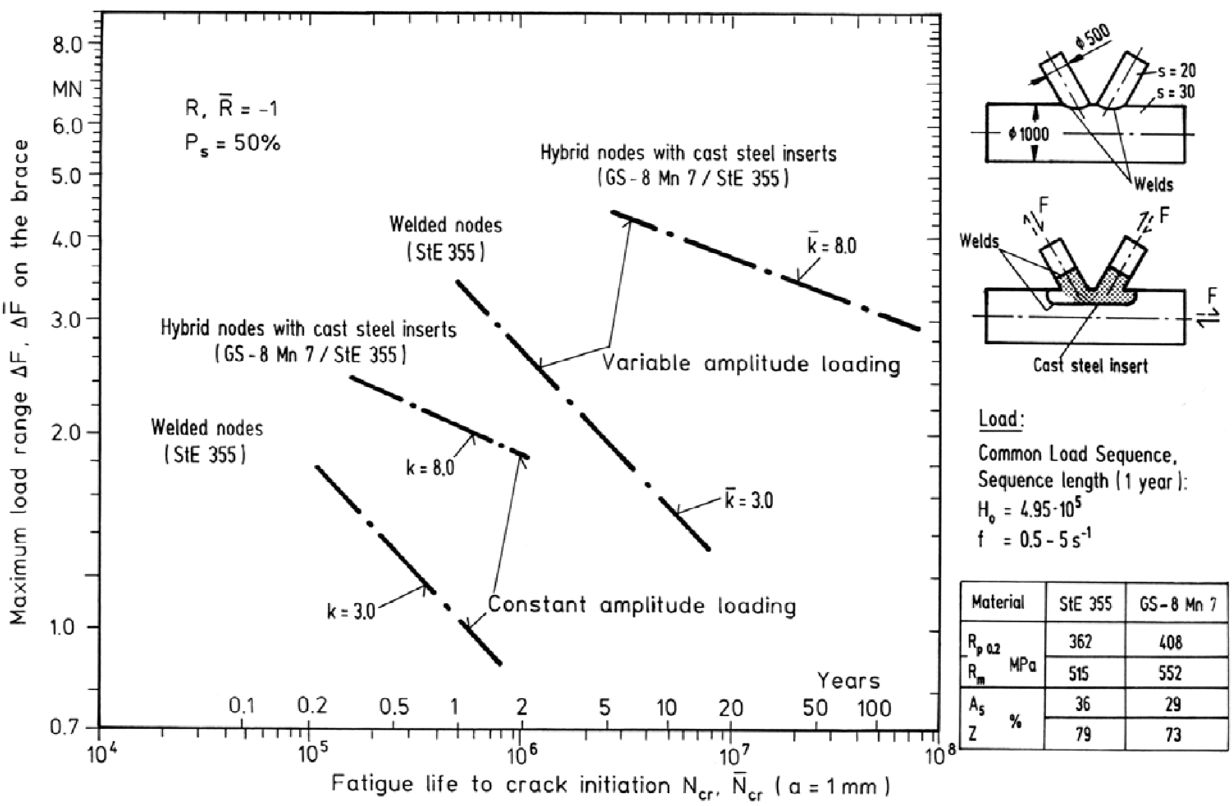

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Fig. 21: Fatigue life to crack initiation of tubular K-nodes under artificial seawater

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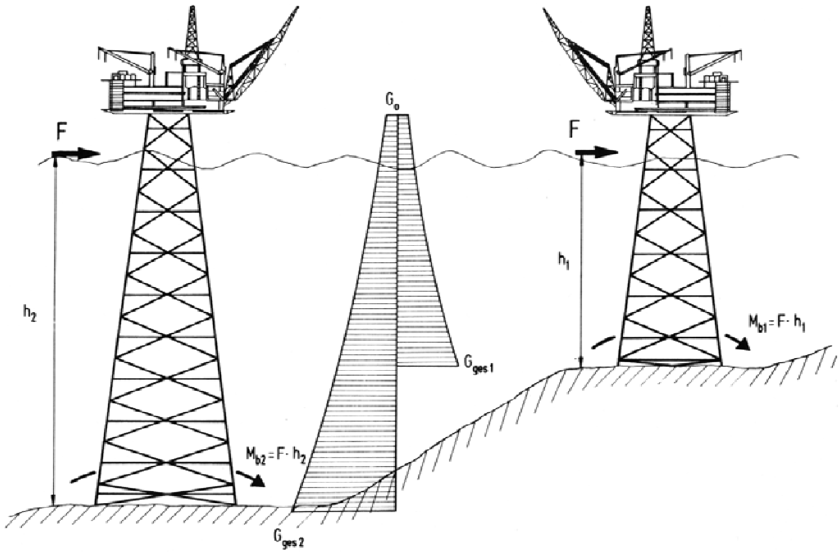

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Fig. 22: Weight distribution and maximum bending moments of offshore-structures in different sea depths

1.4. Light-weight design by manufacturing technologies

As mentioned in section 1.2.2 and displayed in Figs. 11 and 12, the selection of a high-strength material will not improve the fatigue strength of a component in the presence of a high stress concentration; an improvement must be sought first by a reduction of the stress concentration. However, because of geometrical constraints this is not always possible. In such cases, an additional mechanical surface treatment, i.e. shot peening or surface rolling, can increase the fatigue strength significantly, especially when the treatment is applied to a high-strength material. Due to the higher yield strength the beneficial compressive residual stresses generated in high strength materials are higher than in lower strength steels. As a consequence of this, the selection of a higher strength steel is more advantageous with regard to fatigue strength improvement, as displayed in Fig. 23.

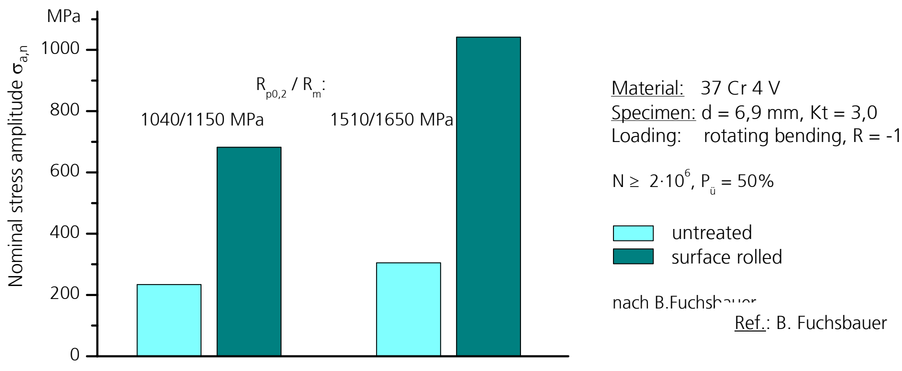

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Fig. 23: Influence of material strength on the increase of fatigue strength due to surface rolling

Surface treatment techniques are applied also to welded joints very effectively, e.g. shot-peening, hammer-peening, ultrasonic impact or ultrasonic peening techniques. Fig. 24 displays the fatigue strength increase obtained by shot-peening of high-strength steels which can be used for a cross-sectional reduction and so for light-weight design [6]. The effectiveness of such treatments of course requires that the weld-toe must be accessible to the treatment.

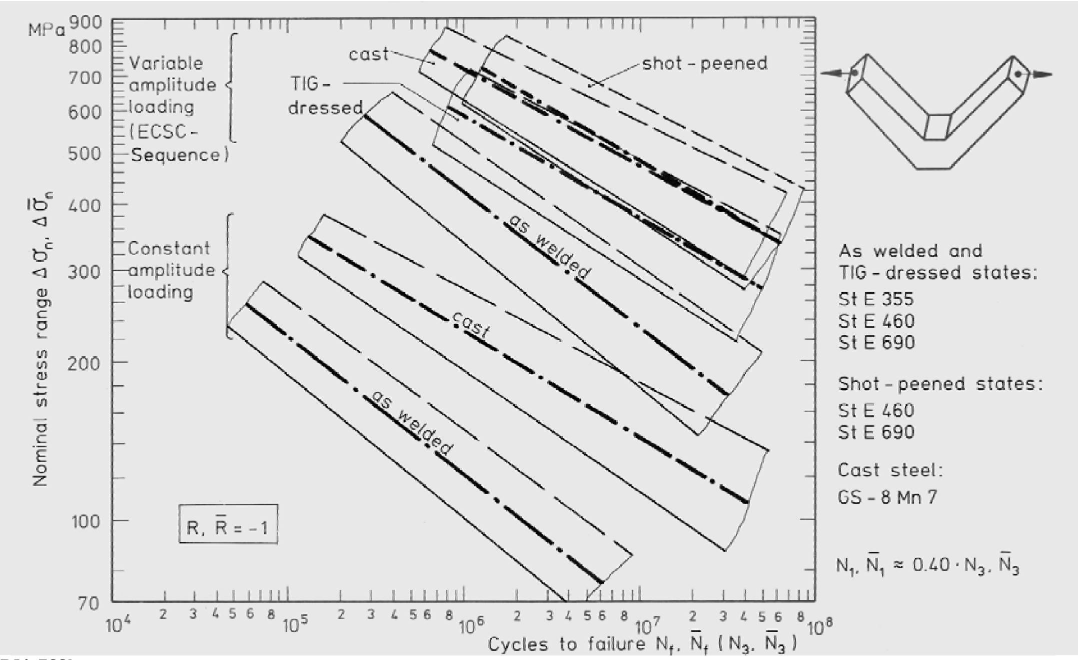

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Fig. 24: Comparison of constant and variable amplitude test results in seawater

Another possibility for fatigue strength increase of welded joints is through local geometrical improvements, e.g. by TIG-dressing [6], Fig. 25. This improvement can be even bigger if, through thermal stress relieving, tensile residual stresses can be removed [6]. However, the fatigue strength increase under variable amplitude loading is smaller than under constant amplitude loading, because at higher stress levels in variable amplitude loading the tensile residual stresses are partially reduced.

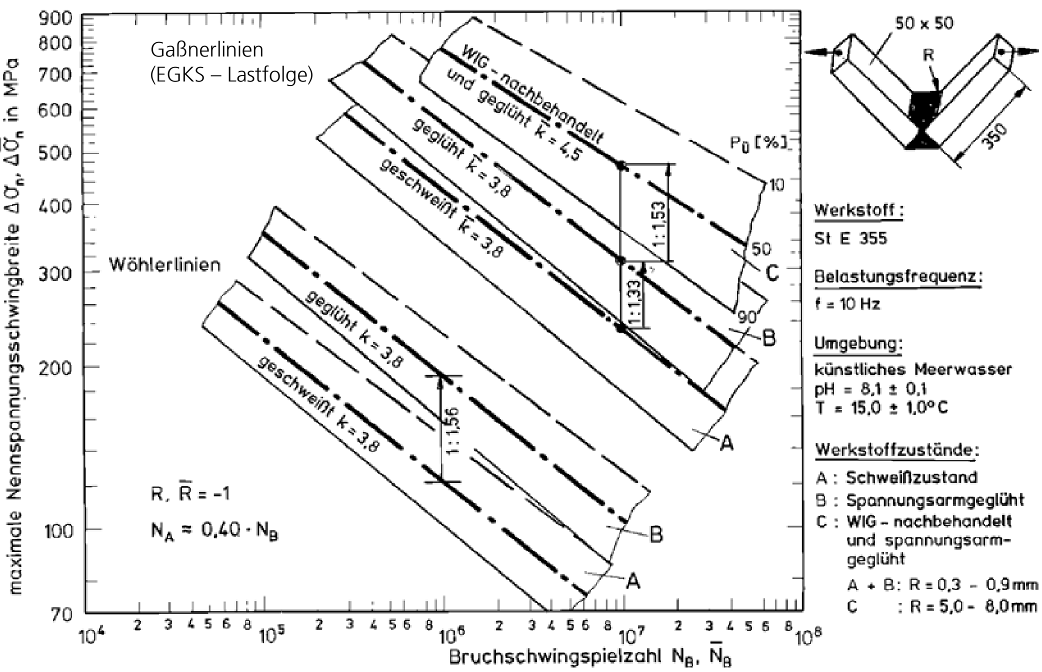

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Fig. 25: Fatigue strength increase by thermal stress relieving and TIG-dressing

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In the manufacture of thin sheet steel vehicle structures, spot welding is now being substituted more and more by laser welding, because, in the case of non-interrupted laser welds, improvements in fatigue strength by a factor of 2 to 5, depending on profile thickness and stiffness, are possible [7], Figs. 26 and 27.

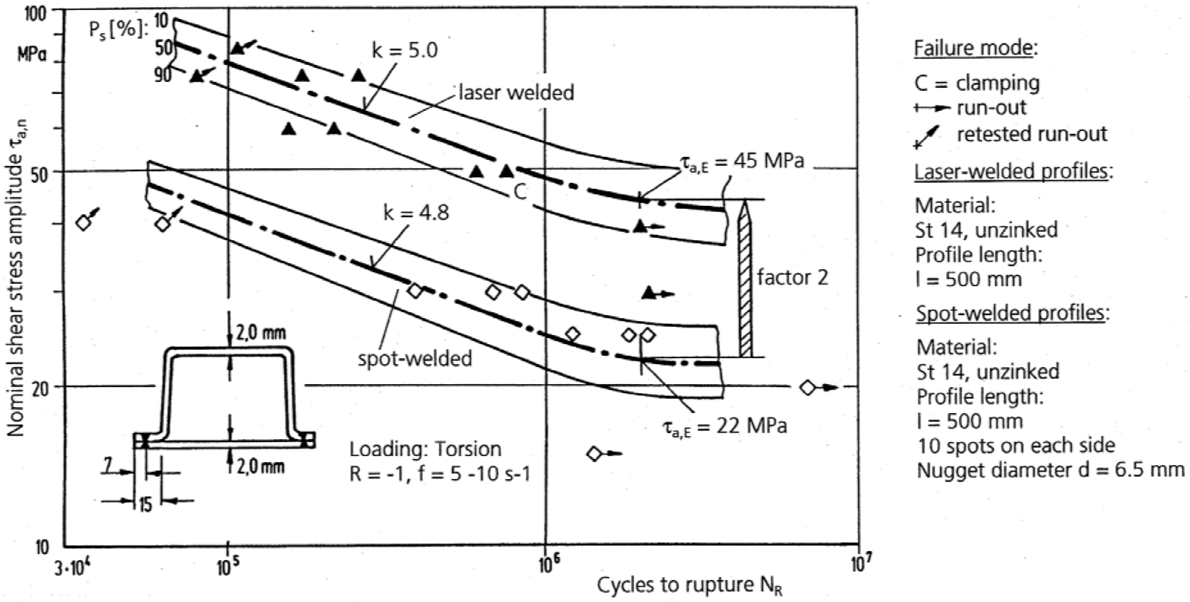

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Fig. 26: Comparison between laser- and spot-welded hat-profiles (sheet thickness 2.0 mm)

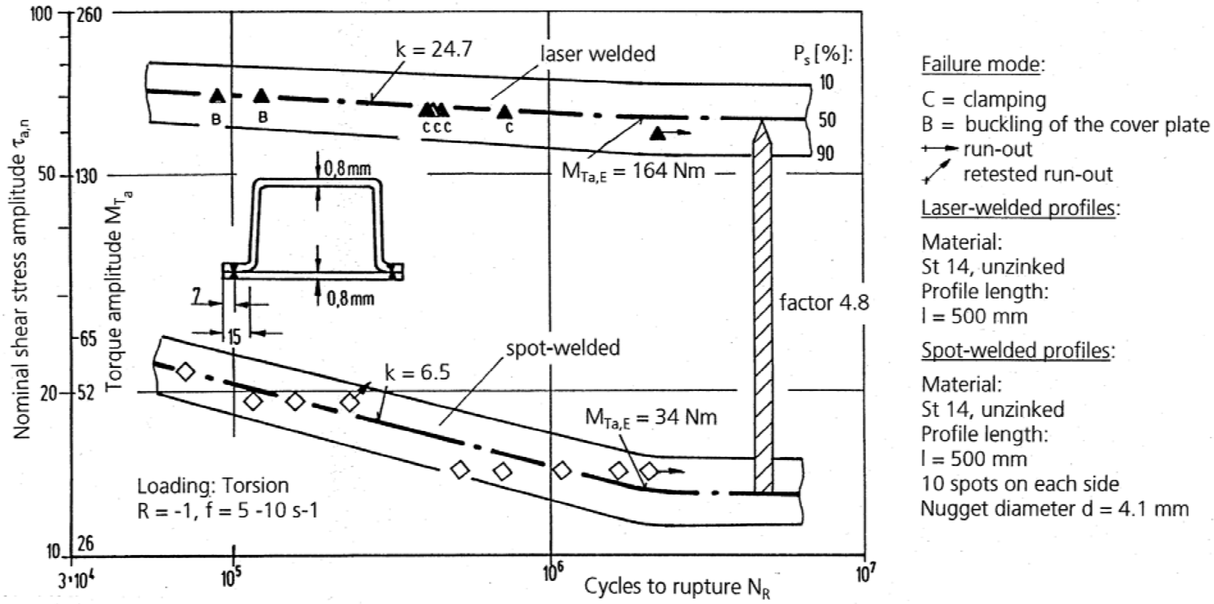

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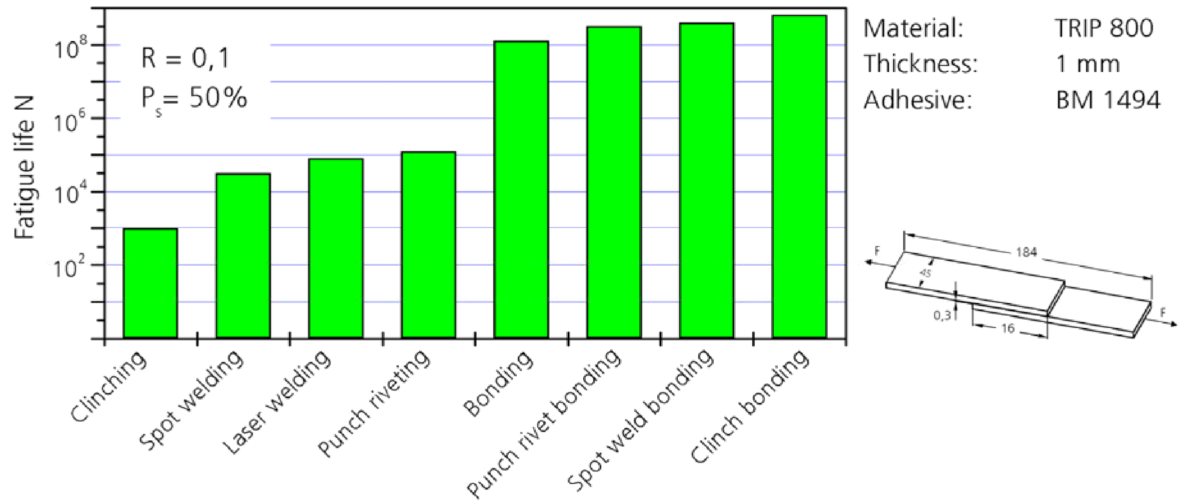
Fig. 27: Comparison between laser- and spot-welded hat-profiles (sheet thickness 0.8 mm)

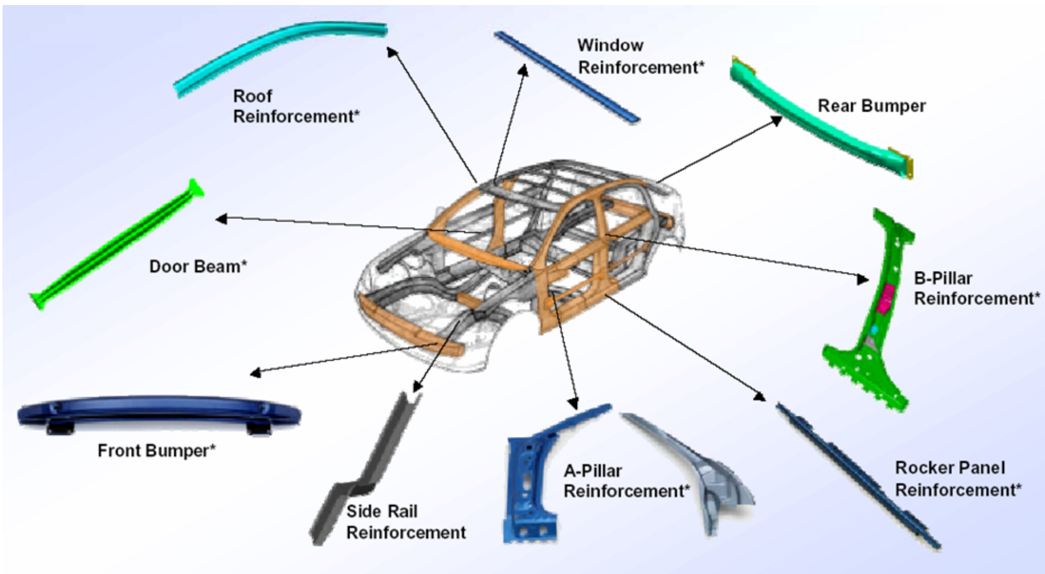


Ref.: R. Jost, DaimlerChrysler AG

DIA 6782e

Fig. 28: Joining techniques and fatigue strength

Also novel forming technologies such as hydro-forming or hot-stamping can lead to an increase of strength, resulting in light weight structures. Fig. 29 shows different structural parts of a car body, for which the production process can transform high-strength steels into ultra high-strength steels.



Ref: Benteler Automobiltechnik

DIA 7404e

Fig. 29: Product examples in ultra high-strength steel

Figs. 30 and 31 present examples of B-pillars and roof frames. Weight is reduced significantly while, at the same time, crash performance and stiffness are optimised. During hot stamping, yield stresses of 220 to 280 MPa for conventional steels can be increased up to 1000 to 1200 MPa, resulting in thinner profiles.

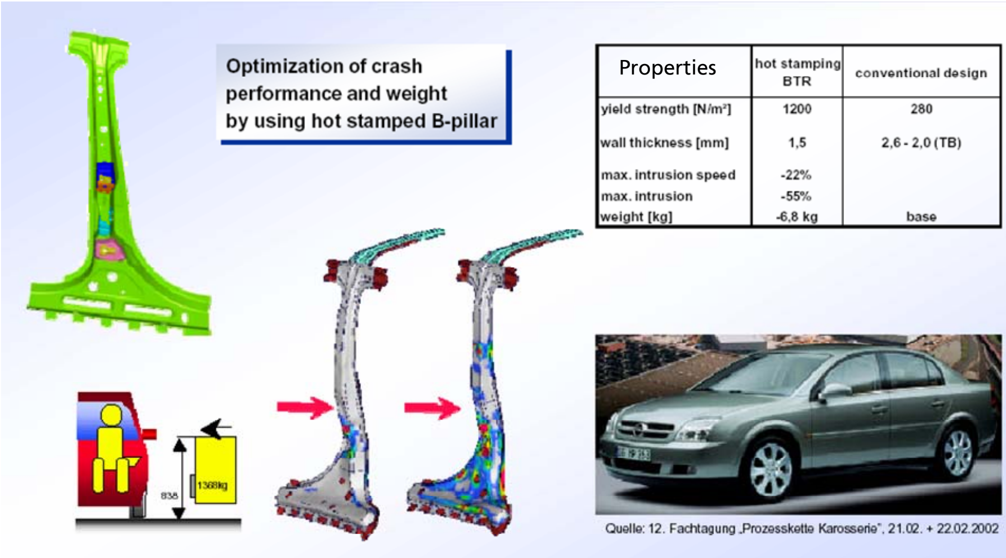


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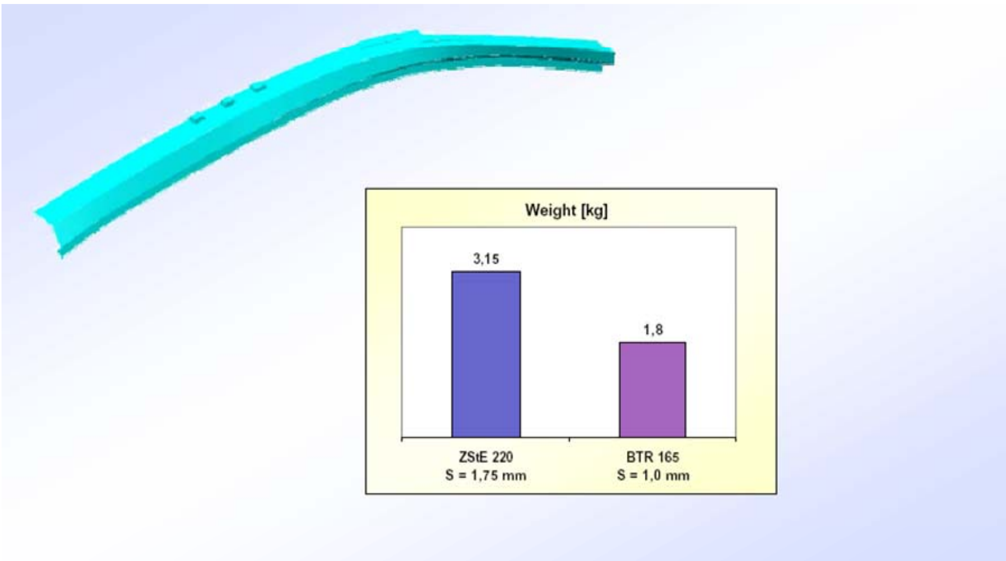
Fig. 30: Improvement of crash performance by hot stamping



Ref: Benteler Automobiltechnik

DIA 7408e

Fig. 31: Comparison roof frames with same performance

1.5. Light-weight design by material substitution

Despite the advantages of high-strength steels in the technical competition, a substitution of steels by light-weight alloys has always been observed, e.g. in commercial vehicles the substitution of steel wheels by aluminium wheels [8, 9], Fig. 32, which is certainly achieved through appropriate design, Fig. 33. The achieved weight reduction from 41 kg to 27.1 kg is due to the fact that the loading of commercial vehicle wheels is dominated mainly by vertical loads.

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a. Welded steel wheel (22.5 x 9.00)

Materials: Disk: St52, Rim: St37
G_{st} = 41 kg

Ref: Hayes Lemmerz Holding GmbH

b. Cast aluminium wheel (22.5 x 9.00)

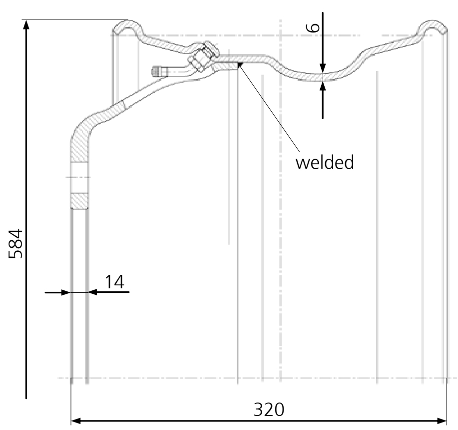
Material: G-AlSi7Mg T6 (A 356 T6)
G_{Al} = 27.1 kg

Ref: Borbet GmbH

DIA 7415e

Fig. 32: Weight-saving by aluminium truck wheels

a. Welded steel wheel

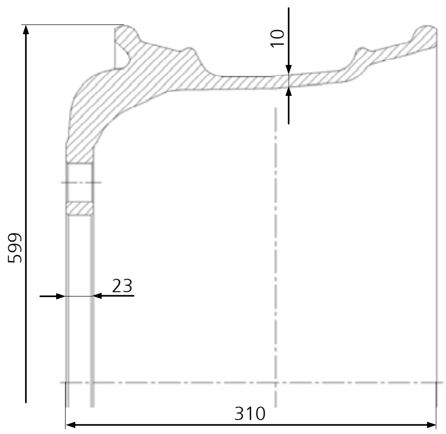


Material: Disk: St 52, Rim: St 37

Weight: 41 kg

Ref.: Hayes Lemmerz Holding GmbH

b. Cast aluminum wheel



Material: G-AlSi7Mg T6 (A 356 T6)

Weight: 27.1 kg

Ref.: Borbet GmbH

DIA 7451e

Fig. 33: Comparison of welded steel and cast aluminium truck wheels (22.5x9.00)

However, in passenger cars in European driving conditions, the horizontal loads are more damaging than the vertical loads. Therefore, aluminium wheels for passenger cars are heavier than steel wheels to compensate for the damaging effect of side loads.

Other examples of material substitution are instrument panel carriers, Fig. 34, where through the introduction of magnesium 6.5 kg was saved; polyamide fuel rails, Fig. 35, with 160 g weight versus 350 g for steel rails; or ceramic intake and exhaust valves with about 20 g weight compared with steel valves with about 50 g weight [10], Fig. 36.

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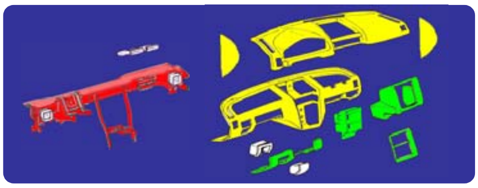


Cross Car Beam in Steel

Component	Mass [g]
Instrument Panel IP	1.900
Air Duct	integrated
Support IP	3.500
Cover Lateral Lh / Rh	200
Cover Driver Side	300
Frame Middle	450
Cover Middle	500
Other Fixtures / Air Ducts	450
Reinforcements	
Steel Cross Car Beam DELTA-Z	10.700
TOTAL MASS	**18.000**

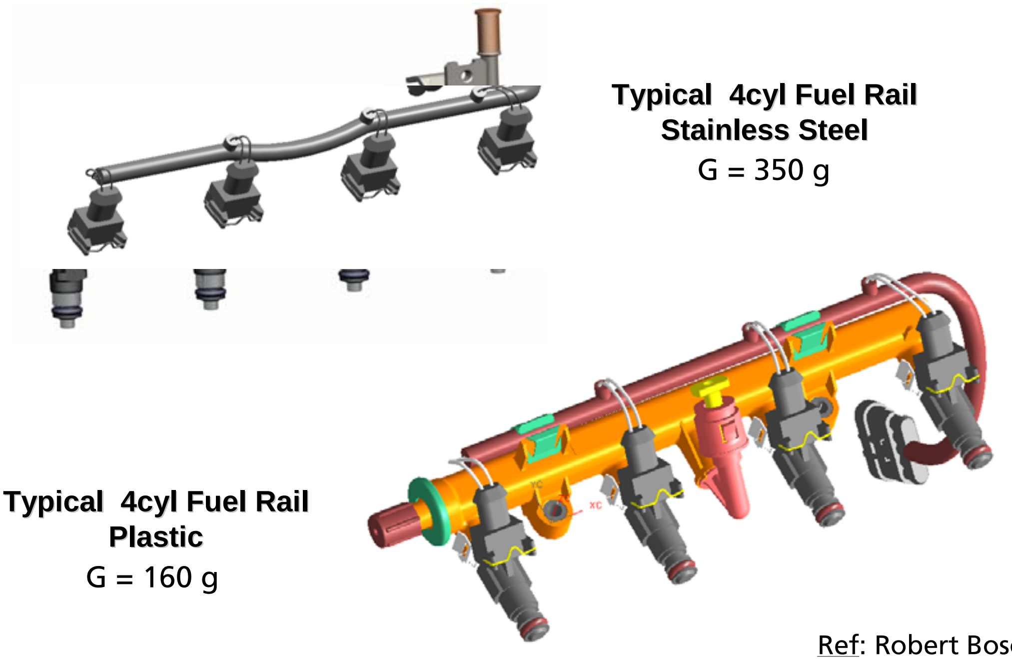
Magnesium Integral Carrier

Component	Mass [g]
Instrument Panel	1.900
Air Duct	1.160
Cover Lateral Lh / Rh	200
Cover Driver Side	300
Cover Middle	500
Frame MIddle	450
Other Fixtures / Air Ducts	990
Reinforcements	**integrated**
Mg-Integral Carrier	**6.000**
TOTAL MASS	**11.500**

Ref: Adam Opel AG

DIA 7416e

Fig. 34: Instrument panel carrier mass comparison steel vs. magnesium



Ref: Robert Bosch GmbH

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Fig. 35: Fuel rail designs in steel and fibre reinforced plastic

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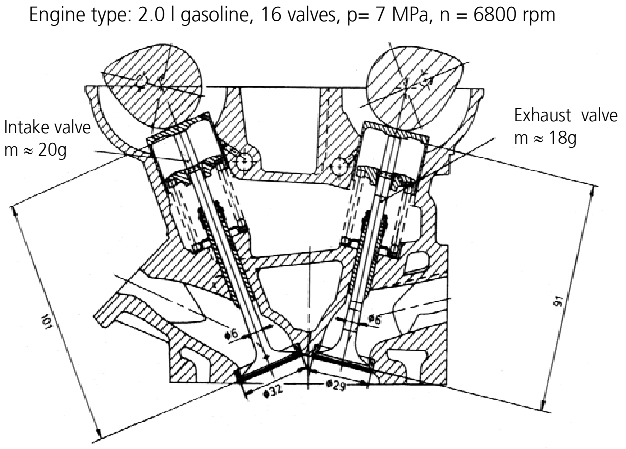

Properties	Si_3N_4 GPSN*) (CerDur 120 GS)	X45CrSi93 (AISI/SAE HNV3)
Densitiy ρ	3.24 - 3.25 g/ccm	7.70 g/ccm
Young's modulus E	290 - 310 GPa	190 GPa
Poisson constant μ	0.27	0.30
Bending strength R_b	20 °C: 1100-1300 MPa 1000 °C: 850-950 MPa	20 °C: 880 - 1030 MPa 800 °C: 70 MPa
Weibull modulus m	15 - 22	-
Hardness HV10	1200 - 1400	-
Fracture toughness K_{Ic}	8-10 MPa $m^{1/2}$	-
Thermal elongation coefficient α	20-100 °C: $1.9 \cdot 10^{-6} K^{-1}$ 20-1000 °C: $3.2 \cdot 10^{-6} K^{-1}$	20-100 °C: $1.3 \cdot 10^{-5} K^{-1}$ 20-700 °C: $1.4 \cdot 10^{-5} K^{-1}$
Thermal conductivity λ	20 °C: 20 W/mK 1000 °C: 13 W/mK	20 °C: 21 W/mK
Thermo-shock parameter $R_1 = \frac{R_b \cdot (1-\mu)}{\alpha \cdot E}$	1060 K	-

*) GPSN = Gas pressure sintered silicon nitride

DIA 7663e

Fig. 36: Valve train middle section with Si_3N_4-valves and material data in comparison to steel

Thus, high-strength steels cannot always be substituted completely, e.g. railway axles and tyres, Fig. 37. But the more lowly stressed disc can be replaced by aluminium enabling a weight of 251 kg for the hybrid wheel versus 326 kg for the steel mono-block wheel.

Monoblock 326 kg
Steel tyre and
steel hub

Hybrid wheel 251 kg
Steel tyre 192 kg
Alu hub 59 kg

Application:
F_{stat} = 160 kN
v_{max} = 160 km/h

DIA 7403e

Fig. 37: Hybrid light-weight railway wheelset

This possibility of combining different materials opens up especially new innovative and economic possibilities for developing light-weight vehicle structures.

2. MODERN LIGHT-WEIGHT DESIGN CONCEPTS OF THE VEHICLE INDUSTRY

Until about 35 years ago the design concept for car bodies was based only on steel. However, after the first energy crisis in the early seventies, the demand for fuel saving by weight reduction produced various design concepts, Fig. 38, leading to multi-material design.

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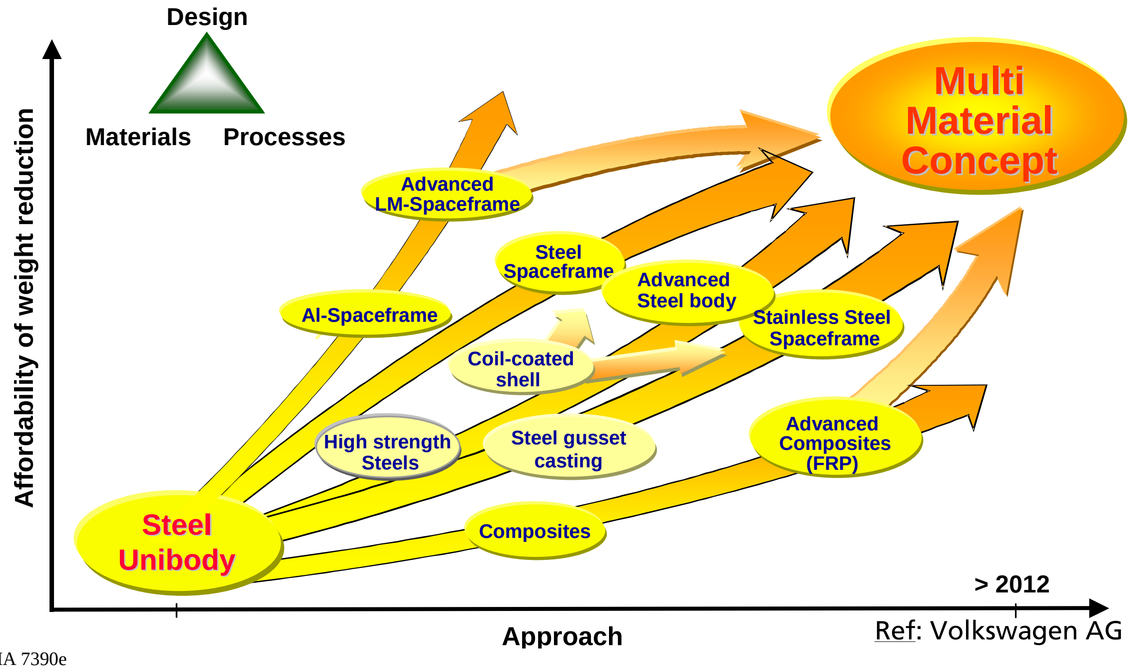

DIA 7390e

Fig. 38: Breakthrough light-weight design by multi-material concept

During this period, a continuous decrease in steel application was observed in car body design [11, 12], Fig. 39, which was balanced by an increased use mainly of polymers and aluminium followed by nonferrous metals such as magnesium, Figs. 40 to 42.

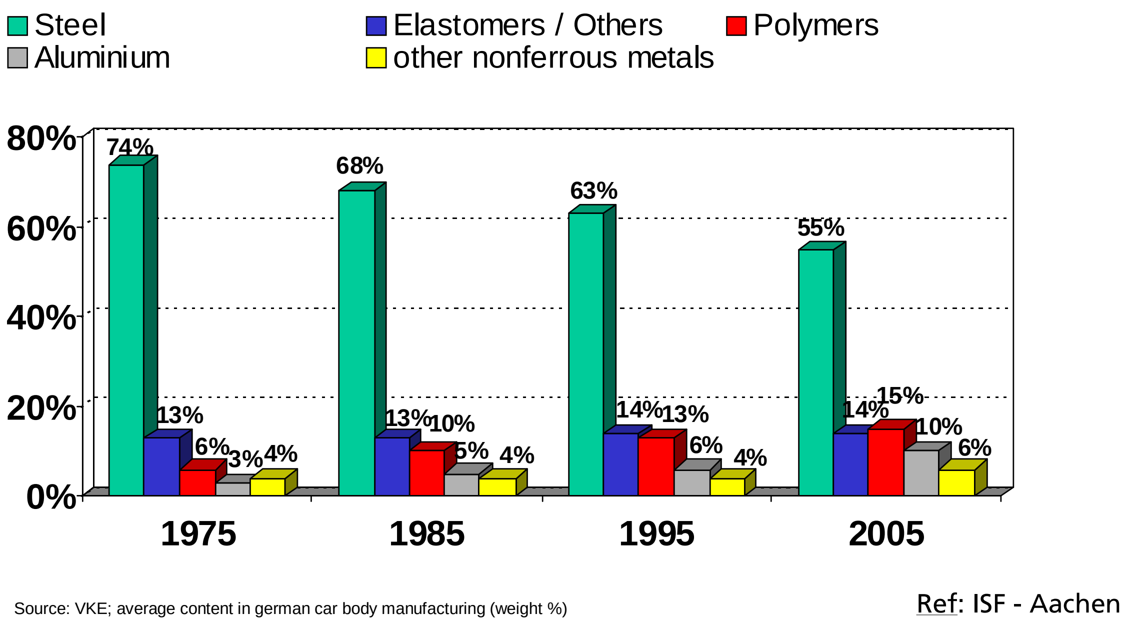

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Fig. 39: Materials in car body design

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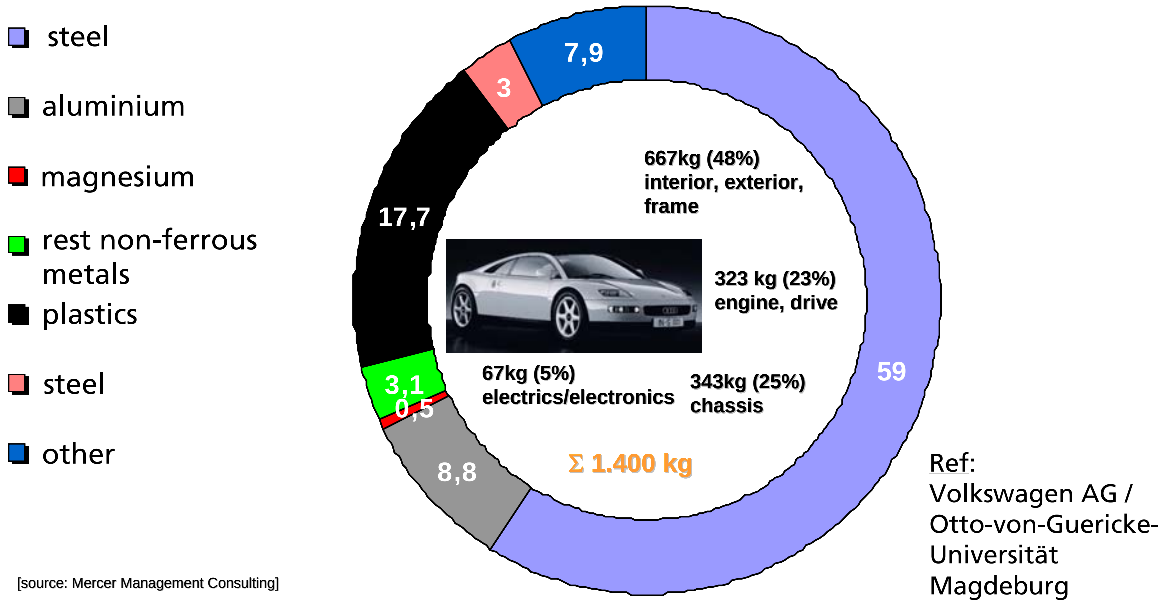

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Fig. 40: Materials and their present weight distribution in the car industry

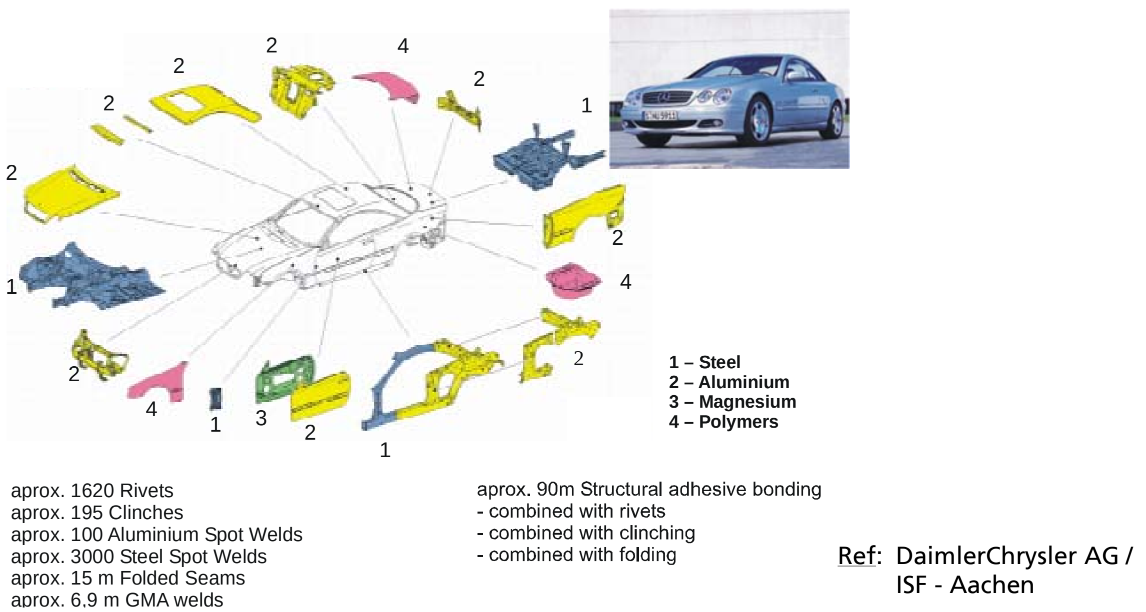

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Fig. 41: Multi-material design

However, the decrease of the application of steel has been compensated on the other hand by the introduction of different high-strength steel qualities [13] and the development of multi-material designs [11, 12], Figs. 41, 42 and 43.

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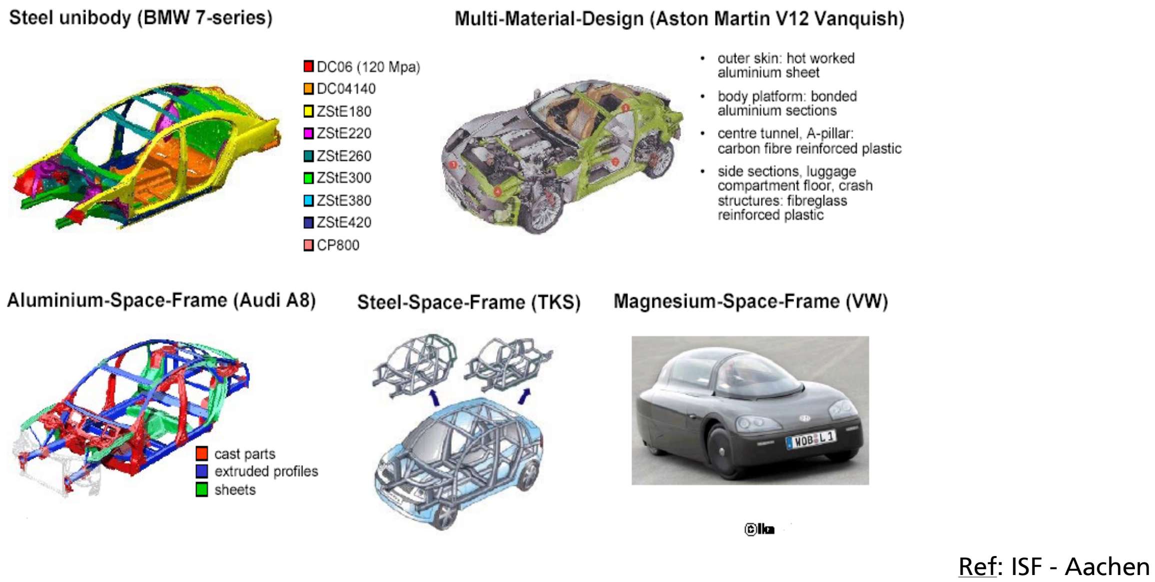

Fig. 42: Modern concepts for car body design

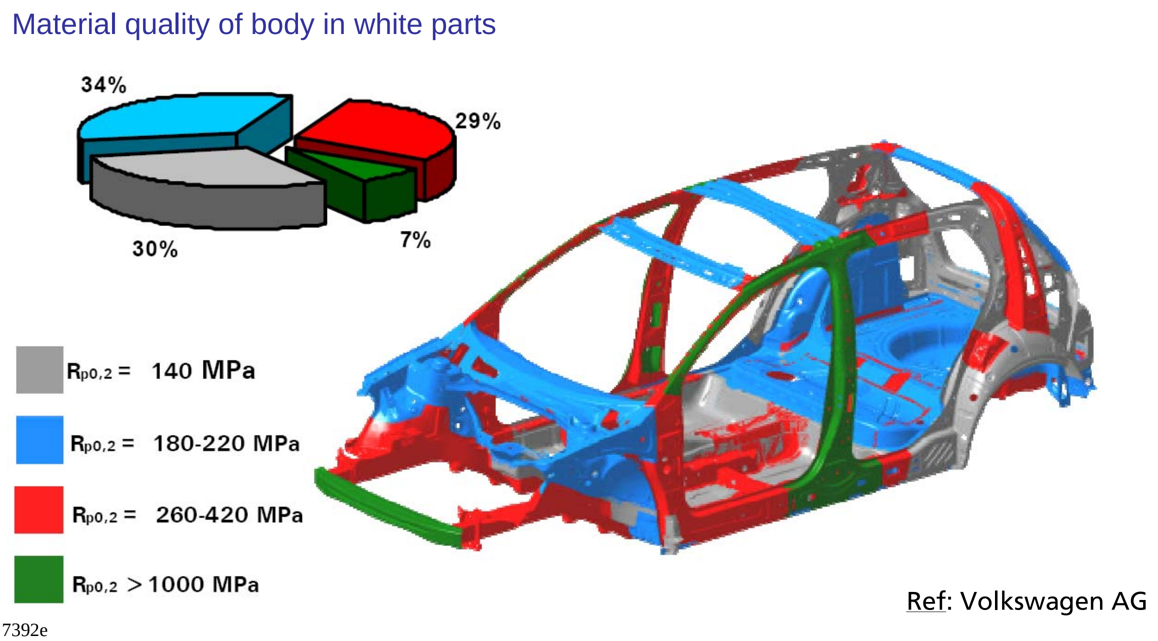

Fig. 43: Multi-material car body structure

The key principle of the multi-material design concept is to place the required strength in the right place, Fig. 43, and so to achieve a light-weight design, i.e. to reduce the current weight of car bodies by about 20%. This concept can be realised only through a good knowledge of loads and stresses in particular areas enabling the selection of the most suitable material.

The multi-material design concept of combining materials with different strength properties is applied not only in the passenger car and commercial vehicle industry. Also in shipbuilding, railway vehicle design, crane structures, offshore rigs and aeronautics the combination of high-strength steels with other materials, i.e. medium strength steels, light-metal alloys, plastics, is an option that attracts serious consideration. However, fundamental research activities, especially with regard to reliable joining techniques and novel assessment methods [14], are still required.

3. CONCLUSIONS AND OUTLOOK

The multi-material concept opens up the following options and advantages, with regard to the durability of light-weight structures:

- Light-weight design is not only a material issue.
- Psychologically, customer demands and fashion trends can be decisive arguments with regard to material selection.
- Technically, light-weight design is the result of interaction between service loading, design, manufacturing technology and costs.
- New trends suggest application of multi-material design concepts.
- The basis of this concept is material selection determined by the required local function and strength of the particular component.
- With regard to fatigue performance, high-strength steels can reveal a superiority in connection with low stress concentrations, on the one hand, and with mechanical surface treatments, on the other hand.
- Particularly for high-strength, crash and impact applications, high-strength steels are the most appropriate materials to choose for the realization of light-weight structures.

However, in this context, the most crucial issue in the next few years will be the development of reliable joining techniques.

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