



STIFFNESS RELEVANCE AND STRENGTH RELEVANCE IN CRASH OF CAR BODY COMPONENTS

Public version of official report 83440 by ika

May 2010

Contents

| | |
|--|----|
| Preamble | 4 |
| 1 Introduction..... | 5 |
| 2 Numerical Analyses..... | 7 |
| 2.1 Subdivision of Body into Components..... | 8 |
| 2.2 Stiffness Analyses | 9 |
| 2.2.1 Approach | 9 |
| 2.2.2 Load Cases..... | 10 |
| 2.2.2.1 Torsion Body-in-White | 10 |
| 2.2.2.2 Bending Body-in-White | 11 |
| 2.2.2.3 Door Sag | 13 |
| 2.2.2.4 Door Overopening | 13 |
| 2.2.2.5 Door Frame Stiffness..... | 14 |
| 2.2.2.6 Door Beltline Stiffness | 14 |
| 2.2.3 Results..... | 15 |
| 2.3 Crash Analyses | 17 |
| 2.3.1 Approach | 18 |
| 2.3.2 Load Cases..... | 19 |
| 2.3.2.1 Frontal Impact - Euro NCAP Based..... | 19 |
| 2.3.2.2 Side Impact - Euro NCAP Based..... | 20 |
| 2.3.2.3 Rear Impact - FMVSS 301 Based | 22 |
| 2.3.3 Results..... | 23 |
| 3 Current Material Application in the Body-in-White..... | 27 |
| 3.1 Published Information on Material Usage in Car Bodies..... | 27 |
| 3.1.1 Subcompact Class..... | 27 |
| 3.1.2 Medium Class | 28 |
| 3.1.3 Crossover SUV | 29 |
| 3.1.4 Small MPV | 30 |
| 3.2 Evaluation of Published Information on Material Usage..... | 31 |
| 3.3 Comparison to Reference Model..... | 32 |

| | | |
|-----|--|----|
| 4 | Lightweight Potential of Future Car Body Material Concepts | 34 |
| 4.1 | Interpretation of Results from Numerical Analyses | 34 |
| 4.2 | Potential of High-Strength Steel | 38 |
| 4.3 | Potential of Aluminium..... | 41 |
| 5 | Interviews with OEM Body Experts | 46 |
| 6 | Summary | 54 |
| 7 | Literature | 56 |

Preamble

This paper is the public version of the official ika report on the study “Stiffness Relevance and Strength Relevance in Crash of Car Body Components”. The public version is an extract from the official report summarising general results of the study.

1 Introduction

The introduction of high-strength materials is consistently claimed to be an efficient measure for a considerable reduction of the car body weight. In fact, higher material strength increases the specific energy absorption capability and the allowable strength. Hence, the application of materials with higher strength allows the reduction of the wall thickness of parts or components without decreasing the crash performance or the safety against plastic failure. This has led to an increasing usage of high-strength steel for car bodies and accompanying advances in weight reduction. However, since the elastic modulus of high-strength and mild steel is not considerably different, reducing the wall thickness of car body components results in a stiffness decrease, which generally cannot fully be compensated by design changes. In addition to durability and safety, stiffness is a key element of the car body's structural performance. Consequently, if the overall structural performance shall not be reduced, significant weight savings by the substitution of mild material with high-strength material can only be achieved for components for which strength is a major requirement. In particular, for components having a strong influence on the body stiffness the weight reduction by material strength increase in combination with thickness reduction is not a performance-neutral measure. This means for the car body as a whole there is a limit of achievable weight reduction by the application of high-strength steel inherent to its functional principle.

The aim of this study is to specify the strength relevance in crash and the stiffness relevance of typical car body components in order to assess the remaining weight reduction potential by application of high-strength steel. Publically available information on the strength relevance in crash and the stiffness relevance of body components is usually limited to qualitative statements as shown in Fig. 1-1. In contrast, this study will provide quantitative values for characteristic body components of a typical compact class vehicle.

| | Strength | Stiffness | Energy Absorption |
|-----------------|----------|-----------|-------------------|
| Floor Structure | ++ | ++ | - |
| Crush Zone | + | ++ | ++ |
| Doors | ++ | + | ++ |
| Supports | ++ | ++ | - |

Fig. 1-1: Structural performance requirements of certain car body domains [OST92]

The values will be determined systematically based on a series of numerical crash and stiffness sensitivity analyses using a reference FE-model of an up-to-date compact class vehicle satisfying all requirements regarding driving performance and safety. The load cases include global torsion and bending for the body-in-white and front crash, side crash as well as rear crash for the full vehicle. The stiffness relevance of the door components will be analysed separately from the body-in-white using the load cases "Door Sag", "Over Opening", "Frame Stiffness" and "Beltline Stiffness". The final values will be related to the size of the component. This ensures for example that if two components show the same effect for a certain load case the smaller component receives a higher relevance value.

For verification purposes the results of the numerical study on stiffness and crash relevance will be compared with published information and literature on material usage in current car bodies. The aim is to investigate, if the components identified as highly strength relevant in the numerical study are currently made from high-strength steel. In addition, the material application of the reference model used for the numerical analyses will be compared to the information on current body material usage in the market. This will enable to access the ability of this model to serve also as a state-of-the-art reference for both, the numerical study itself and an evaluation of the potential of future material concepts.

Based on the results of the numerical analyses it will be assessed which body components are potentially suitable for nearly performance neutral weight reduction by material strength increase. More specifically, on the one hand the results will be used to evaluate the limit of further weight reduction using high-strength steel by the example of the reference vehicle. On the other hand the strength relevance in crash and the stiffness relevance of the components will be used to assess the lightweight potential of aluminium.

Finally, the results of the numerical analyses of strength relevance in crash and stiffness relevance of car body components will be compared to the opinion of experts from different OEMs on this topic. These interviews are part of the study and include, in addition to the questions on strength and stiffness relevance, the collection of opinions on general topics associated with company strategies regarding lightweight design and aluminium application in particular.

2 Numerical Analyses

The numerical analyses represent an extensive part of the study. The results provide quantitative values for the stiffness relevance and the strength relevance in crash for typical compact class car body components. This forms the basis for a systematic evaluation of the weight saving potential regarding future car body material concepts. The FE-model of the reference vehicle from the EC-project “SuperLightCar” (SLC) is used as a reference compact class vehicle model for this study. This FE-model shown in Fig. 2-1 is similar, but not identical, to the VW Golf V FE-model in terms of stiffness and crash performance. It has to be mentioned that the results of a numerical analysis of the stiffness and strength relevance of the individual components within a car body system will depend on the chosen methodology for the evaluation. Thus the approximate quantitative results determined in this study have to be interpreted carefully keeping in mind the assumptions taken in the approach described in the following. There will also be an inherent scatter among different vehicle models.

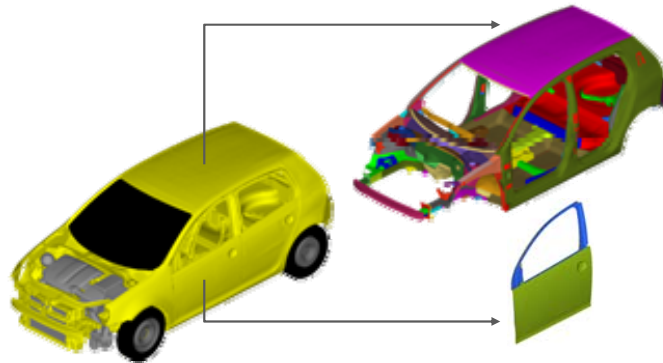


Fig. 2-1: SLC-reference FE-model

Stiffness relevance and strength relevance in crash have been selected as criteria for the study, since these are important properties with respect to the global body performance. They can be assigned to relatively large and generic body components like the B-pillar for example. The subdivision of the reference car body into generic components is described in the following subchapter. The nodes and brackets connecting the components are considered as an integral part of the components and not analysed separately. For universality reasons it is also important that standardised load cases exist to assess the properties. Those are available for the vehicle stiffness and crash performance. In accordance with this the numerical analyses can be divided into stiffness and crash analyses each employing different load cases.

Basically, the relevance of a certain component is determined by sensitivity analyses. Therefore, the performance of the unmodified reference FE-model for the different load cases is determined first. The performance is represented by special evaluation criteria for each load case. The details regarding evaluation criteria are described later. After that the material characteristics of all the parts forming a certain component are changed. More specifically, for the stiffness load cases the elastic modulus and for the crash load cases the yield

strength is halved. This is done for each component and load case. The magnitude of change in evaluation criteria comparing the results of the unmodified reference model to the results of the model with changed material characteristics for a certain component serves as the indicator for the relevance of that component in the load case analysed. Finally, to achieve an overall result the results from the stiffness analyses have to be combined and the results of the crash analyses have to be combined. In addition the results have to be related to the size of the component.

2.1 Subdivision of Body into Components

Prior to the numerical analyses the body structure is subdivided into relevant components that can consist of one or more parts. The objective is to define part groups that represent typical, generic body components in order to be independent from the specific design of the chosen reference vehicle to a maximised extent. However, single parts of the reference vehicle are not split to be assignable to different components. Additionally, in order to limit the number of calculations for the sensitivity analyses the number of single components has to be restricted. As a compromise of the above mentioned criteria the entire body of the reference vehicle is divided into 22 components for the body-in-white, as shown in Fig. 2-2 and 4 components for the door, as shown in Fig. 2-3.

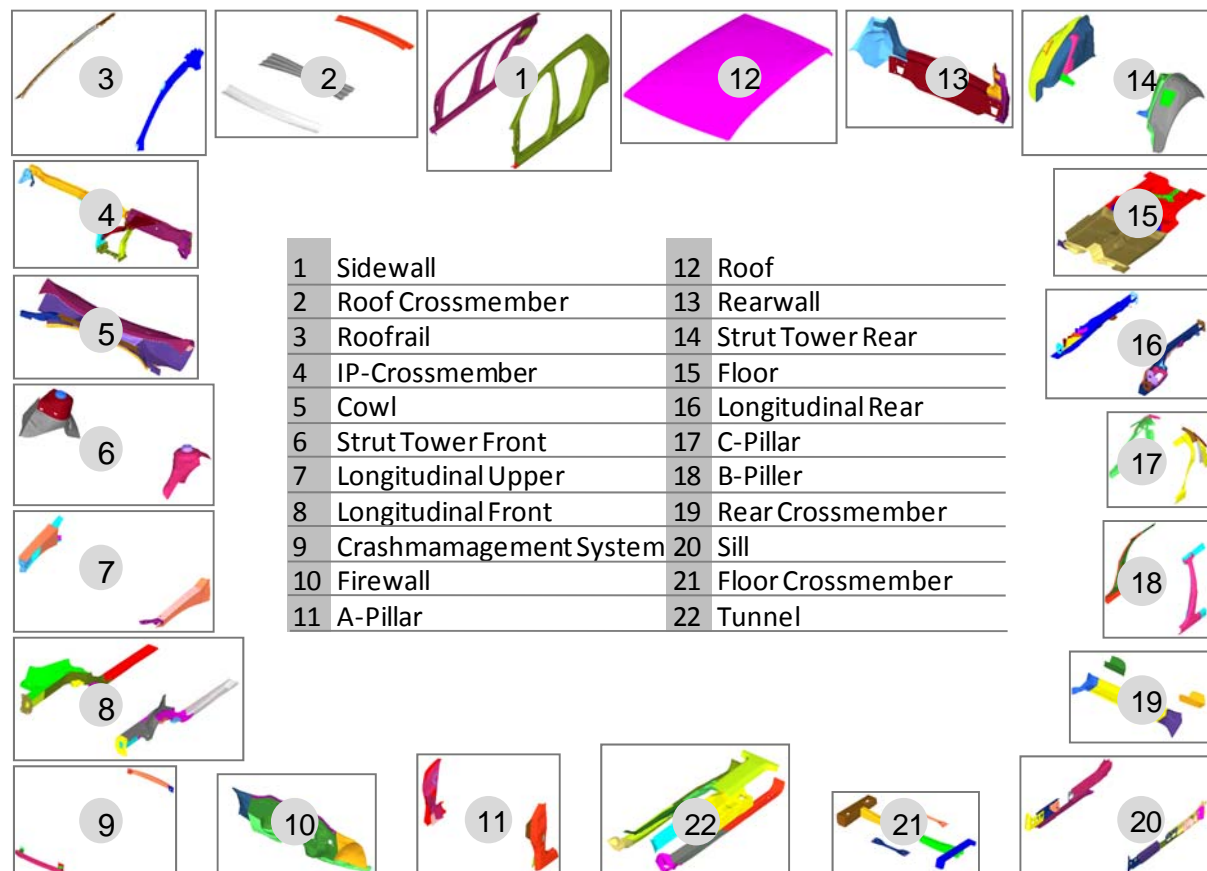


Fig. 2-2: Subdivision of body-in-white into 22 components

It can be observed in Fig. 2-1 that the full vehicle model of the SLC-reference vehicle does not include the hood and the boot lid, the SLC project only addresses lightweight design for the body structure. Consequently, for this study that considers the lightweight potential of both body structure and hang-on parts the front door serves as a representative. This is a worst case approach, because the door is supposed to have the highest crash relevance among the closures.



Fig. 2-3: Subdivision of door into components

2.2 Stiffness Analyses

The following subsections describe the approach used in the stiffness analyses in order to determine quantitative values characterising the global stiffness relevance of the body components defined above. This includes a description of the evaluation process. The load cases selected for the analyses are specified and the final results are presented.

2.2.1 Approach

The body-in-white and the door are analysed separately using different load cases. The analyses are carried out with the linear-static FE-solver Optistruct. First, for each load case a scalar stiffness value is calculated for both the body-in-white and for the door with unmodified components. Then for each load case the elastic modulus of the component to be analysed, for example the B-pillar of the body-in-white or the door frame of the door, is halved. After that, the calculation is repeated to determine the new stiffness value which is lower than the stiffness value of the unmodified FE-model. The difference between the stiffness of the unmodified FE-model and the FE-model with reduced elastic modulus of a certain component serves as an indicator for the stiffness relevance of the respective component. This means that the higher the decrease in stiffness is the higher is the stiffness relevance of the component.

The stiffness relevance is normalised in order to return a value between 0 and 1 for all load cases, since the order of magnitude of the stiffness value and therefore of the stiffness relevance is very different among the load cases. Therefore, the difference in stiffness is divided by the maximum difference in stiffness of all components analysed for the load case.

The stiffness relevance of a component in a certain load case is then related to the size of the component. Therefore, the stiffness relevance is divided by the surface area of the component. This ensures for example that if two components show the same effect on stiffness for a certain load case the smaller component receives a higher relevance value. Finally, for the body-in-white load cases and for the door load cases a combined stiffness value is calculated.

2.2.2 Load Cases

The load cases for the stiffness analyses of the study have been selected by ika and EAA. The objective has been to select global load cases. For the body-in-white this is possible using the semi-standardised load cases global static torsion and global static bending. These load cases are called semi-standardised, since the detailed test procedure varies among the OEMs. The procedure used in this study refers to the definition of the SLC project. In addition to static torsion and bending the dynamic stiffness represented by the first torsion and bending mode is monitored, but not considered for evaluation.

In the SLC test procedure for static stiffness the body-in-white is tested without closures, since closures generally do not contribute to the static stiffness of the vehicle. However, closures do have their own stiffness requirements. The stiffness performance of closures is assessed via component tests separated from the vehicle. These tests are specific to the OEMs. However, the load cases “Door Sag”, “Overopening” “Frame Stiffness” and “Beltline Stiffness” as used in this study represent typical stiffness tests for car doors.

2.2.2.1 Torsion Body-in-White

For analysis of the static torsional stiffness the body-in-white is constrained at the upper rear axle mounts as shown in Fig. 2-4. The rocker that is connected to the upper front axle mounts fulfils two functions. First, it blocks the rotation around the transversal axis. Second, it transfers the torsion torque of 6800 Nm to a vertical pair of forces at the upper front axle mounts.

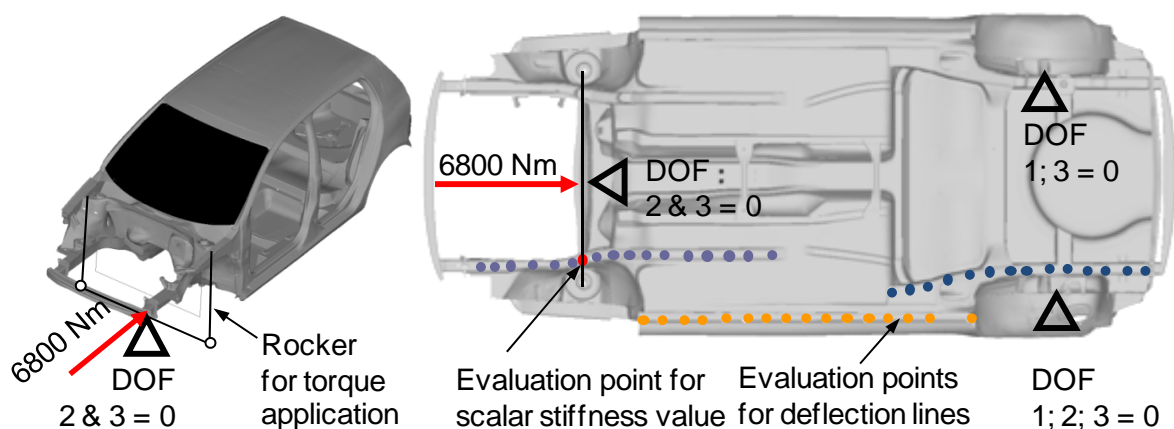


Fig. 2-4: Constraints, load application and evaluation points for torsion

In the stiffness analyses the vertical deflection of the front longitudinal, the sill and the rear longitudinal are recorded at the evaluation points marked in Fig. 2-4. Based on the deflection values and the undeformed transversal location of the evaluation point the torsion lines can be calculated. These lines show the rotation angle of the body-in-white over the body length. Fig. 2-5 shows the torsion lines of the unmodified reference body-in-white as an example. In addition to the torsion lines a scalar stiffness value is calculated. This value is defined as the torsion torque divided by the torsion angle at the intersection of the front longitudinal with the rocker. This scalar stiffness value, called torsional stiffness, is used for comparing the torsional stiffness analyses and to determine the torsional stiffness relevance of a certain component.

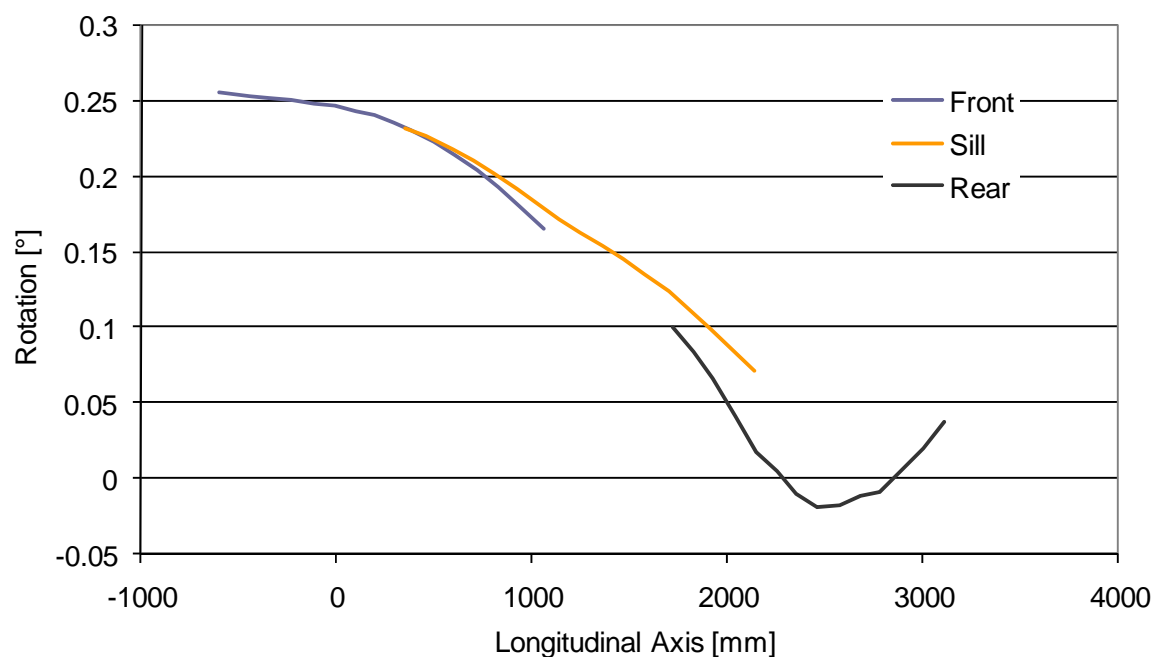


Fig. 2-5: Torsion lines of the unmodified reference body-in-white

2.2.2.2 Bending Body-in-White

For analysis of the static bending stiffness the body-in-white is constrained at the upper rear axle mounts as shown in Fig. 2-6 in the same way as for the analysis of the torsional stiffness. However, in contrast to the torsional stiffness load case, the vertical translation of the upper front axle mounts is completely blocked by constraining the rotation of the rocker around the longitudinal axis. A total vertical load of 9221 N is applied at the front and rear seats.

Like in the torsional stiffness analyses the vertical deflection of the front longitudinal, the sill and the rear longitudinal are recorded at the evaluation points marked in Fig. 2-6.

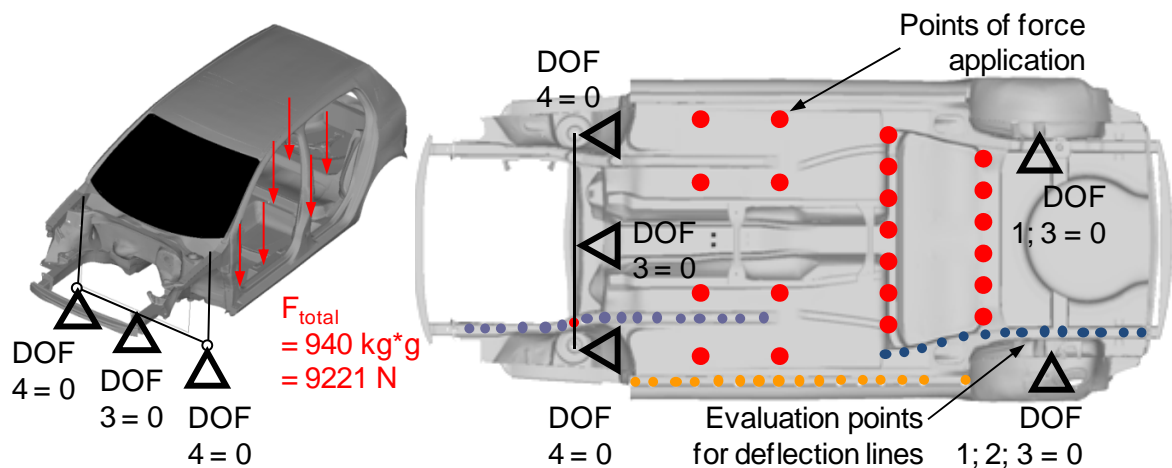


Fig. 2-6: Constraints, load application and evaluation points for bending

For the bending stiffness the bending lines can directly be drawn from the vertical deflections of the evaluation points. Fig. 2-7 shows the bending lines of the unmodified reference body-in-white as an example. In addition to the bending lines a scalar stiffness value is calculated. This value is defined as the total load of 9221 N divided by the maximum vertical displacement of the evaluation points. The scalar stiffness value, called bending stiffness, is used for comparing the bending stiffness analyses and to determine the torsional stiffness relevance of a certain component.

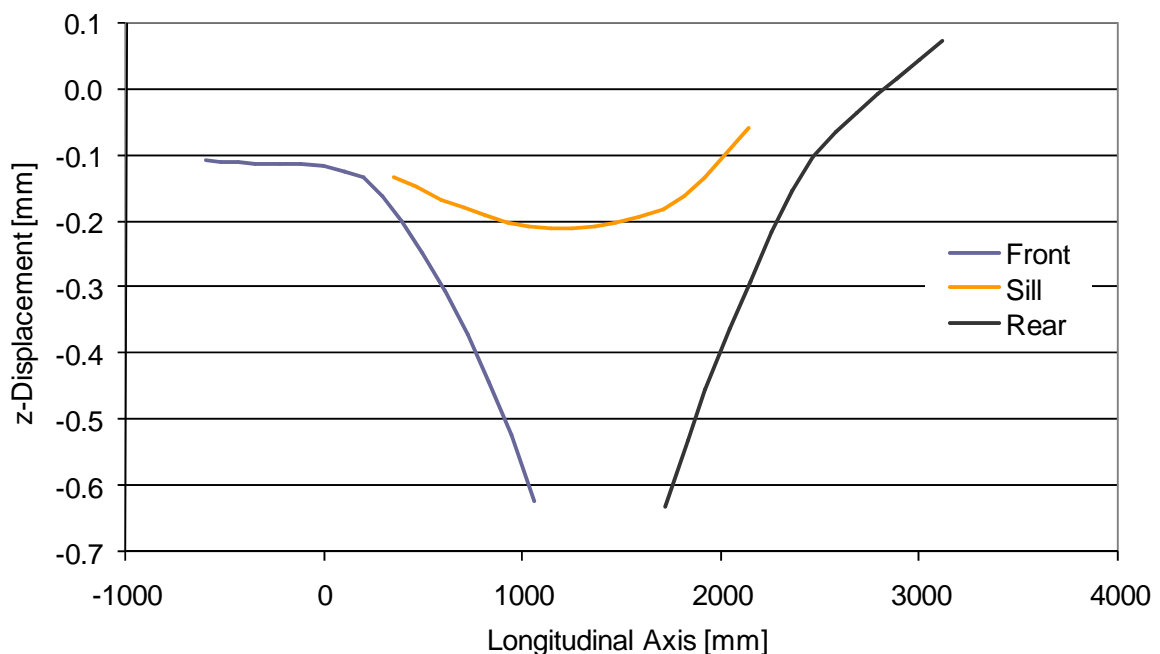


Fig. 2-7: Bending lines of the unmodified reference body-in-white

2.2.2.3 Door Sag

For the door component load case “Door Sag” the door is rigidly constrained at the mounting points for the hinges as shown in Fig. 2-8. All degrees of freedom are constraint except for the rotation around the hinge axis. A force of 1000 N is applied in vertical direction at the lock. This force application point is constrained in transversal direction in order to suppress a global rotation of the door around the hinge axis. The scalar stiffness value for the load case “Door Sag” is calculated by dividing 1000 N by the total displacement at the force application point.

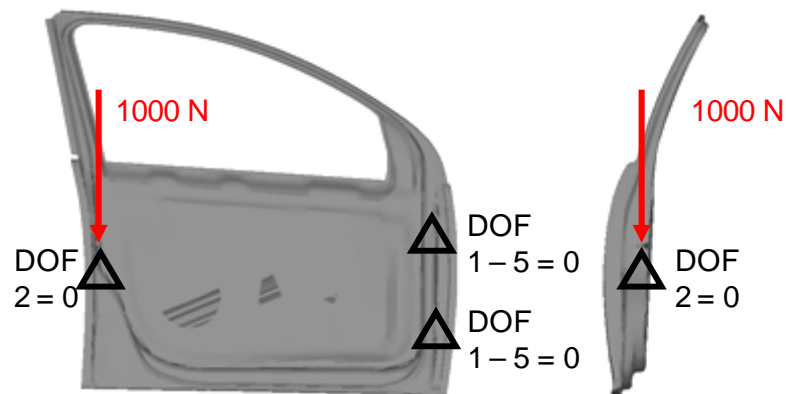


Fig. 2-8: Constraints and force application for the load case “Door Sag”

2.2.2.4 Door Overopening

For the door component load case “Door Overopening” the door is rigidly constrained at the mounting points of the hinges as shown in Fig. 2-9. All degrees of freedom are constraint. A force of 300 N is applied in transversal direction at the lock. This force application point is not constrained. The scalar stiffness value for the load case “Door Overopening” is calculated by dividing 300 N by the total displacement at the force application point.

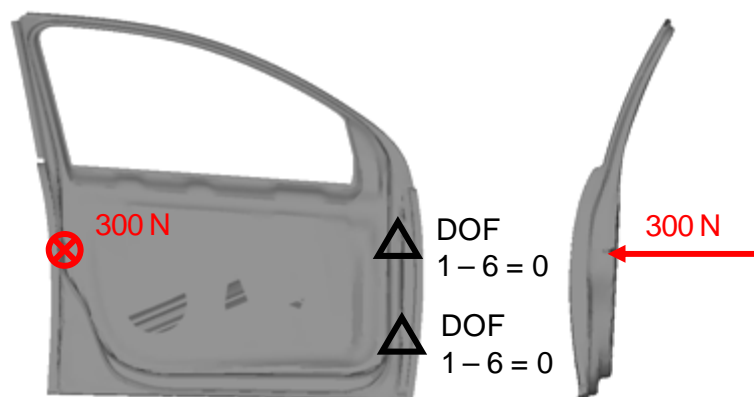


Fig. 2-9: Constraints and force application for the load case “Overopening”

2.2.2.5 Door Frame Stiffness

For the door component load case “Door Frame Stiffness” the door is rigidly constrained at the mounting points of the hinges as shown in Fig. 2-10. All degrees of freedom are constraint except for the rotation around the hinge axis. A force of 350 N is applied in transversal direction at the inner side of the upper corner of the door window frame. This force application point is constrained in transversal and in vertical direction in order to suppress a global rotation of the door around the hinge axis and sagging. The scalar stiffness value for the load case “Door Frame Stiffness” is calculated by dividing 350 N by the total displacement at the force application point.

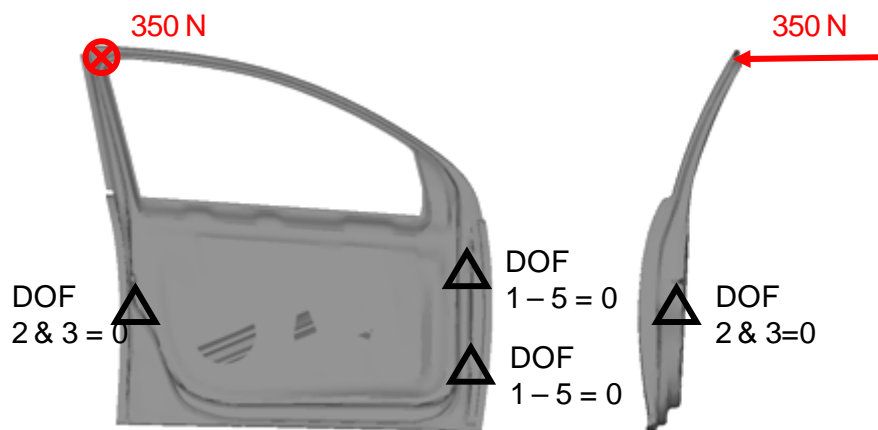


Fig. 2-10: Constraints and force application for the load case “Frame Stiffness”

2.2.2.6 Door Beltline Stiffness

For the door component load case “Door Beltline Stiffness” the door is rigidly constrained at the mounting points of the hinges as shown in Fig. 2-11.

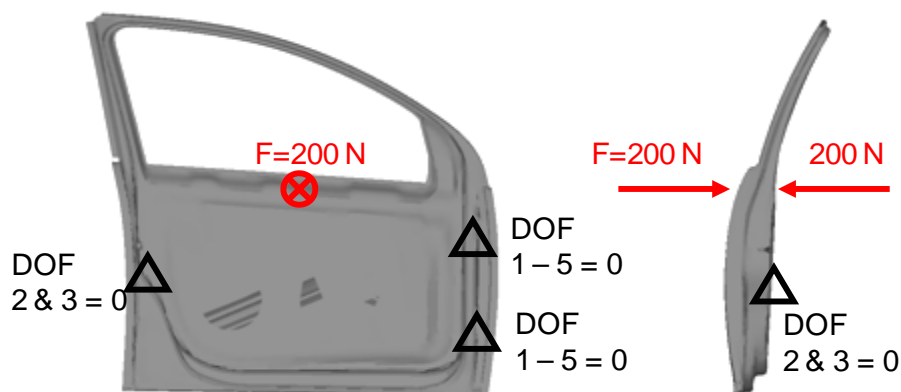


Fig. 2-11: Constraints and force application for the load case “Beltline Stiffness”

All degrees of freedom are constraint except for the rotation around the hinge axis. Two facing forces of 200 N each are applied in transversal direction on the door belt line at the cen-

tre of the window opening. The lock is constrained in transversal and in vertical direction in order to suppress a global rotation of the door around the hinge axis and sagging. The scalar stiffness value for the load case “Door Beltline Stiffness” is calculated by dividing 400 N by the sum of the total displacements at both force application points.

2.2.3 Results

In this section the final results of the stiffness relevance analyses for the body-in-white and the door components are documented. In the following tables the stiffness relevance of each component is represented by a value between 0 and 1 with 1 meaning highest stiffness relevance. All of the values are related to the size of the component. The stiffness relevance of the body-in-white components is shown in Fig. 2-12 separately for bending stiffness relevance and torsional stiffness relevance. As expected the relevance of a certain part can be totally different for bending and torsion. Consequently, in order to enable a comparison of the body-in-white components regarding stiffness relevance the bending stiffness relevance and the torsional stiffness relevance of the components have to be combined. The combined stiffness relevance of the body-in-white components is shown in Fig. 2-13. In general the results are according to expectations. Components that are typically known to have a strong influence on the static body stiffness like the suspension strut towers or the sill show high relevance values.

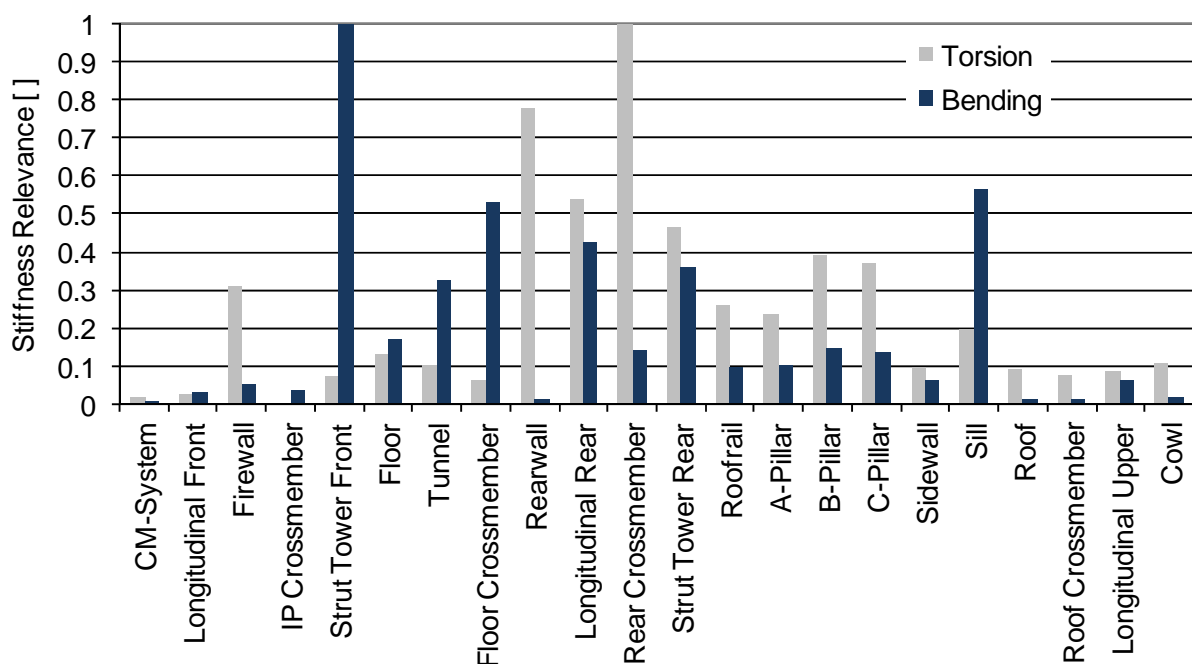


Fig. 2-12: Stiffness relevance of body-in-white components for all load cases

However, the stiffness relevance of the frontal longitudinal beams and the IP crossmember is lower than expected. A possible explanation is that regarding the IP crossmember stiffness is important in terms of eigenfrequencies. For the longitudinal beams in addition to eigen-

frequencies stiffness is required for good dynamic local body stiffness. These load cases are not considered in this study.

The stiffness relevance of the door components is shown in Fig. 2-14 separately for the load cases “Door Sag”, “Over Opening”, “Frame Stiffness” and “Beltline Stiffness”. Like for the body-in-white a combined stiffness relevance representing the entire load cases analysed is required for comparison of the stiffness relevance of the different door components. The values representing the combined stiffness relevance of the door components are shown in Fig. 2-15.

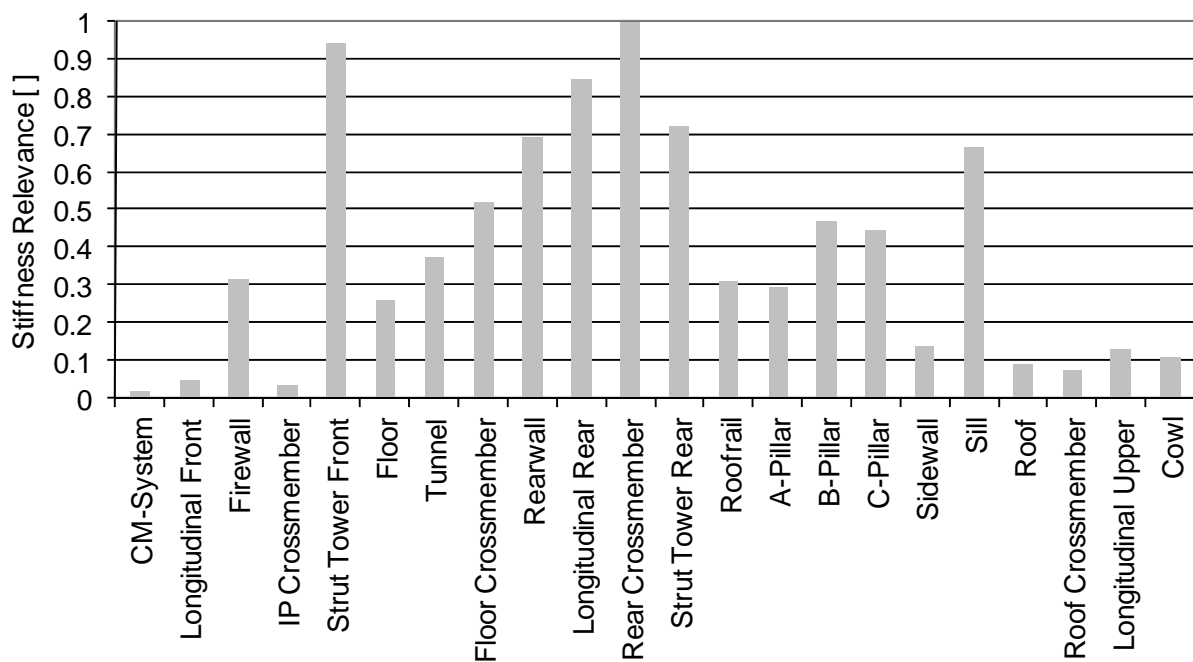


Fig. 2-13: Stiffness relevance of body-in-white components (combined load cases)

The high stiffness relevance of the hinge reinforcement is not according to expectations. The reason is that for all of the load cases except for “Beltline Stiffness” a local deformation at the hinges results in a rigid body motion that enhances the displacement at the load application point.

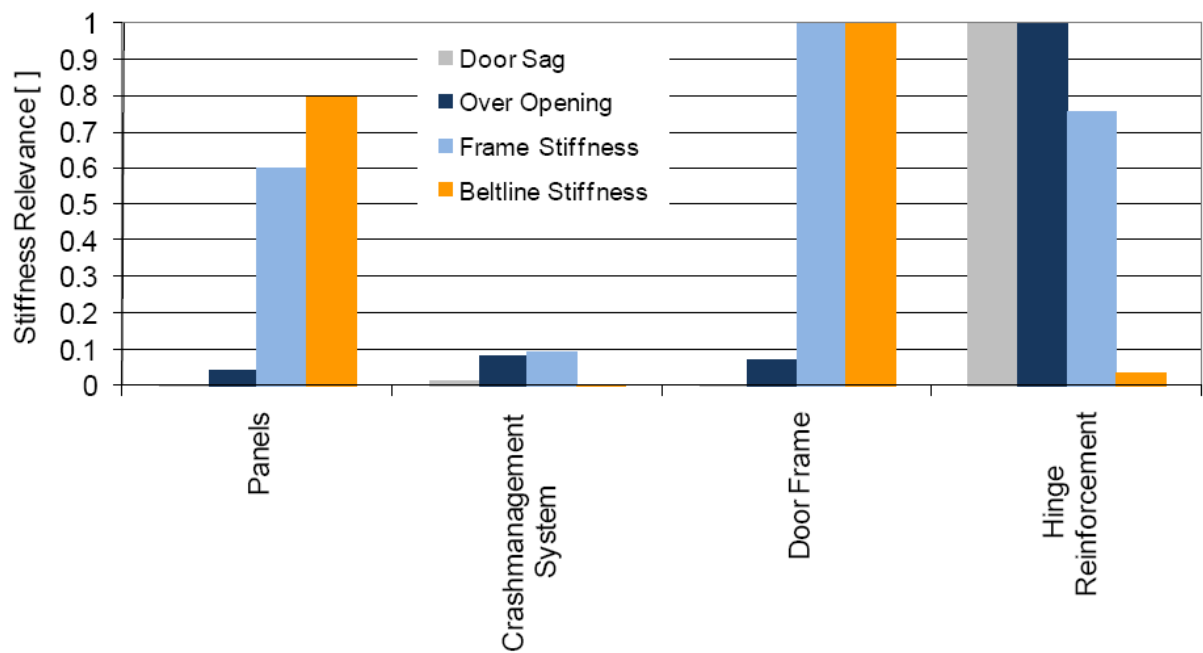


Fig. 2-14: Stiffness relevance of door components for all load cases

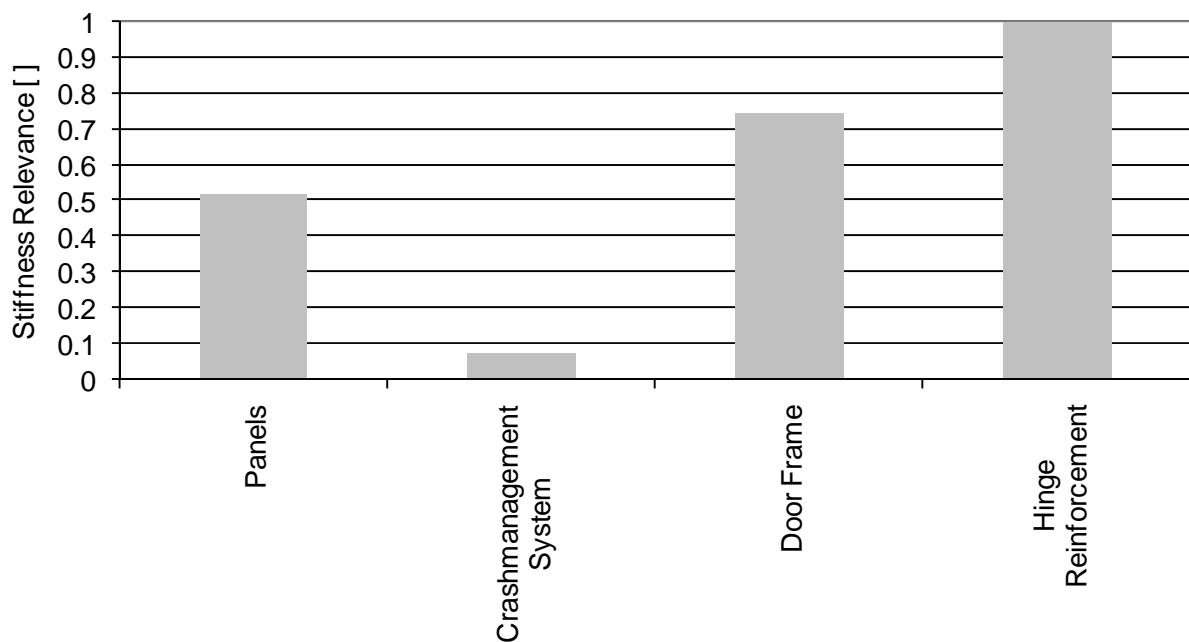


Fig. 2-15: Stiffness relevance of door components for combined load cases

2.3 Crash Analyses

The following subsections describe the approach and the evaluation process used in the crash analyses. That approach enables to determine quantitative values characterising the

relevance of the strength of typical body components with respect to the structural crash performance of the vehicle. The load cases selected for the analyses are specified and the final results are presented.

2.3.1 Approach

The approach for determination of the strength relevance in crash for a certain body component is similar to the determination of the stiffness relevance. However, in contrast to the stiffness analyses for the crash analyses the body-in-white and the doors are analysed together using the same load cases, since doors generally contribute to the structural crash performance of the vehicle. The analyses are carried out with the explicit FE-solver LS-Dyna.

First, the unmodified SLC model is analysed to identify reference values for intrusions of characteristic points of the body for each load case. The intrusion of a certain point is its deformation in direction of crash relative to the undeformed area of the vehicle. The intrusions have been selected as the main evaluation criteria for the crash performance, since low intrusion results from a combination of energy absorption and structural integrity both at the proper body areas.

After analysis of the reference vehicle the material strength of each body-in-white and door component is halved by scaling the plastic flow curve of the materials. For each modified component the calculation of all load cases is repeated. The absolute values for intrusions are calculated and documented for each load case and component.

In order to determine the crash relevance of the components the increase in intrusions of the models with strength reduced components compared to the reference model is used. However, for this comparison the increase in intrusion of a certain load case cannot simply be summed, since the intrusions of the reference model show large differences in magnitude at the different points. For example the intrusion at the suspension strut mount is much higher than the intrusion at the A-pillar. Consequently the magnitude of the absolute change in intrusion will be higher at the suspension strut mount. By simple summation the areas with the large intrusions would be overrated, since only the relative change in intrusions is relevant. Therefore, prior to the summation the increase in intrusion for each point is normalised using the maximum increase in intrusion among all components analysed. This is done separately for each load case. In case that the intrusion of a certain point decreases caused by material strength reduction of a component the normalised intrusion of this point is set to 0. The intrusion magnitude serves as an indicator for the crash relevance of a component. The intrusion magnitude is the sum of the normalised intrusions at the evaluation points for a certain component and a single load case. The intrusion magnitude of each component in the different load cases is normalised using the maximum intrusion magnitude in order to return a value between 0 and 1 representing the strength relevance in crash of the component in the certain load case.

To access the total crash relevance of a certain component the results of front, side and rear crash have to be combined. This is done by summation of the intrusion magnitude of the dif-

ferent load cases. This sum is divided by the maximum summed intrusion magnitude among all components in order to return a value between 0 and 1 representing the total strength relevance in crash of the component.

The strength relevance in crash of the components is related to their sizes. This is done by dividing the normalised and totalised intrusions by the surface area of the component prior to the second normalisation. This ensures for example that if two components show the same effect on the change in intrusions the smaller component receives a higher relevance value.

2.3.2 Load Cases

In contrast to the body-in-white stiffness analyses where the entire body is stressed when applied with torsion or bending load for example, global vehicle load cases for crash performance do not exist. In fact, standardised crash tests generally affect only a local domain of the body which is in the area of the impact zone. Consequently, the load cases for this study have to be composed in a way that all body components are stressed when the load cases are considered in combination. This is done by selecting a front, a side, and a rear crash configuration, as described in the following subsections. The compilation of the crash load cases is a compromise of minimising the number of load cases and simulation runs respectively and maximising the representation of conditions to which a component is actually subjected in traffic or in the spectrum of existing crash tests. This includes that certain existing load cases cannot be considered. Therefore the results have to be reviewed critically with regard to this constraint.

For reasons of simplification the vehicle configuration is the same for the front crash, the side crash and the rear crash, which is valid for an A to B comparison. This means the vehicle is crashed without dummies and additional masses for all load cases, resulting in a total crash mass of 1250 kg. The crash simulations are evaluated based on the intrusion of certain points which are unique for each load case. In addition to the intrusions the acceleration at the centre of the vehicle and the internal energy of both the full vehicle body as well as the single body components are monitored.

2.3.2.1 Frontal Impact - Euro NCAP Based

The Euro NCAP based front crash used for this study can be characterised as follows:

- Impact speed: 64 kph (40 mph)
- Overlap: 40 %
- Offset deformable barrier
- Zero degree impact
- Simulation time 120 ms

The crash configuration for the front crash is shown on the left side in Fig. 2-16. The red dots on the cut-away on the right side of Fig. 2-16 mark the evaluation points where the intrusions and the acceleration are measured. The intrusion depth is calculated at the footwell, the wheelhouse, the footrest, the steering-column passage, the A-pillar, the front suspension-strut mount and the steering column. The displacement of the A-pillar is determined to evaluate the risk of door jam. The intrusions are measured relatively to the undeformed area in the rear of the vehicle. The deformation of the unmodified reference vehicle model can be seen in the picture sequence in Fig. 2-17.

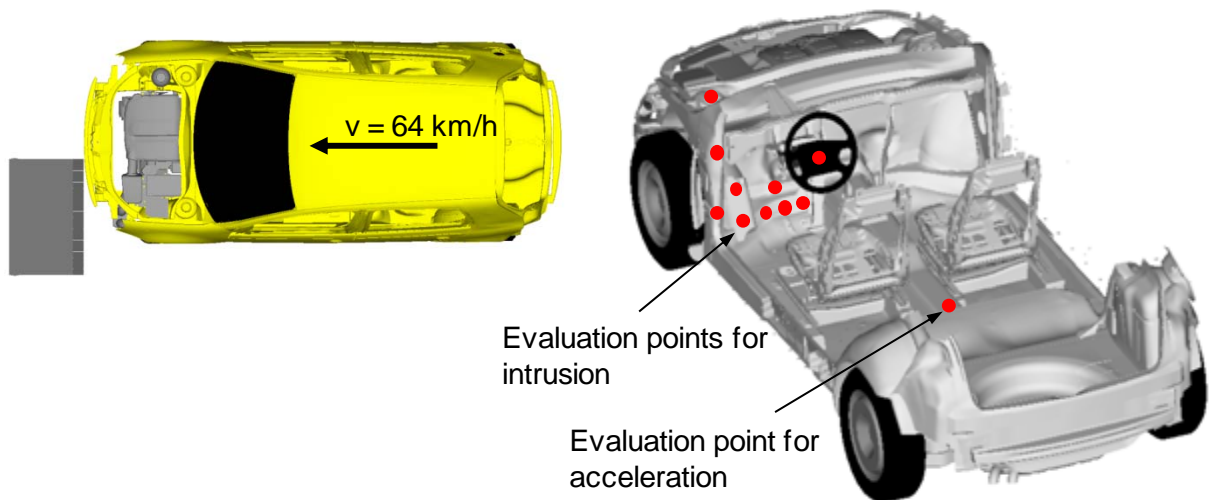


Fig. 2-16: Crash configuration and evaluation points for front crash

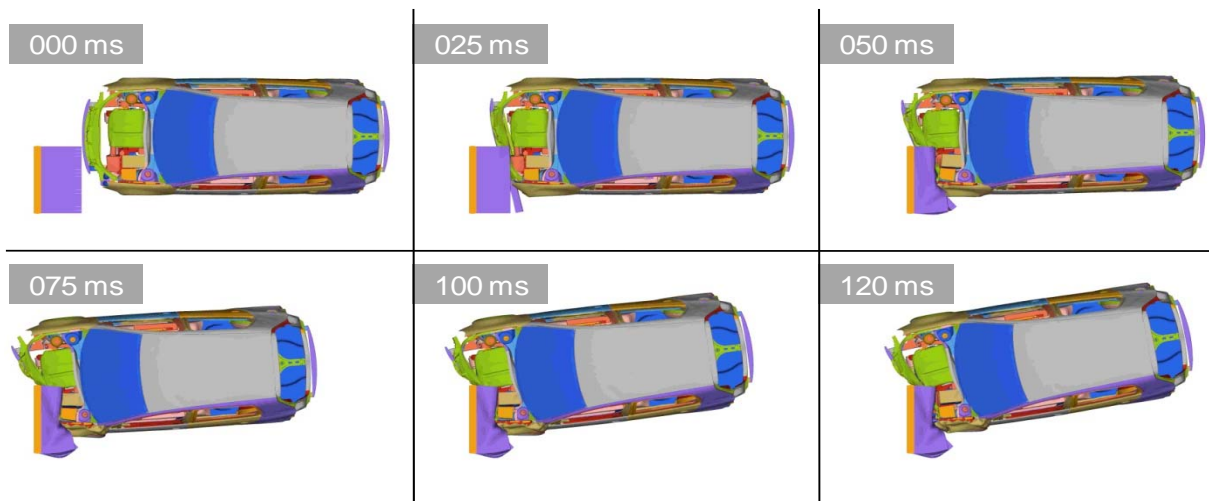


Fig. 2-17: Sequence of front crash with unmodified reference model

2.3.2.2 Side Impact - Euro NCAP Based

The Euro NCAP based side crash used for this study can be characterised as follows:

- Impact speed: 50 kph (30 mph)

- Barrier weight: 950 kg
- Deformable moving barrier
- Zero degree impact
- Simulation time 140 ms

The crash configuration for the side crash is shown on the left side in Fig. 2-18. The red dots on the vehicle on the right side of Fig. 2-18 mark the evaluation points where the intrusions and the centre acceleration are measured. The intrusion depth is calculated at the B-pillar top (root frame), the upper door beam, the B-pillar middle, the B-pillar bottom (rocker panel), the front door upper beam, the front door crash beam, the rear door upper beam and the rear door crash beam. The intrusions are measured relatively to undeformed area on the passenger-side of the vehicle. The deformation of the unmodified reference vehicle model can be seen in the picture sequence in Fig. 2-19.

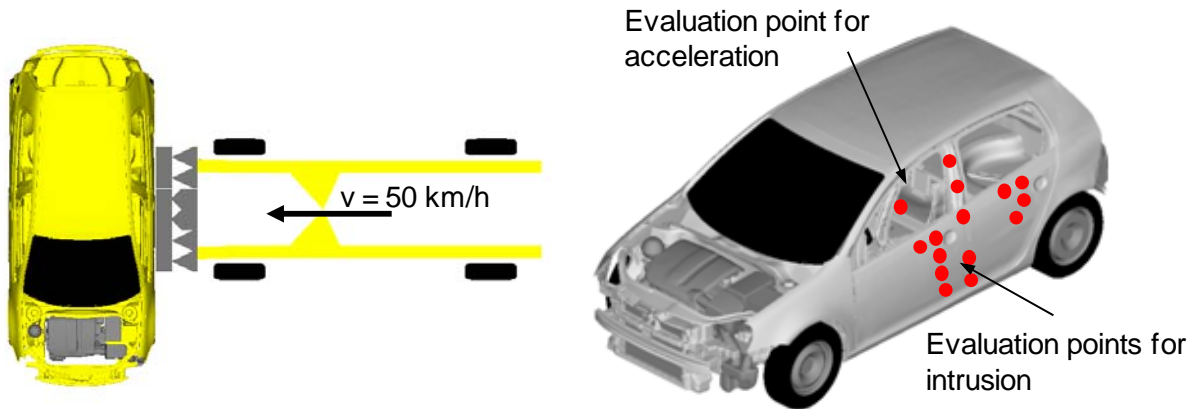


Fig. 2-18: Crash configuration and evaluation points for side crash

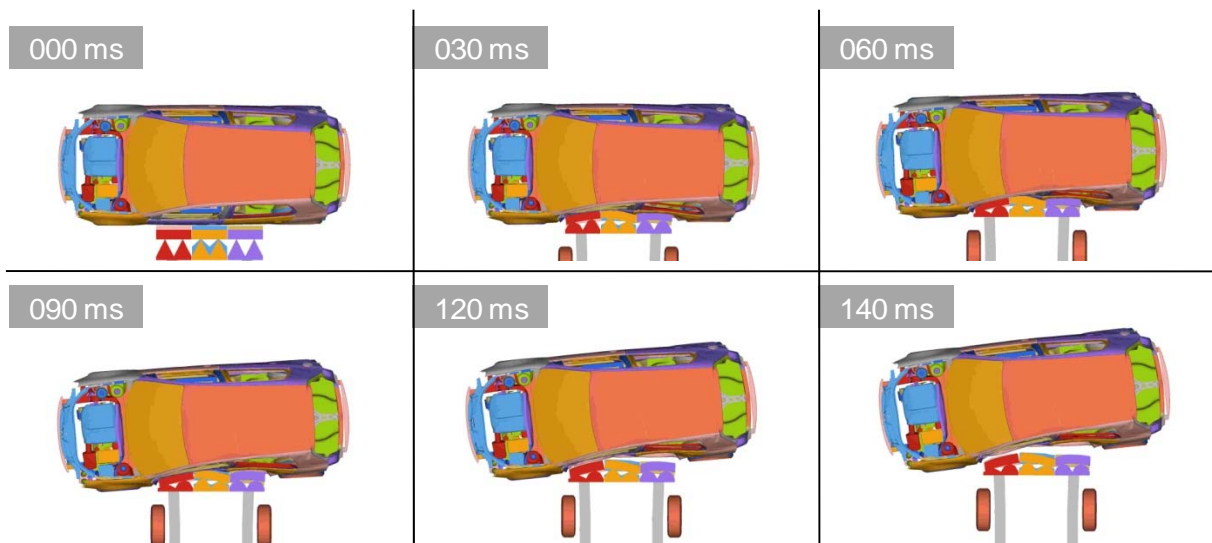


Fig. 2-19: Sequence of side crash with unmodified reference model

2.3.2.3 Rear Impact - FMVSS 301 Based

The Euro NCAP based rear crash used for this study can be characterised as follows:

- Impact speed: 48 kph (30 mph)
- Barrier weight: 1800 kg
- Overlap: 100 %
- Rigid moving barrier
- Simulation time 80 ms

The crash configuration for the rear crash is shown on the left side in Fig. 2-20. The red dots on the vehicle on the right side of Fig. 2-20 mark the evaluation points where the intrusions and the acceleration are measured. The intrusion depth is calculated at the rear bumper, the boot sill and the C-pillar. Similar to the A-pillar intrusion in the front crash the C-pillar intrusion is determined to evaluate the risk of door jam. The intrusions are measured relatively to the undeformed area in the front of the vehicle. The deformation of the unmodified reference vehicle model can be seen in the picture sequence in Fig. 2-21.

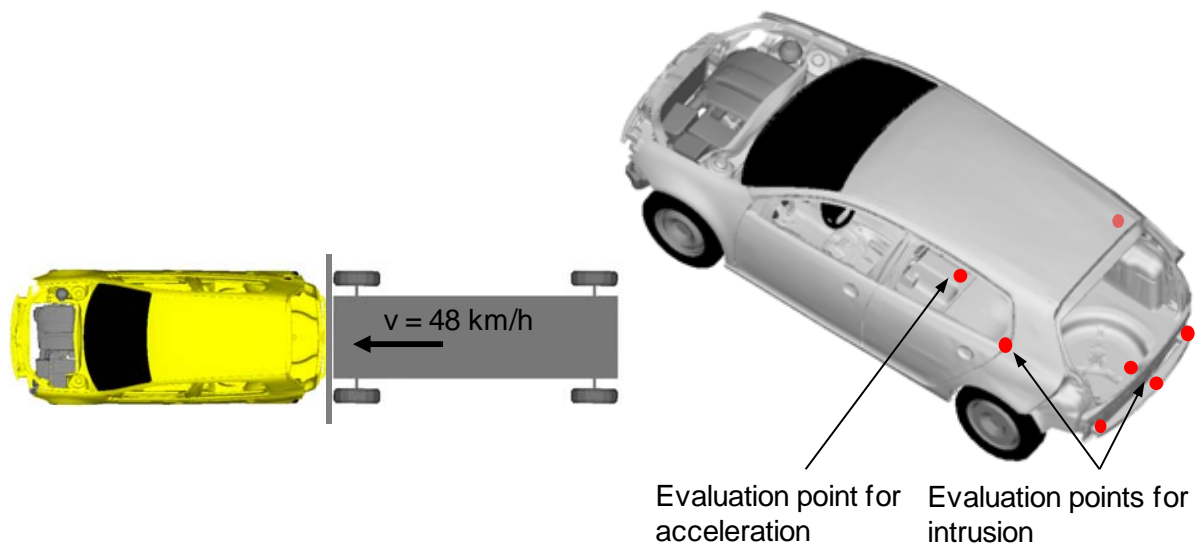


Fig. 2-20: Crash configuration and evaluation points for rear crash

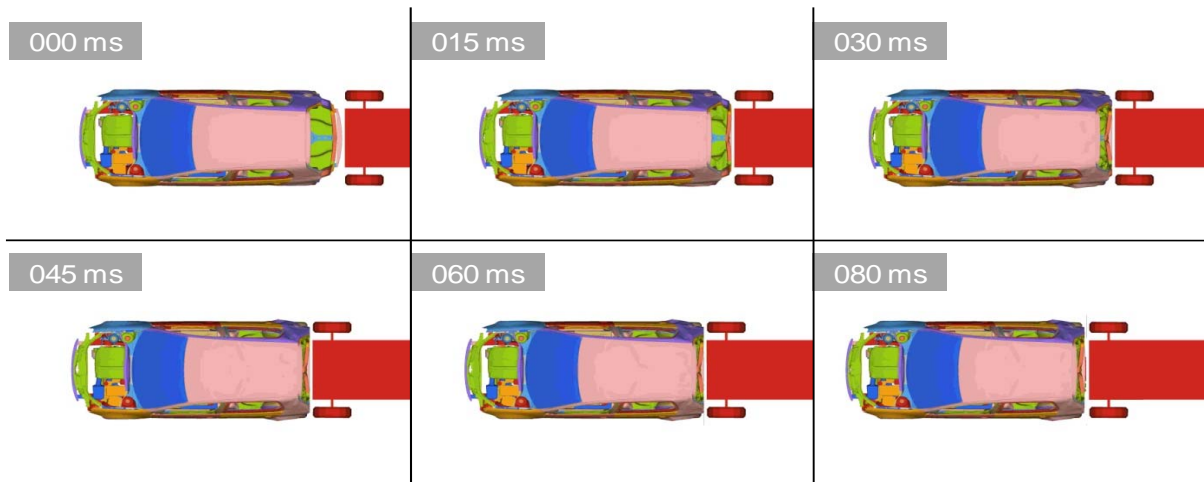


Fig. 2-21: Sequence of rear crash with unmodified reference model

2.3.3 Results

In this section the final results of the analyses regarding strength relevance in crash for the body-in-white and the door components are documented. In the following tables for each component the strength relevance in crash is represented by a value between 0 and 1 with 1 meaning highest strength relevance. The entire values are related to the size of the corresponding component.

The strength relevance in crash of the body-in-white components is shown in Fig. 2-22 separately for strength relevance in front, side and rear crash. As previously mentioned the crash load cases affect only a local domain of the body which is in the area of the impact zone. Consequently, the relevance of a certain part can be totally different for front, side and rear crash. For the strength relevance in crash this issue is even more distinct than for the stiffness relevance where a similar situation occurs. In order to enable a comparison of the body-in-white and door components with respect to strength relevance in crash a single value representing the total relevance regarding the three load cases is required. This is done by selecting the maximum relevance value of the component among the three load cases as the total relevance value, since the components have to be dimensioned for the dominant case. The total strength relevance in crash of the body-in-white components is shown in Fig. 2-23.

In general the results are according to expectations. Components that are typically known to have a strong influence on the structural crash performance like the B-pillar, the longitudinal members, the CM-system but also the strut towers show high relevance values. However, the strength relevance in crash of the roofrail and the IP crossmember is lower than expected.

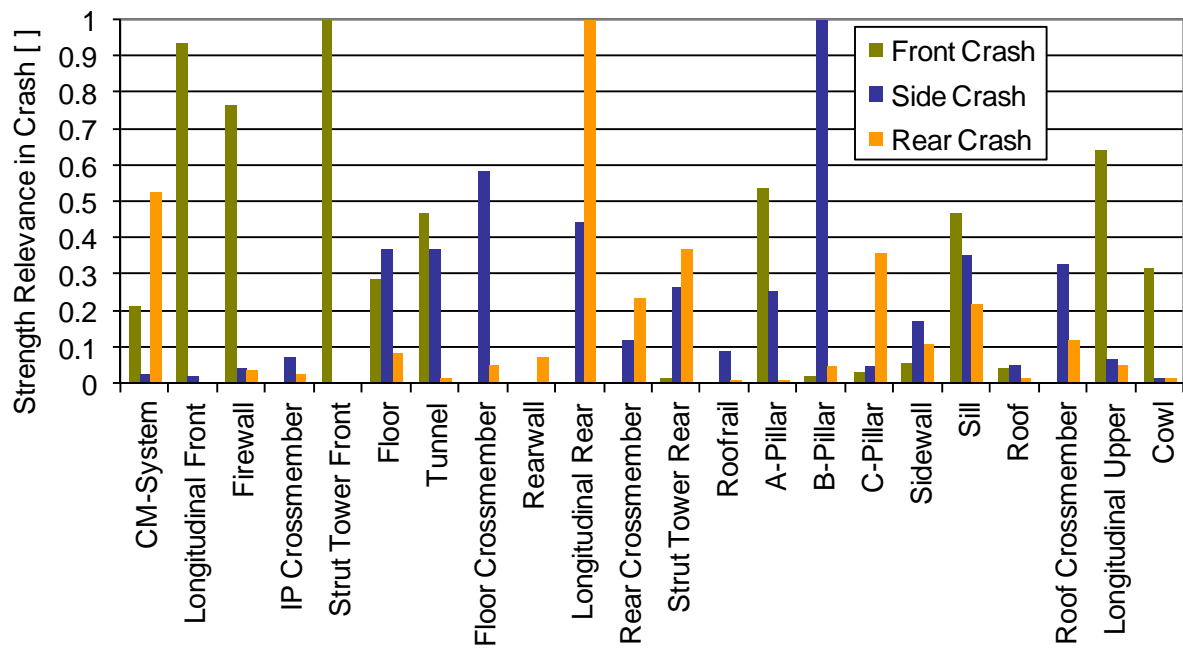


Fig. 2-22: Strength relevance in crash of body-in-white components for all load cases

For the roofrail the reason is that the roof crush test where the roofrail fulfils a dominant strength function is not considered in this study. The IP crossmember however appears to have lower relevance for the side crash as it is generally stated.

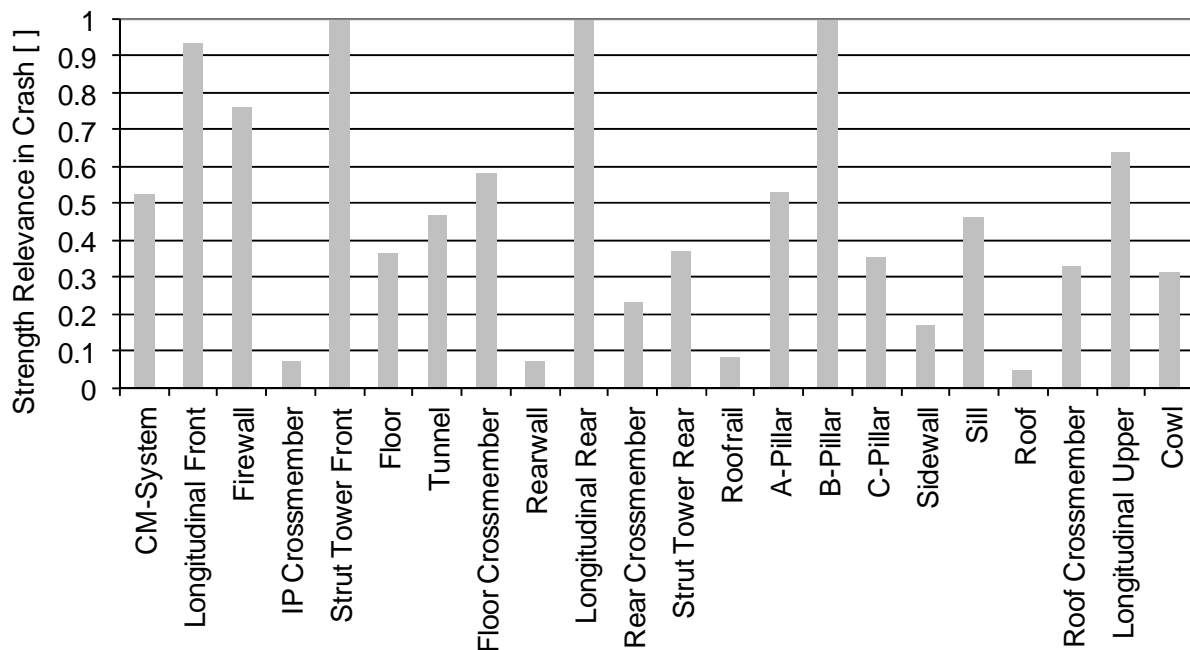


Fig. 2-23: Strength relevance in crash of door components for combined load cases

The strength relevance in crash of the door components is shown in Fig. 2-24 separately for the load cases front, side and rear crash. The values representing the total strength relevance of the door components is shown in Fig. 2-25.

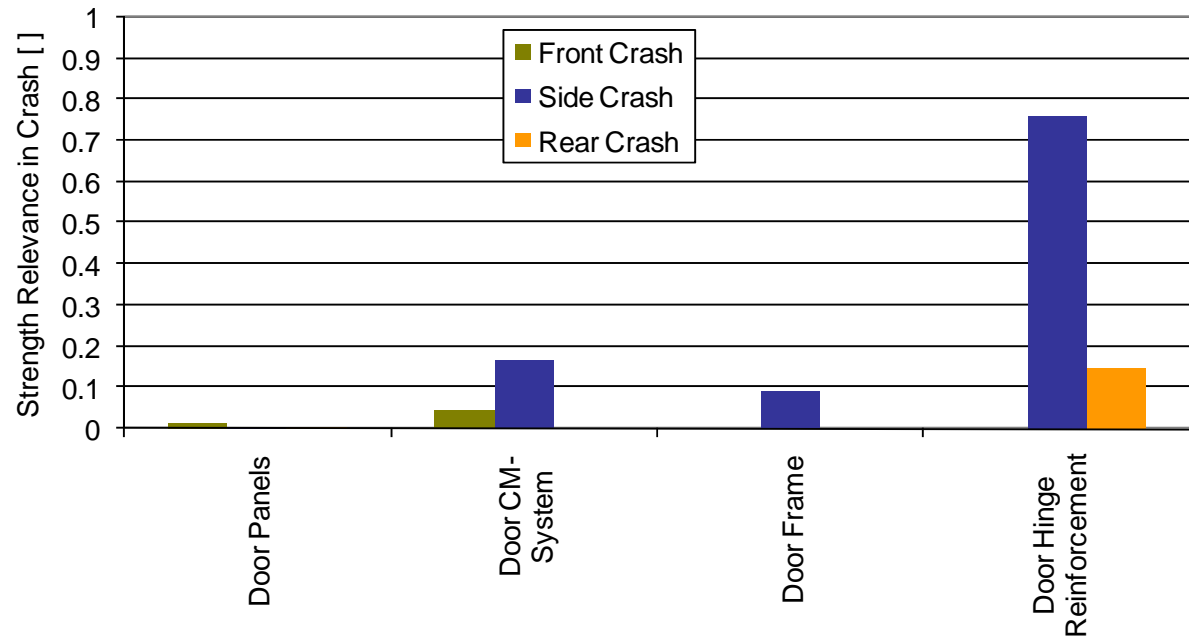


Fig. 2-24: Strength relevance in crash of door components for all load cases

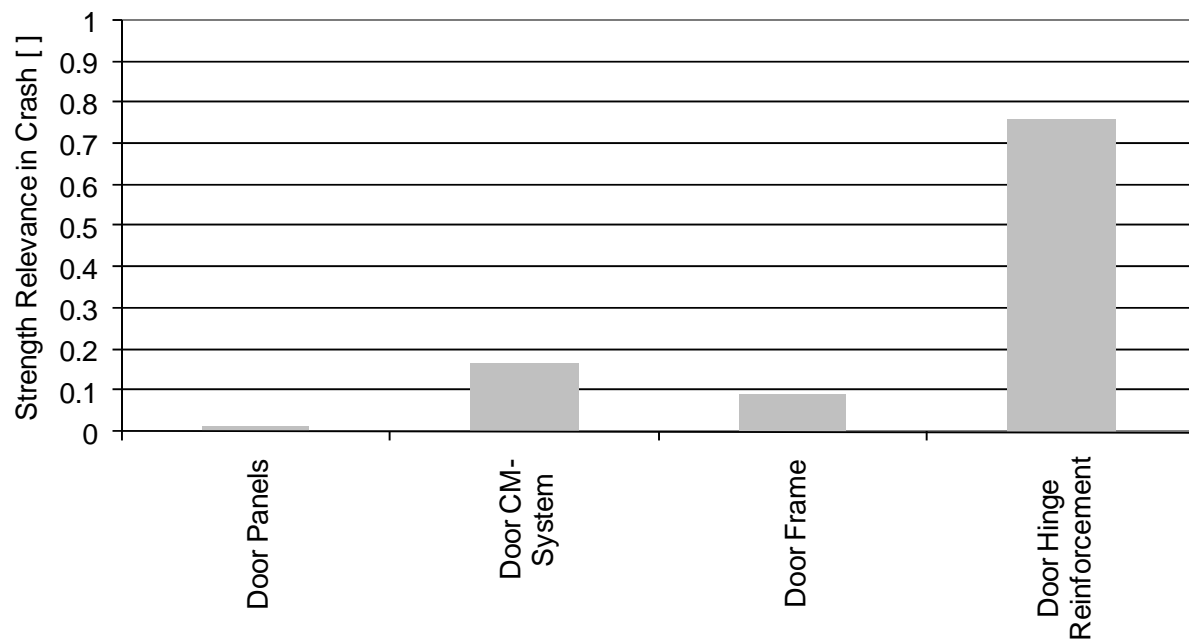


Fig. 2-25: Strength relevance in crash of door components for combined load cases

Unexpectedly, the influence of the door CM-system on the structural crash performance is relatively low. This is particularly interesting for the frontal crash, since the door CM-system is often claimed to form a load path for this crash while in fact the load transferred via the CM-system is small for the frontal crash.

3 Current Material Application in the Body-in-White

In the following chapter the results of the numerical study on stiffness and crash relevance of body components will be compared with published information and literature of material usage in current car bodies. In addition, the material usage of the reference model from the numerical analyses is compared to the information on current body material usage on the market. This will enable to access the ability of this model to serve also as a reference for the evaluation of the potential of future material concepts.

3.1 Published Information on Material Usage in Car Bodies

Publically available information on the materials and grades applied for the different body components in current vehicles can be found in car body conference proceedings. In order to get an overview of the state-of-the-art in body material application conference proceedings from the years 2007 and 2008 have been reviewed within this study. Vehicles presentations are considered only if they contain actual yield strength values and not only strength ranges for the body components. A total of 17 vehicles that offer this information depth have been identified. These analysed vehicles are classified to receive a better overview. The 17 vehicles can be classified into the classes subcompact, medium, crossover SUV and small MPV.

3.1.1 Subcompact Class

In the subcompact class four vehicles with sufficient information have been identified. These are the Fiat 500 (2007), the Opel Corsa (2006), the Ford Fiesta (2008) and the Seat Ibiza (2008). In Fig. 3-1 the overview of material usage concerning the average yield strength is shown.

There is a high range of the yield strength between the different body components. Ultra high-strength steels are used for crash management systems, B-pillars, roof rails and sills. Although several B-pillars have average yield strength of 800 MPa, there is a range between the different cars. The highest yield strength for a B-pillar is found in the Opel Corsa with 1000 MPa [MAN06], whereas the lowest one is used in the Seat Ibiza with a value 670 MPa [AUG08]. In consideration of the material usage of the different pillars, the Ford Fiesta has to be highlighted. It is the only car, which has similar and quite high used yield strength in B- and the A-pillar as well [LIE08]. The other subcompact vehicles show a huge difference in the used materials for the mentioned body components, so the average yield strength for the A-pillar is half as high as the value for the B-pillar. In comparison to the values of the CM-system and the B-pillar, all the other components show lower average yield strength Components like the roof, the sidewall, the C-pillar and the rear strut tower are processed in low strength steel.

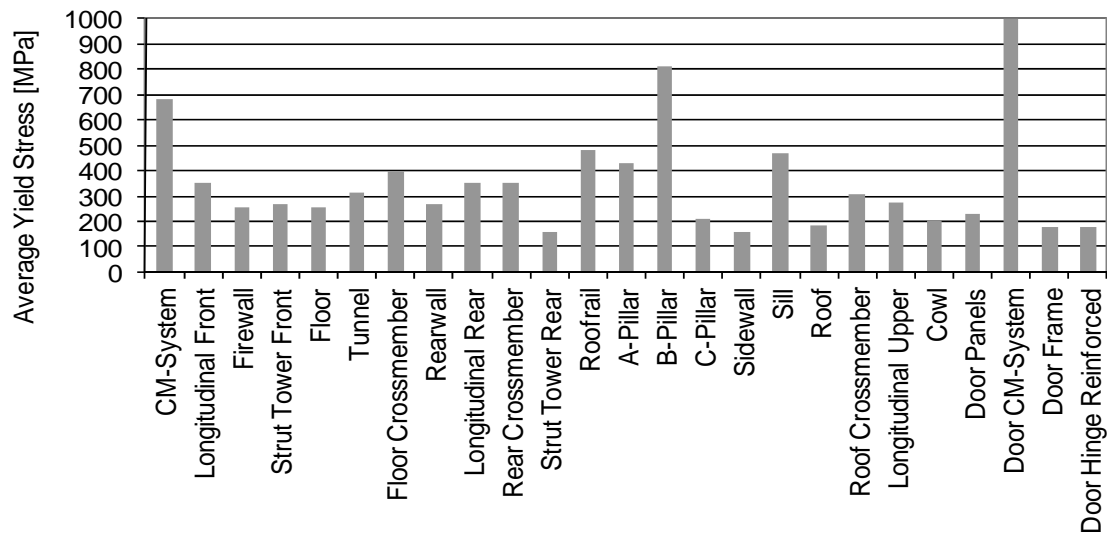


Fig. 3-1: Overview of material usage (average yield strength) in the subcompact class

3.1.2 Medium Class

As a representative choice for the medium class the vehicles Honda Accord (2007), the Renault Laguna III (2007), the Lada 2116 (2010), the Citroen C5 (2008), the Skoda Superb (2008), the Toyota Avensis (2008) and the Nissan Teana (2008) are considered. For the European cars the yield strength is the essential parameter, whereas for the Japanese cars the tensile strength is used to describe the characteristics of the body components.

Fig. 3-2 shows a primarily usage of high strength and mild steel grades for these vehicles. Only a few manufacturers use UHSS grades in crash relevant components like the front CM-system, the tunnel, the B-pillar and the door CM-system. In comparison to the vehicles of the subcompact class, there is a lower overall level of the used average yield strength.

The tensile strength is used to describe the material characteristics of Japanese cars.

Fig. 3-3 shows an overview of the material usage in these vehicles. In comparison to the European vehicles also the floor cross-member and the sill are made from ultra high-strength steels, whereas the material usage of the other components is quite similar.

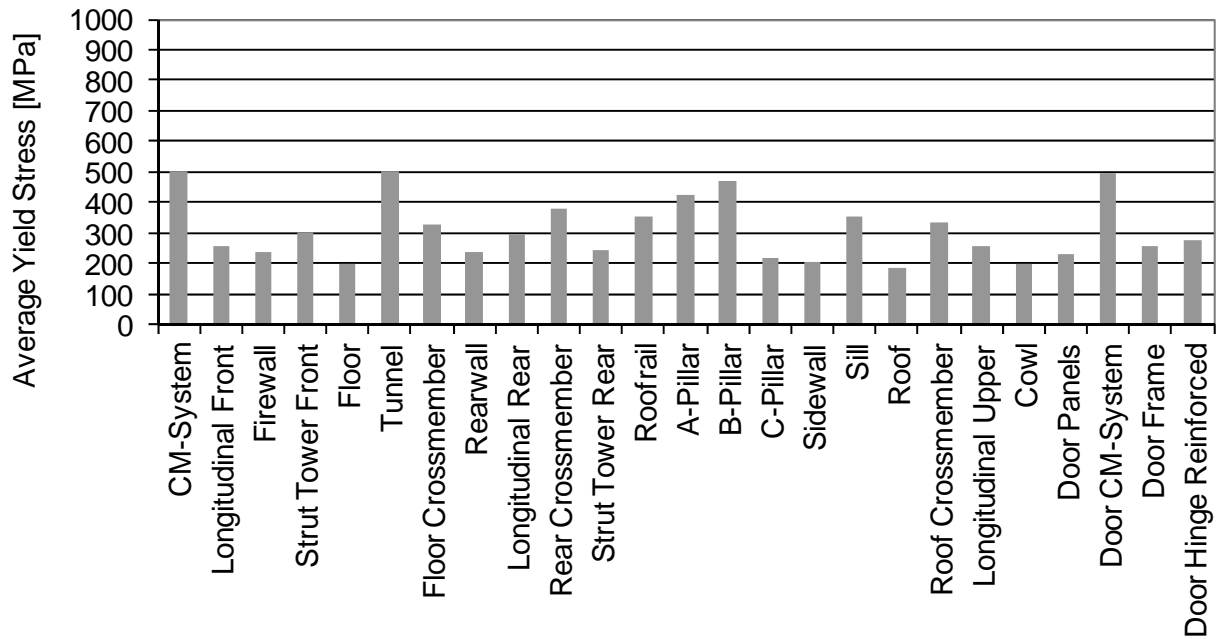


Fig. 3-2: Overview of material usage (av. yield strength) in the medium class

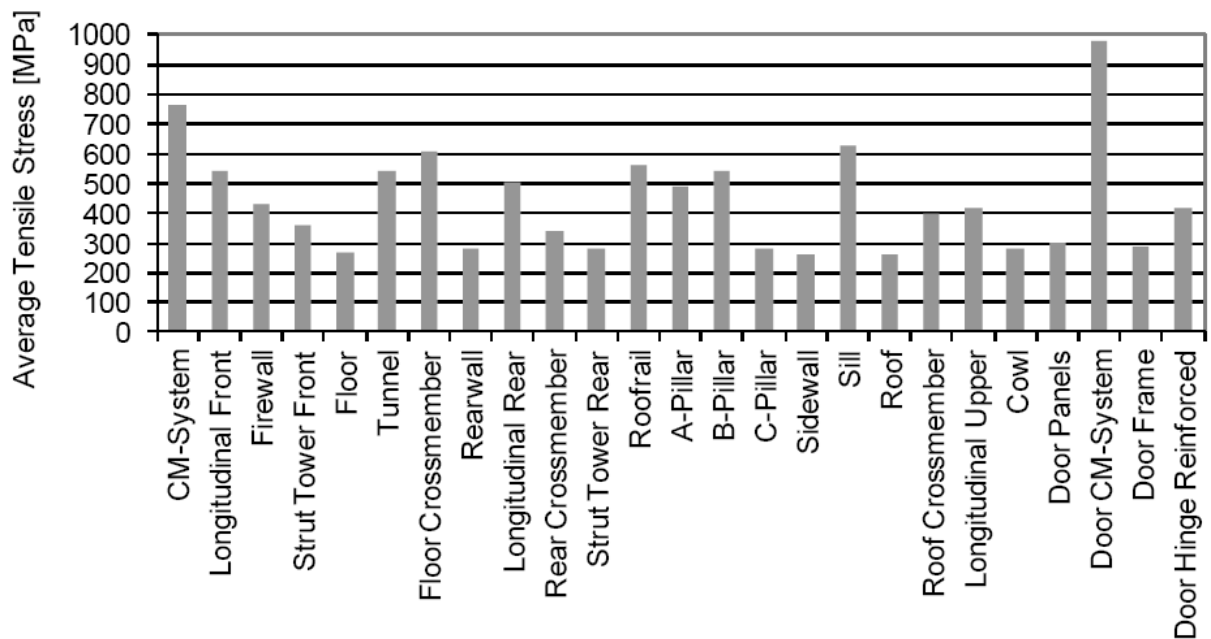


Fig. 3-3: Overview of material usage (av. tensile strength) in the Japanese medium class

3.1.3 Crossover SUV

The next identified class describes the material usage of crossover SUVs. The investigated models are the Nissan Qashqai (2007), the Opel Antara (2007), the Land Rover Freelander 2

(2007), the Volvo XC60 (2008) and the VW Tiguan (2007). The overview of material usage in this crossover SUVs is shown in Fig. 3-4.

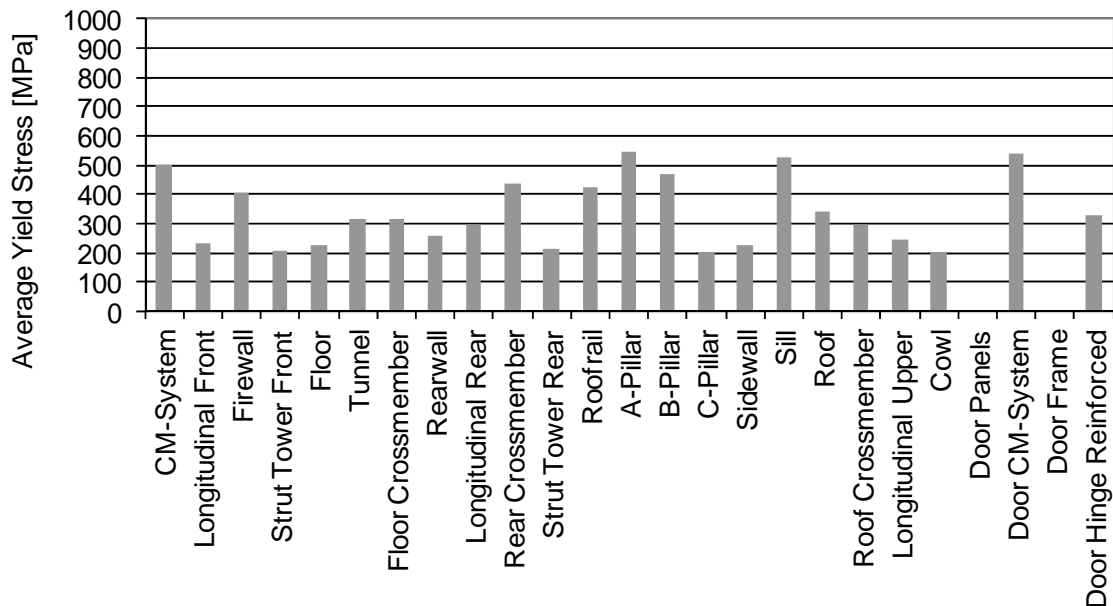


Fig. 3-4: Overview of material usage (average yield strength) in crossover SUVs

In these vehicles the front and the door crash management systems, the sill as well as the A- and B-pillars are mainly produced from high-strength steel. Basically the vehicles made by Opel, Land Rover and Nissan are made of mild- and low-strength steel grades [PIN07, WHI07, MIC07]. In contrast to that, the Volvo and the VW have higher rates of high-strength steel [NED08, RAB07]. The material usage in the Volvo XC60 represents an exception in the crossover SUV class and should be highlighted. It has an intensive usage of UHSS in its crash management system and even in the rear longitudinal beam, the A-pillar. Also the sill is made of ultra-high-strength steel.

3.1.4 Small MPV

The last contemplated class is the small MPV class. The identified vehicles are the Skoda Roomster (2006) and the Citroen C4 Picasso (2006). As a summary the overview of the material usage of small MPVs is shown in Fig. 3-5.

There are some differences but also similarities between both vehicles. E.g. the Citroen C4 Picasso has a CM-system that is made of aluminium [PAT07]. In contrast to the Citroen, the Skoda has a CM-system produced of high-strength steel [SIM06]. The door crash management system in both vehicles is also made of HSS. But in sum the Roomster has a higher rate of high-strength steel grades. For both cars mainly steel with yield strength lower than 300 MPa is used.

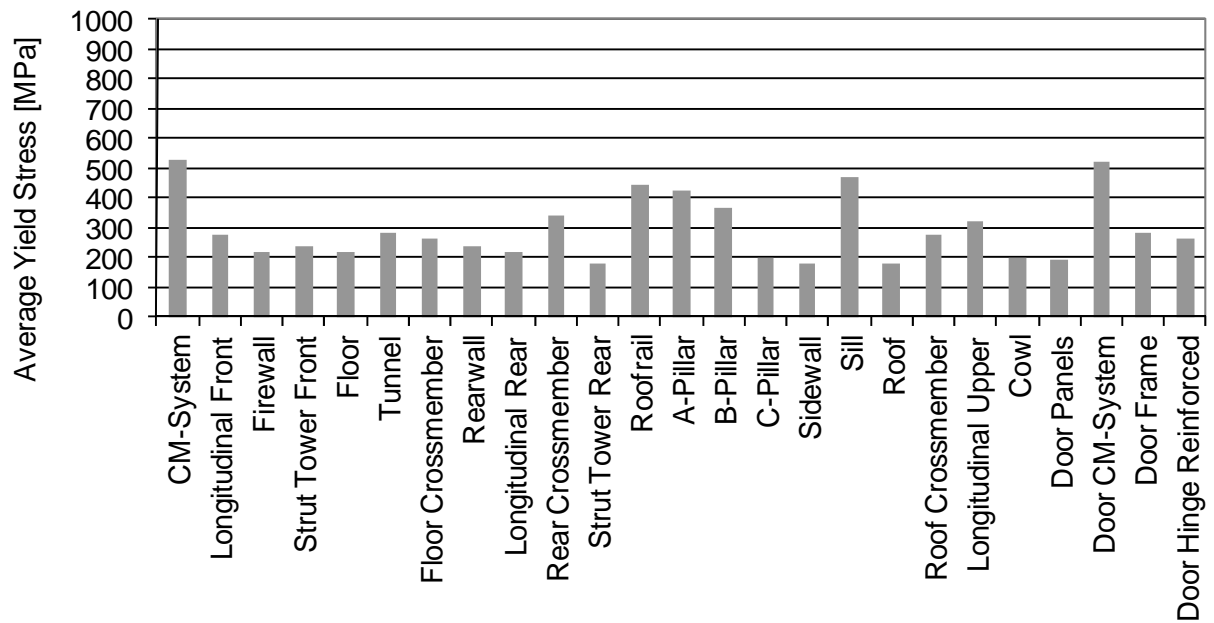


Fig. 3-5: Overview of material usage (average yield strength) in small MPVs

3.2 Evaluation of Published Information on Material Usage

After considering each of the mentioned classes, a comparison of all classes can be completed. In Fig. 3-6 the comparison of the material usage in all classes is shown.

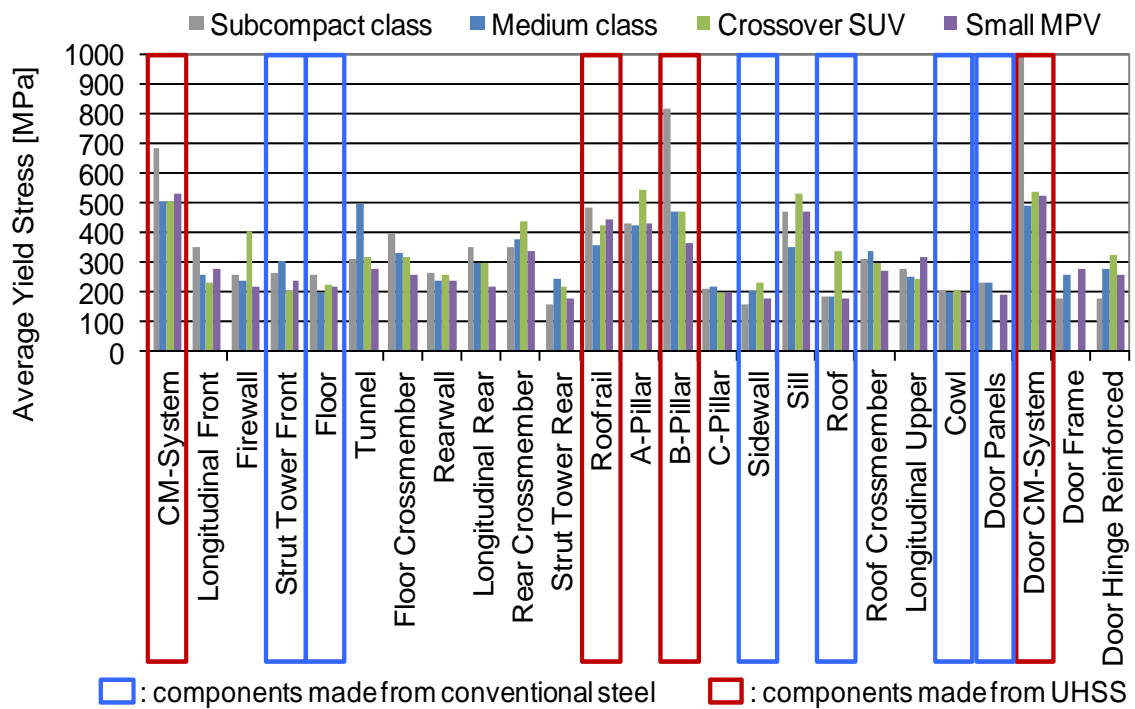


Fig. 3-6: Comparison of material usage in all classes

Components which are only made from conventional steel are highlighted with a blue box. Components made from ultra-high-strength steel are highlighted with a red box. In all regarded classes the front strut tower, the floor, the sidewall as well as the sill, the roof, the cowl and the door panels are made from conventional steel. In addition to that, the CM-system, the roofrail, the B-Pillar and the door crash management-system are made from ultra-high-strength steel. It is also noticeable, that many of the components show the highest yield strength in the subcompact class. The CM-system and the B-pillar of subcompact class vehicles have much higher average yield strength than the ones of other classes.

3.3 Comparison to Reference Model

The SLC-reference model is a compact class vehicle. This vehicle class is located between the subcompact class and the medium class. Consequently, the material usage of the SLC-reference vehicle is compared to the arithmetic average of the material strength determined for subcompact class vehicles and medium class vehicles in the literature research. In Fig. 3-7 the average component yield strength values are shown for the SLC-reference vehicle and the average of assessed subcompact and medium class vehicles. The SLC-reference shows a state-of-the-art steel material concept meaning that modern high strength and ultra high strength steels are applied.

Fig. 3-7 shows, that the average component material strength of the SLC-reference qualitatively matches to the average material component strength of the subcompact and medium class vehicles from the literature research very well. However, quantitatively there are some differences. In particular for the SLC-model, the average material strength of the B-pillar, the roofrail and the CM-system is higher than for the subcompact and medium class vehicles. For the CM-system there is a difference of 400 MPa between the SLC-reference and the result of the literature research.

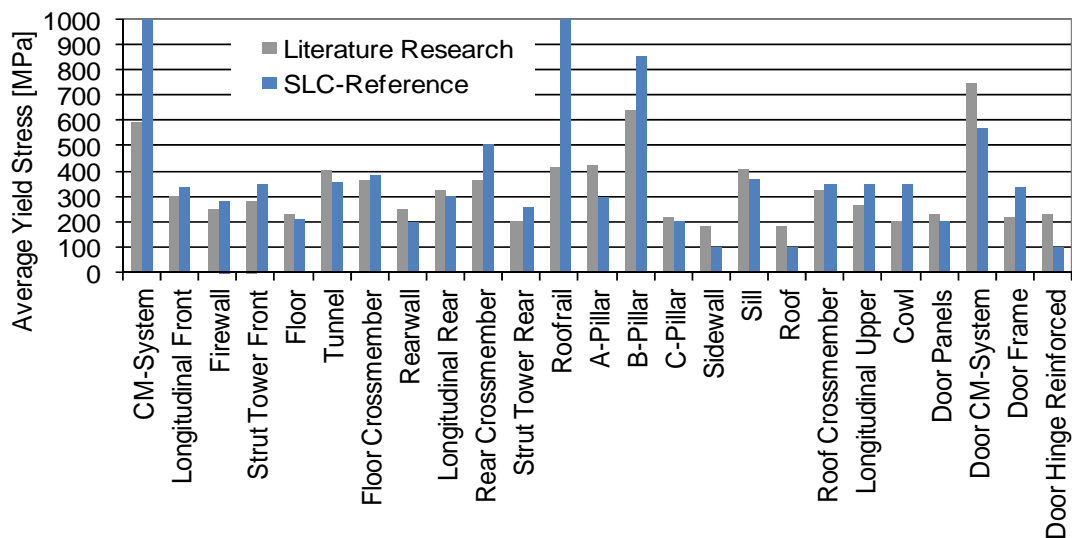


Fig. 3-7: Comparison of research results (subcompact and medium) to SLC-reference

The yield strength of the roofrail is in the SLC-reference almost 600 MPa higher, than the yield strength of the literature research. Nevertheless, for most of the components there are only small quantitative differences in material strength. Therefore, the material concept of the SLC-reference model can be regarded as state-of-the-art within its class. Thus, it can serve as a reference for the following evaluation of the lightweight potential of future material concepts.

4 Lightweight Potential of Future Car Body Material Concepts

To describe the lightweight potential of future car body materials concepts the results of the numerical analyses are interpreted, first. Afterwards a potential approach is presented describing how the quantitative information on stiffness and strength relevance of car body components can be used to assess the remaining weight reduction potential of current car bodies. The approach is applied exemplarily for the SLC-reference vehicle considering both a future high strength steel scenario and an aluminium scenario.

4.1 Interpretation of Results from Numerical Analyses

The results from the numerical analyses are described in this chapter. In a first step the evaluation is completed for an evaluation of the stiffness and the strength relevance in crash for all load cases. Fig. 4-1 shows this evaluation in the front crash by usage of the size related values (see chapter 2). The diagram is separated in three areas. Components in the upper left part of this diagram (e.g. the rear crossmember) have high stiffness relevance and low strength relevance in crash. The components in the lower right part (e.g. the longitudinal front) have low stiffness relevance and high strength relevance in crash. In the middle area components can be found that are important concerning stiffness as well as strength in case of a crash.

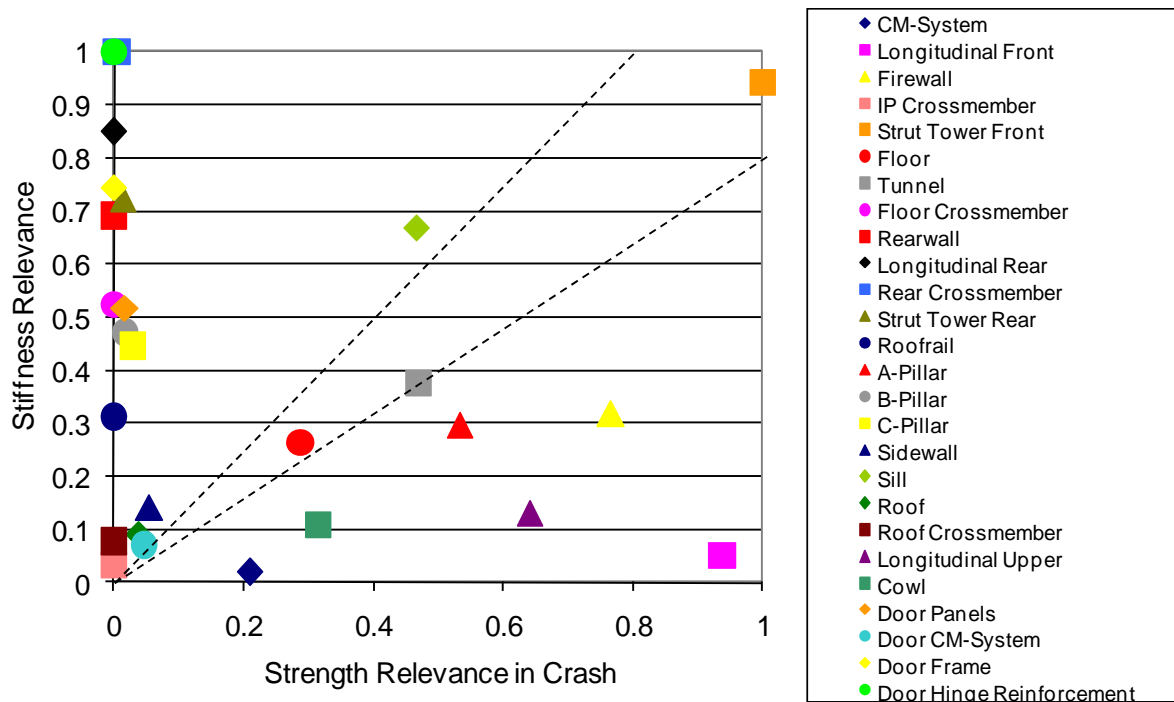


Fig. 4-1: Evaluation of body components (front crash)

The position of the components in the diagram shows the relation between strength and stiffness of each component. E.g. the strut tower front has in that load case high stiffness relevance and high strength relevance in crash, but the rear crossmember has high stiffness

relevance and no strength relevance. Expectedly in that load case, the components with high strength relevance in crash are located in the front area of a vehicle.

In the side crash load case much more components are affected concerning the strength relevance in crash (Fig. 4-2). The components with the highest strength relevance in crash are the B-pillar, the door hinge reinforcement and the floor crossmember. These components have medium stiffness relevance.

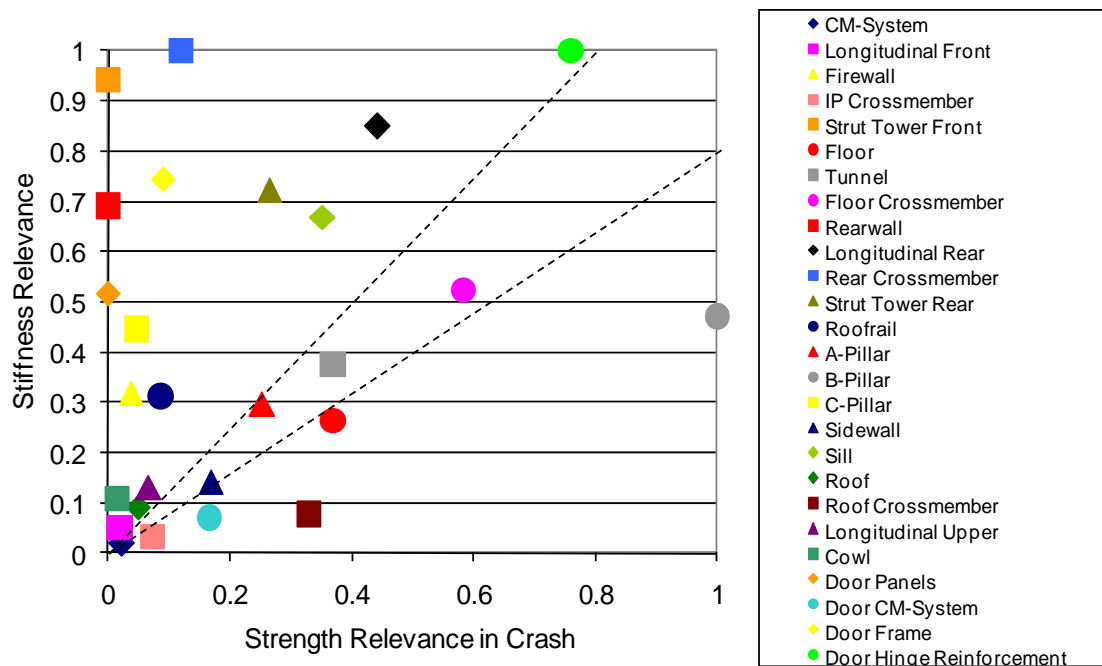


Fig. 4-2: Evaluation of body components (side crash)

Fig. 4-3 shows the most important components for the rear crash. These are the longitudinal rear, the crash management system, the strut tower rear and the C-pillar. The single evaluations of these crash load cases are gathered to one overall evaluation (Fig. 4-4). Therefore the maximum values of the single crash load cases are taken. This means e.g. that the tunnel has the highest strength relevance in crash in the front load case. So the highest value is taken for the evaluation of the overall strength relevance. The value for the stiffness relevance always stays on the same level, because it does not depend on the crash load cases.

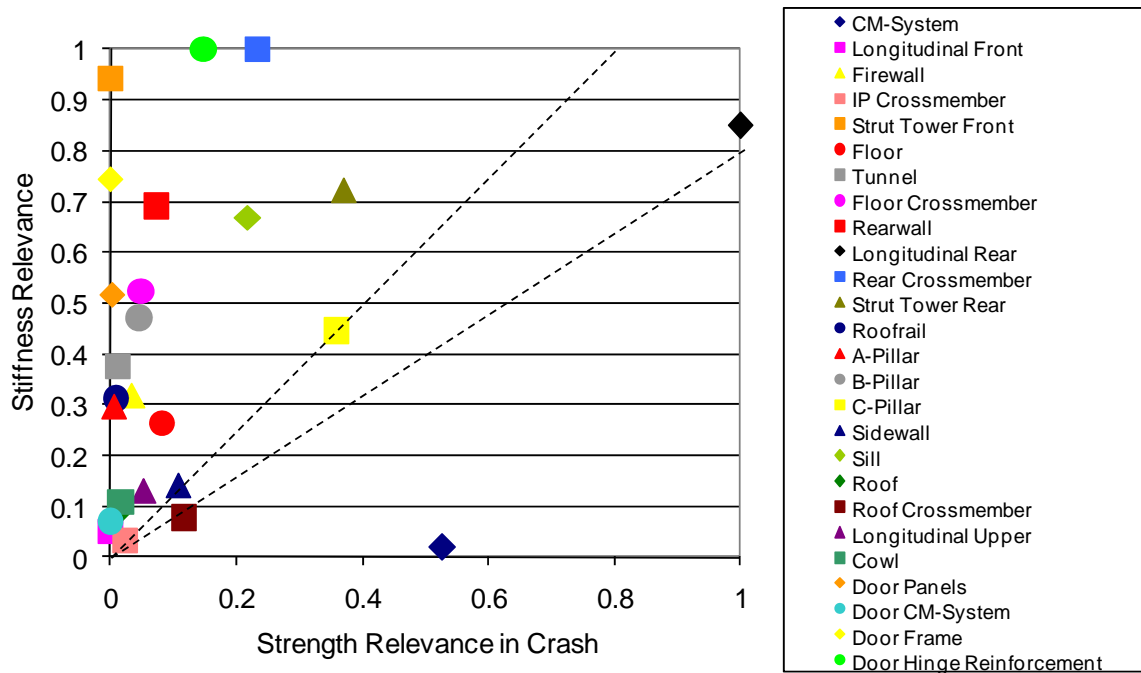


Fig. 4-3: Evaluation of body components (rear crash)

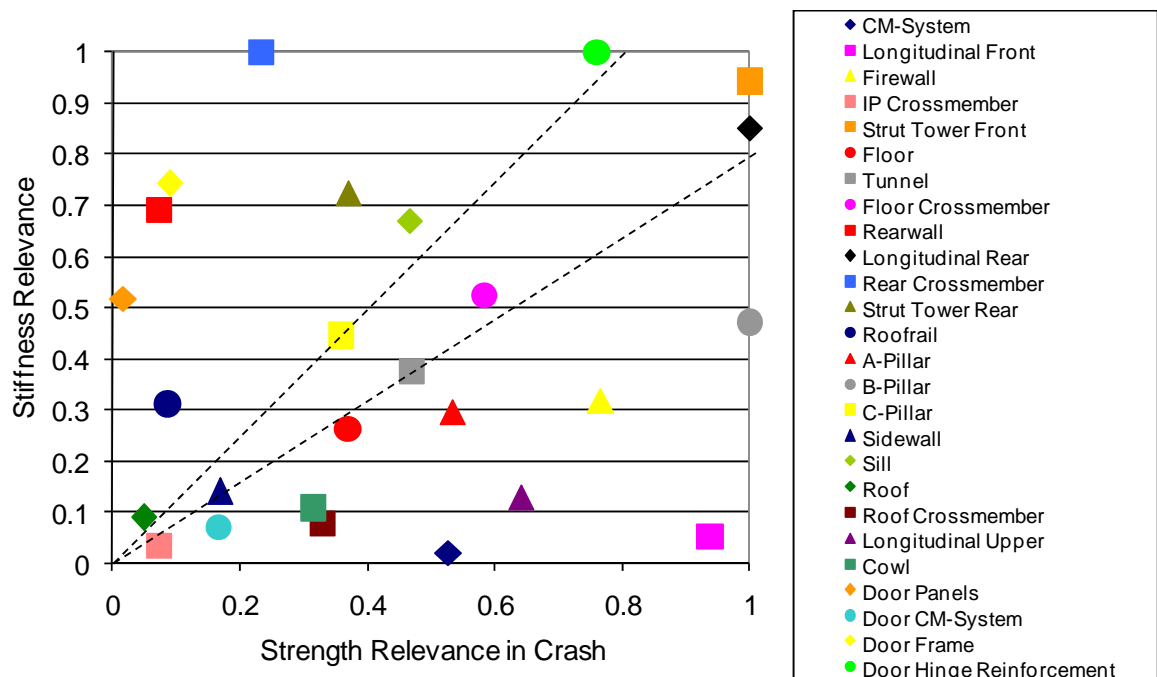


Fig. 4-4: Evaluation of body components (maximum values)

In chapter 3.2 (Fig. 3-6) the most relevant components for the usage of UHSS and conventional steel are highlighted. Now they are compared with stiffness relevance and the strength relevance in crash (maximum values) of the SLC-reference. This evaluation is summarised in Fig. 4-5. In addition the criteria yield strength is introduced. It can be calculated by the division of the average yield strength of a component with the value of the maximum average

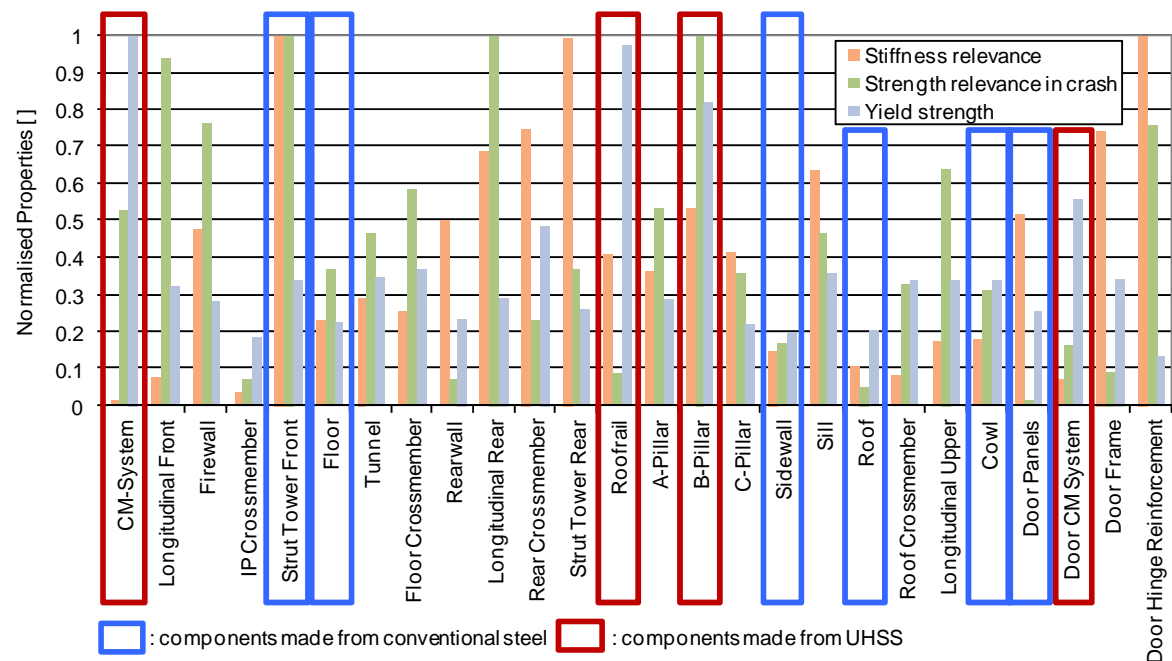


Fig. 4-5: Overview of the evaluation results

Components typically made of conventional steel have low yield strength in this diagram. In addition they also have low demands on stiffness and crash, except in the strut tower front. That might be a reason, why this component is already realised as an aluminium part in vehicles like the BMW X5. On the other side all components that are highlighted as parts typically made from UHSS have higher values for the yield strength. In most cases these components have high demands on strength in case of a crash.

The position in the evaluation of these components is shown in Fig. 4-6. Except the roofrail, all other components identified as typically made of UHSS can be found in the area for high strength relevance in crash and low stiffness relevance. The roofrail would also be more crash relevant if the rollover would be considered as an additional load case. The body components that are typically made of conventional steel can be found in all areas, but with values for strength relevance in crash lower than 0.4. Only the strut tower front has very high strength relevance.

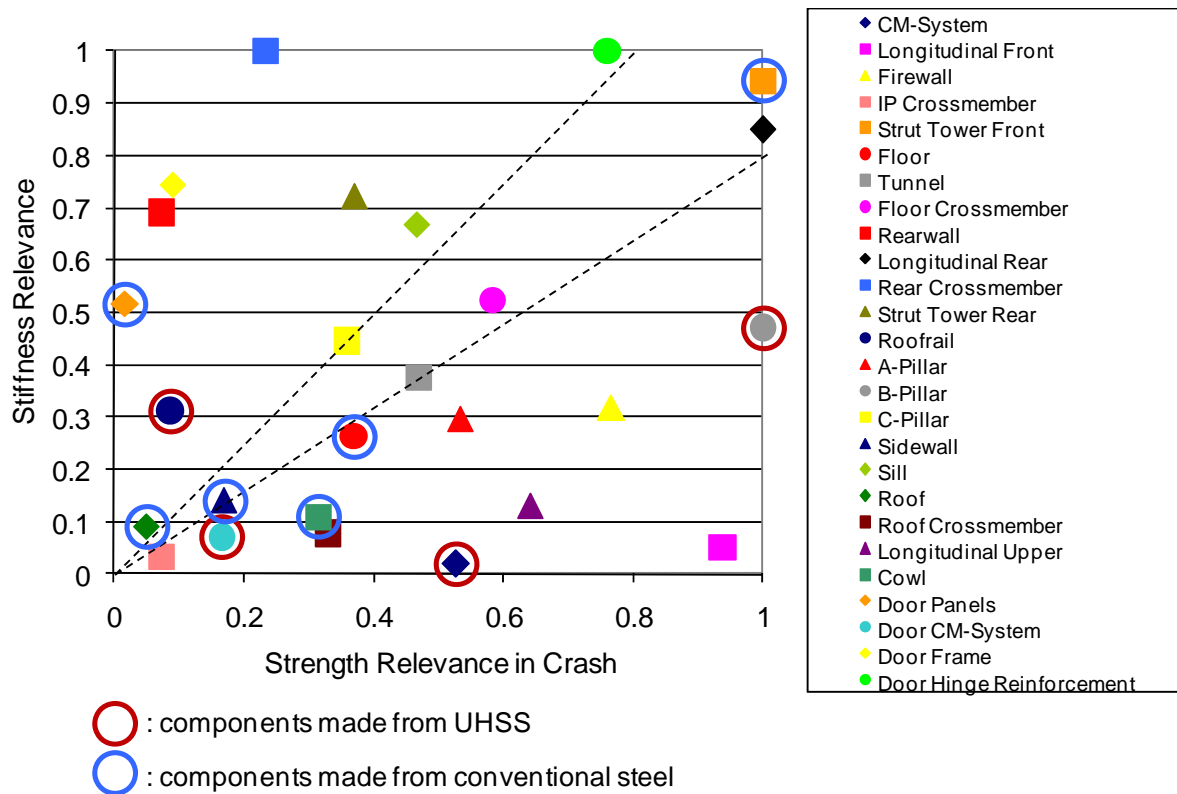


Fig. 4-6: Evaluation of the UHSS body components

4.2 Potential of High-Strength Steel

The following subsection describes a possible approach of assessing the weight reduction potential for a certain body component of steel when increasing the yield strength of the steel used for that component based on the following boundary conditions:

- Typical, empirical ranges for weight reduction achievable by strength increase have to be available.
- The increase in yield strength for a certain component is proportional with the strength relevance of this component and the difference between maximum yield strength available and current yield strength of the component. This is in order to apply high strength material according to the actual requirements.
- The weight reduction potential decreases with increasing stiffness relevance, since it is difficult to compensate for the decrease in stiffness caused by downgauging of highly stiffness relevant components.
- Differences in ultimate strain, formability, joinability, etc. of steel grades are not considered.
- Buckling stability is not particularly accounted for.
- Package restrictions are not considered.

Empirical ranges for possible weight reduction of steel components by strength increase is publically available from various steel manufacturers. An example is given in [SUE09]. The typical ranges claimed are shown in Fig. 4-7.

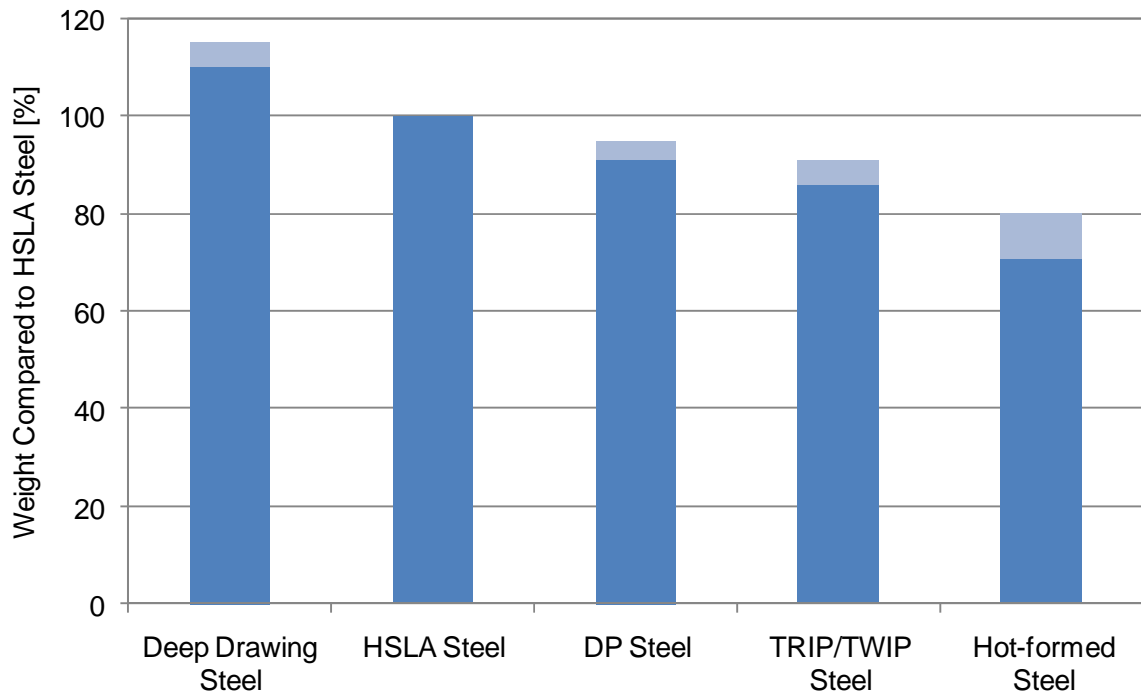


Fig. 4-7: Typically published weight reduction potential of steel grades

Considering the typical yield strength levels of the steel grades referred to in Fig. 4-7 a linear regression line for determination of the possible weight reduction enabled by a certain increase in material strength can be derived. This regression line is shown in Fig. 4-8. Together with the strength relevance, the stiffness relevance, the limit of weight reduction (downgauge) concerning stiffness and the current yield strength of the components, the regression line forms the basic input for the assessment approach shown in Fig. 4-9. As the flow scheme in Fig. 4-9 indicates, the possible weight reduction for a certain component is determined separately for equivalent strength and equivalent stiffness or tolerable stiffness reduction respectively. The minimum of both is regarded as the possible weight reduction for the specific component, since this defines the critical dimensioning.

In order to determine the weight reduction possible for equivalent stiffness of the component the maximum possible weight reduction has to be defined. For the exemplary application of the approach this value is set equal to the maximum weight reduction possible for equivalent strength. With 44 % this is a progressive approach. After that, the actual weight reduction for a certain component can be calculated based on the stiffness relevance of the component and the above described correlation between weight reduction and stiffness relevance. A linear approach is used in this case.

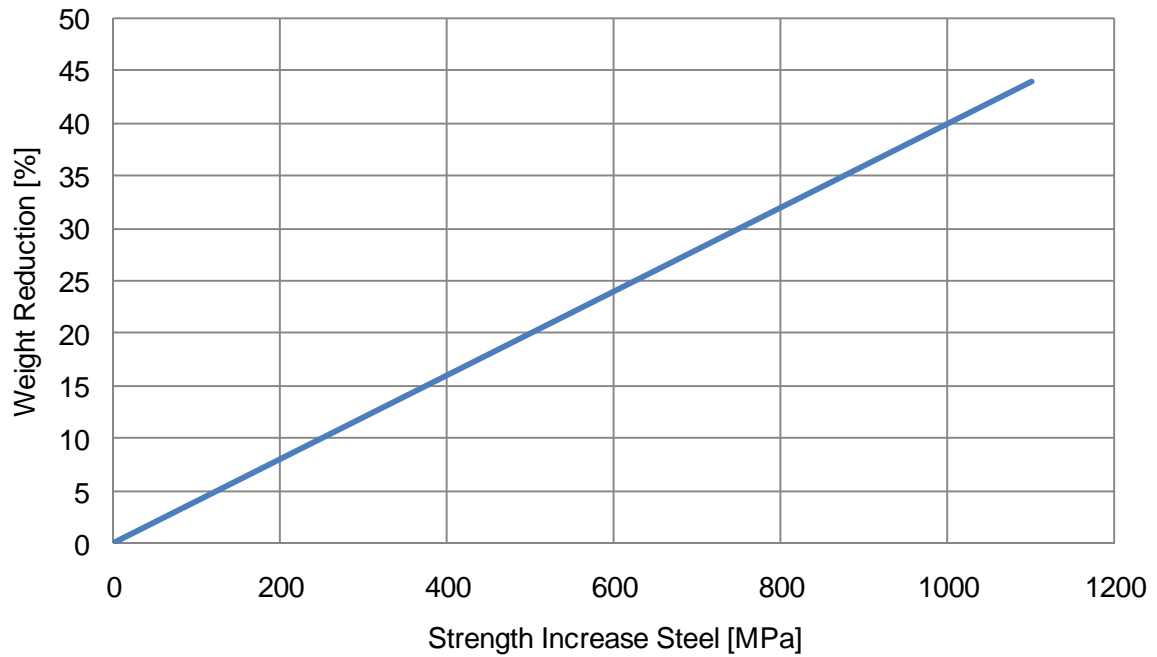


Fig. 4-8: Regression line for weight reduction by steel strength increase

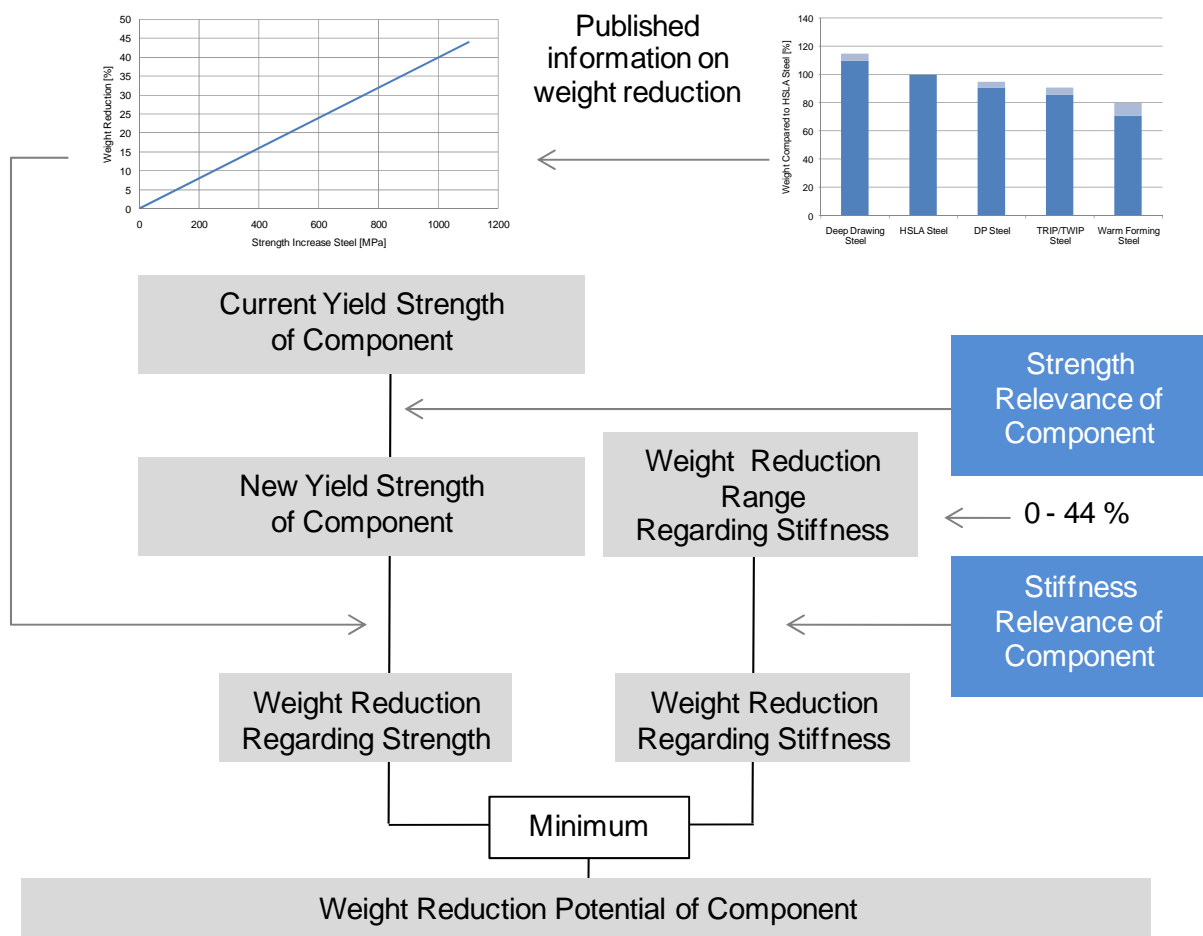


Fig. 4-9: Flow scheme of approach for weight reduction assessment (steel)

For determination of the possible weight reduction for equivalent strength two steps are required. First, an appropriate material strength increase is calculated for the specific component. As mentioned above, this is done by increasing the material strength linearly with the strength relevance of the component. The maximum increase is defined by the difference of maximum yield strength of steel grades, which is 1200 MPa for the exemplary approach considered, and the current yield strength of the component. In the subsequent step the possible weight reduction can be calculated using the new yield strength of the component and the regression line shown in Fig. 4-8.

For the SLC-reference vehicle the required input data for the approach described above is available. Therefore, the approach can exemplarily be applied for the structure of this vehicle in order to obtain an indication regarding the remaining weight reduction potential achievable in current car bodies by intensive application of high-strength steels.

Following the approach the limit of achievable weight reduction by application of high-strength steel is assessed to be 11 % in total for the entire car body including closures. This requires almost doubling the average yield strength of the entire components from 338 MPa to 648 MPa. However, it has to be mentioned, that for the components limited by the requirement of tolerable stiffness reduction the new yield strength can be decreased. In addition, the weight reduction potential of 11 % can be regarded to be at the upper limit, because of the simplifications made for the boundary conditions, e.g. buckling stability, and the high maximum limit of weight reduction set for tolerable stiffness decrease.

4.3 Potential of Aluminium

The following subsection describes a possible approach of assessing the weight reduction potential for a certain body component when aluminium is substituted for steel.

In order to compare the results, this approach is similar to the approach assessing the potential of high-strength steel as described in the previous subchapter. Consequently, most of the boundary conditions are consistent:

- Typical, empirical ranges for weight reduction achievable by substitution of aluminium for steel have to be available.
- The yield strength of the aluminium alloy used for a certain component is determined proportional with the strength relevance of this component and the difference between maximum yield strength available and minimum yield strength of aluminium. This is in order to apply high strength material according to the actual requirements.
- The weight reduction potential decreases with increasing stiffness relevance, since it is difficult to compensate for the decrease in stiffness caused by downgauging of highly stiffness relevant components. For reasons for comparability the relation between weight reduction potential decrease and stiffness relevance is identical with the approach used for determination of the potential of high-strength steel. However, in

practice the higher wall thickness of aluminium components enables larger section increase for stiffness compensation without buckling issues.

- Differences in ultimate strain, formability and brittleness of aluminium grades are not considered.
- Package restrictions are not considered.

The maximum achievable weight reduction using aluminium in comparison to steel is different for strength in crash dominated and stiffness dominated components. In addition, the actual weight reduction for strength in crash dominated components is depending on the yield strength of the substituted steel component. Empirical ranges of the achievable weight reduction when substituting aluminium for steel are provided by Hydro Aluminium [PED09].

Compared to a similar steel component using aluminium the weight of stiffness dominated components can be reduced by up to 50 % in a range starting from 0 %. The actual weight reduction depends on the shape of the part and the load case. The highest weight reduction can be achieved for thin-walled, plane structures. The lowest weight reduction can be achieved for beams. However in practice with respect to typical sections and loads of automotive beams the lower value for weight reduction is rather 30 %, not 0 %.

If the design of a component is dominated by the requirement for strength in crash, the achievable weight reduction when substituting aluminium for steel depends on several influencing factors. First of all, it has to be determined whether energy absorption, e.g. for crash boxes, or strength in terms of deformation resistance, e.g. for B-Pillars, is the main design criterion of the component. This is necessary since the achievable weight reduction is higher for energy absorbing components because of the strong influence of the sheet-thickness on both crush-force and buckling stability. In addition, the actual weight reduction is not only depending on the yield strength of the substituted steel component but also on the yield strength of the aluminium alloy used for substitution. This means for a steel component with the same yield strength different values of weight reduction can be achieved depending on the chosen yield strength of the aluminium alloy. The diagram at the top of Fig. 4-10 summarises the mentioned influencing factors in a simplified linear approach.

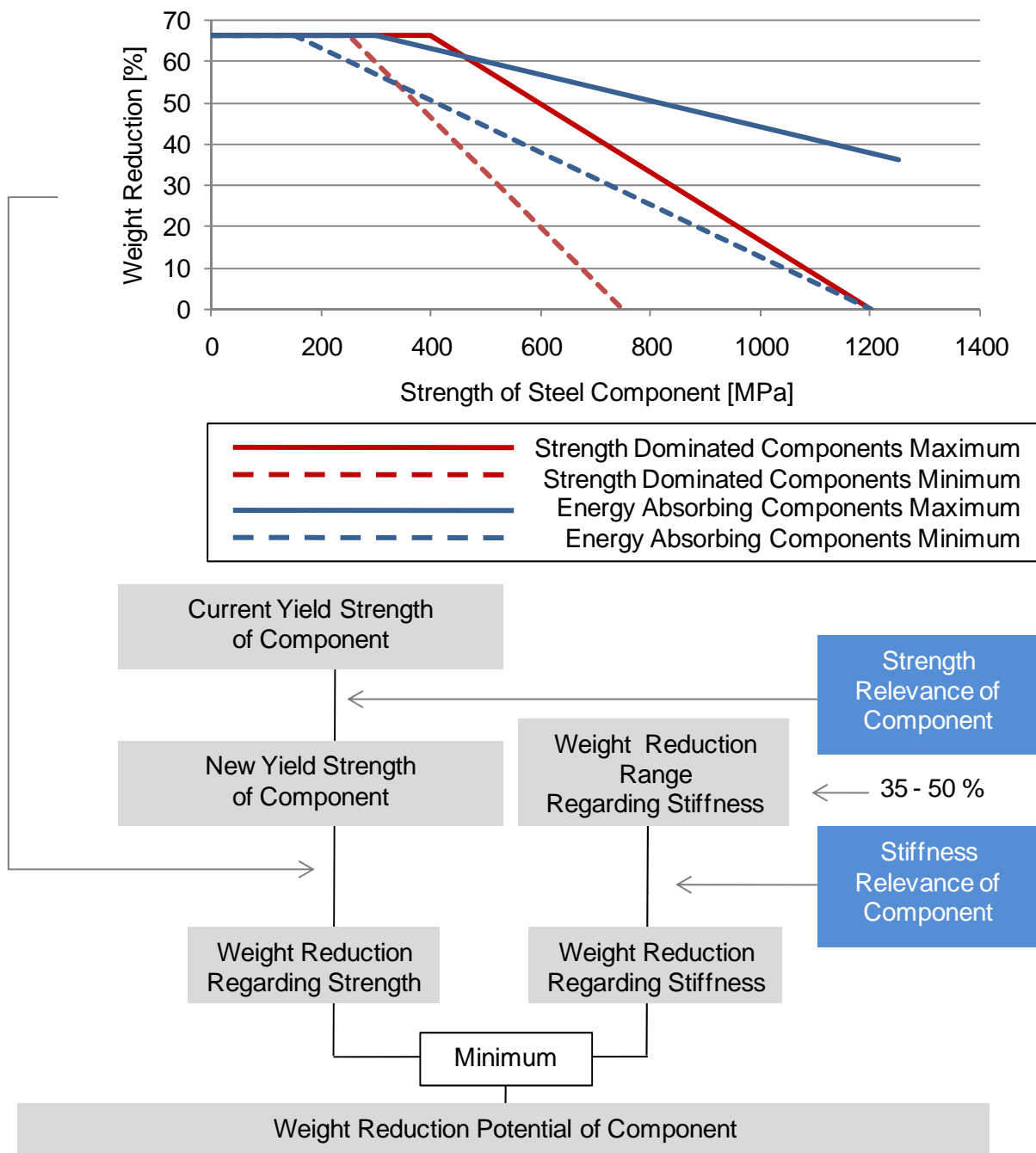


Fig. 4-10: Flow scheme of approach for weight reduction assessment (aluminium)

For strength dominated components a weight reduction of 66 % defined by the density ratio of aluminium and steel can be achieved until the yield strength of steel exceeds the maximum available yield strength of aluminium. Then the achievable weight reduction decreases and is equal to zero for yield strength of steel that is three times the aluminium yield strength, since the stresses have to be reduced by upgauging. The regression lines for energy absorbing components are determined by numerical and experimental studies.

The approach for assessment of the weight reduction potential of aluminium as shown by the flow scheme in Fig. 4-10 is similar to the approach for high-strength steel shown in Fig. 4-9. As the flow scheme in Fig. 4-10 indicates, the possible weight reduction for a certain component is determined separately for equivalent strength and equivalent stiffness. The minimum of both is regarded as the possible weight reduction for the specific component, since this defines the critical dimensioning.

In order to determine the weight reduction possible for equivalent stiffness of the component the maximum and minimum achievable weight reduction is defined by the range from 30 % to 50 % as described above [PED09]. The actual weight reduction for a certain component with regard to stiffness can be calculated based on the stiffness relevance of the component and the above described correlation between weight reduction and stiffness relevance. A linear approach is used in this case.

In the approach proposed two steps are required for determination of the achievable weight reduction for equivalent strength. First, an appropriate material strength is calculated for the specific component. As mentioned above, this is done by increasing the material strength linearly with the strength relevance of the component. For strength dominated components the yield strength of the aluminium alloy used can vary in a range from 250 MPa to 400 MPa while the range for energy absorbing components is from 150 MPa to 250 MPa. However, if the yield strength of the substituted steel component is lower than the minimum aluminium yield strength, the yield strength of the steel component is selected for the aluminium component. In the subsequent step the possible weight reduction can be calculated using the yield strength of the aluminium component, the yield strength of the substituted steel component and the according regression line from the diagram shown at the top of Fig. 4-10.

For the SLC-reference vehicle the required input data for the approach described above is available. Therefore, the approach can exemplarily be applied for the structure of this vehicle. This enables a comparison of the assessed weight reduction potential of a high-strength steel intensive vehicle as described in the previous subchapter to the weight reduction potential of a full aluminium vehicle. In addition, the results can serve as a basis to identify suitable components for aluminium application in a multi-material design approach.

Following the approach the achievable weight reduction when substituting aluminium for steel in a state-of-the-art car body including closures is assessed to be 40 %. The average yield strength of the aluminium car body is with 244 MPa lower than the average yield strength of the steel car body with 338 MPa. Like for the high-strength steel intensive car body it has to be mentioned, that for the components limited by the stiffness requirement the new yield strength could be decreased.

The weight reduction potential of 40 % can be regarded to be at the upper limit. In practice, additional aspects will have to be considered such as the joinability, the performance of the joints or nodes connecting the different components or the NVH performance. Therefore it may not be possible to fully exploit the indicated weight reduction potential of high strength

aluminium alloys. However, similar restrictions may also apply to the substitution of ultra-high-strength steel grades for conventional steel grades.

It has to be mentioned that in contrast to perpetually mentioned arguments the weight reduction potential of aluminium is limited by strength requirements for few components, only. The reason is that even in state-of-the-art car bodies most of the steel components are still made from steel grades that show yield strength in ranges that aluminium can compete with. This situation can be regarded to change in the future only to a limited extent, since many components are not suitable for efficient high-strength material usage. For many components stiffness will maintain the decisive criterion.

It can be expected that in future body concepts mountable components will have the best chances to be made of light materials. If lightweight design becomes more important due to emission regulations the market penetration of aluminium closures in the middle class and the compact class is a realistic scenario.

5 Interviews with OEM Body Experts

The results of the FE-simulations and the literature research are compared with experts' answers. Therefore experts, who work in the automotive industry, are interviewed. To ensure the consistence of the interviews, a questionnaire is used, that contains the important questions. As an introducing question, the importance of politics, ecology, economy driving dynamics and alternative powertrains concerning the importance for lightweight design is evaluated. The experts are asked to evaluate the importance of these factors of a scale between 1 (very important) and 6 (very unimportant). By this approach it is possible to identify the influence e.g. of the reduction of fuel consumption (ecology) or the optimisation of profit (economy) on the lightweight design. The resulting answers are summarised in Fig. 5-1.

In general the experts say that the importance of all factors except economy will increase in future. The reason for that is the decrease of CO₂-emissions as the most important factor. This point is estimated to be the main driver for future innovations. For that reason ecology will get more importance than economy in future. In addition alternative powertrains will get more importance pushed by the increasing influence of politics. Because of the higher system weight of these powertrain components, lightweight design is very important. Additionally the European Union enlarges the pressure on the automotive industry to develop innovative technologies. In comparison to that, also driving dynamics is a relevant factor for the usage of lightweight design, but alternative powertrains are estimated to be more important in future.

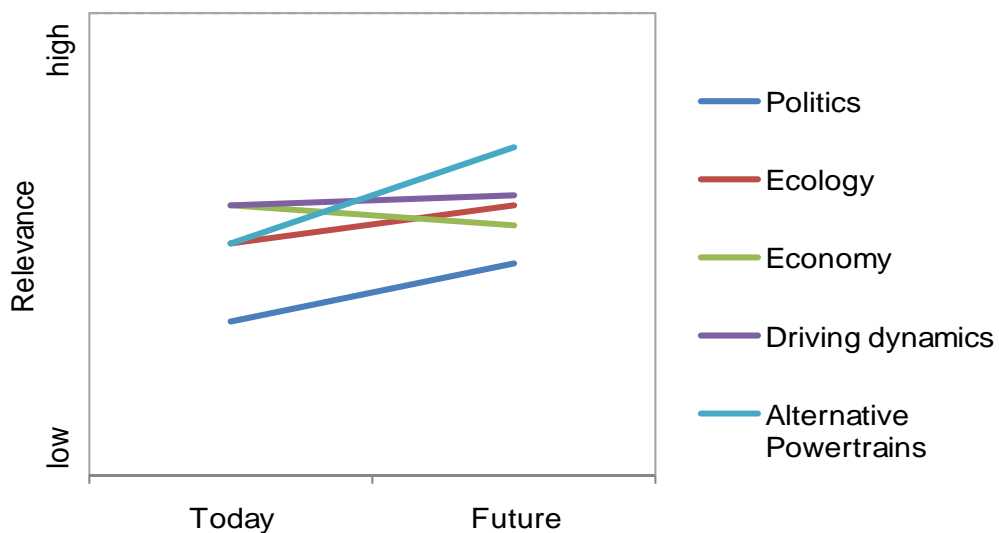


Fig. 5-1: Development of drivers for lightweight design

In the next question the experts are asked to describe the ranking of lightweight design for the reduction of fuel consumption and emissions in comparison to other measures. Therefore five measures are identified, that are more important than lightweight design (Fig. 5-2). If a column is located in the right area of this diagram, lightweight design is less important than

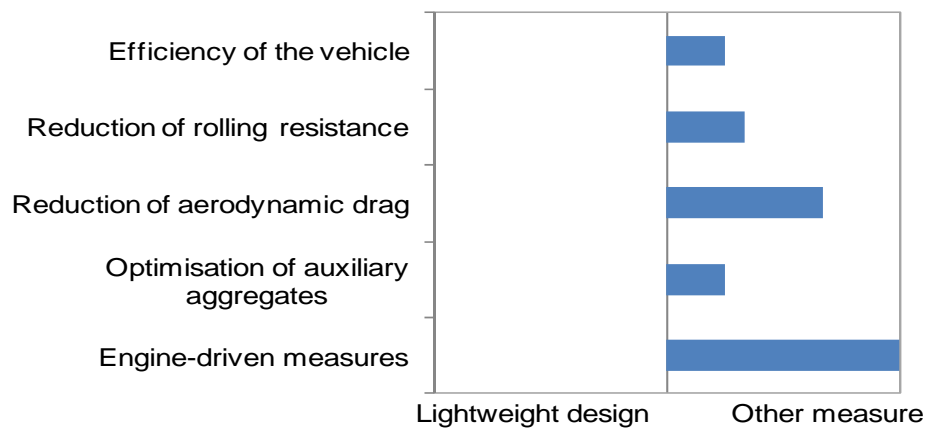


Fig. 5-2: Ranking of lightweight design

As the most important measures for all OEMs the reduction of fuel consumption by engine driven measures are identified, because 1/3 of the CO₂-emissions result from engine factors. As the second very important measure, especially in a short-term time, the reduction of the aerodynamic drag was named. The reason is, that modifications of the body are easier to realise, than lightweight measures. An example for these measures is adjustable lamellae in front of the cooling system or underbody coverings that are easy to realise and improve the aerodynamic drag of a vehicle. On the third place the reduction of the rolling resistance is an important factor, especially as a short-term measure. Complementary measures will be introduced by law in 2012. Additional short-term measures as the optimisation of auxiliary aggregates will decrease the emissions of vehicles and improve the vehicle's efficiency (e.g. transmission loss). Beneath the improvement of the air-conditioning system's efficiency also the introduction of light emitting diodes (LEDs) are expected to have potential for lowering the fuel consumption.

In addition the importance of some further factors for lightweight design should be described (Fig. 5-3). This shows that lightweight design has a high importance for the image of some companies. Although lightweight design is not advertised to the customers of most OEMs, it is an important measure. Most people buy a vehicle because of its driving dynamics and lightweight design is a part of it. So, it has an important role for the image of a company, but it is not the most important one. Additionally lightweight design is mentioned more and more in automotive journals and on conferences. Concerning the life value, lightweight design is expected to have a small importance. Less importance is expected for the influence of lightweight design on recycling and legislative regulations or taxes. Here the recycling of steel and aluminium is no problem, but CFRP (e.g. in multi-material design) is more difficult to recycle. Concerning the fulfilment of legislative regulations, lightweight design is only important

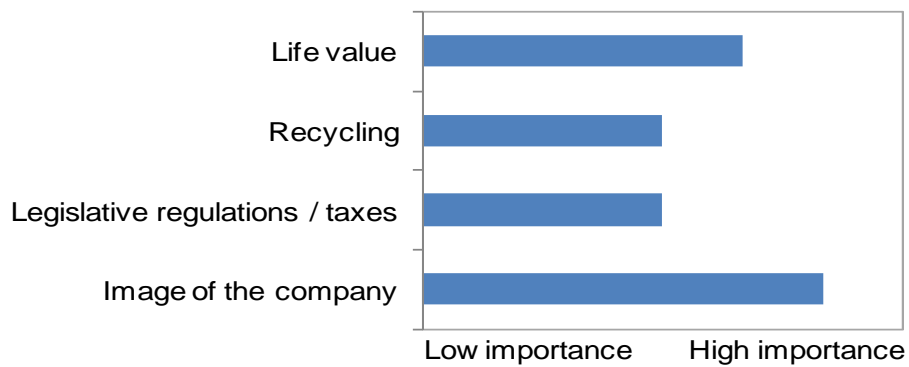


Fig. 5-3: Importance of lightweight design

The relevance of lightweight design for the different vehicle sections is shown in Fig. 5-4. The most important section for the usage of lightweight design is the front vehicle followed by the roof and the closures. The sidewall is classified by the OEM's experts with a medium relevance. The floor section only has a low relevance and the rear vehicle has nearly no relevance for the usage of lightweight components.

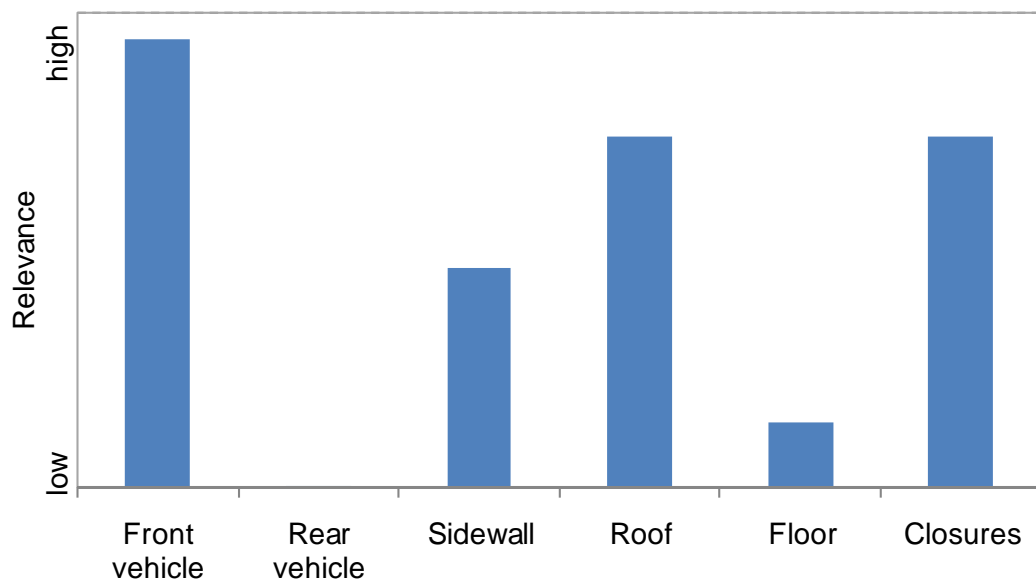


Fig. 5-4: Relevance of lightweight design for vehicle sections

In the next question the experts are asked to identify materials that will be used in future bodies. The highest potential for a future application is expected by the usage of ultra high-strength steel followed by aluminium. The relevance of aluminium is lower than that of ultra high-strength steel, because of its higher price and some technological challenges. Therefore

aluminium is expected to be used mainly for closures (e.g. in the upper middle class). Conventional steel and fibre reinforced plastics are expected not to be as relevant as ultra high-strength steel and aluminium in future. Because of the high price of carbon fibres, the experts think, that glass fibres are more important for the high volume classes, e.g. in closures or the cowl. Only expensive sport cars have the economic potential for a usage of carbon fibre reinforced plastics. For the usage of magnesium in future vehicle bodies the interviewed experts expect a very low potential. Magnesium is only used in some niche vehicles, e.g. the engine support beam of the Audi R8.

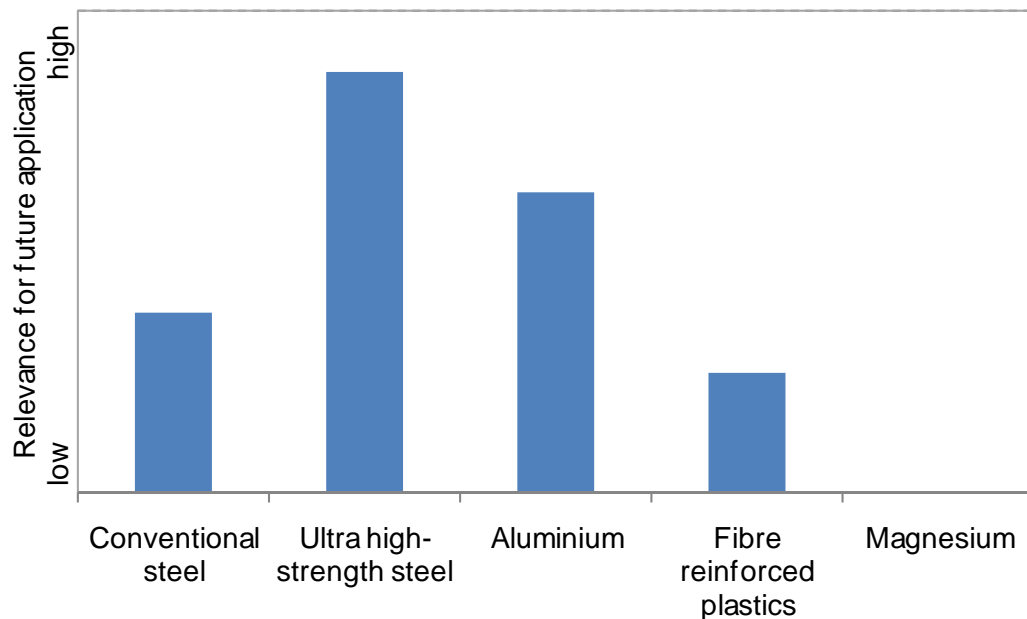


Fig. 5-5: Potential of different materials for future application

After that the experts are asked to name the most important components with potential for the application of aluminium. All interviewed experts named the closures (e.g. doors, fenders, hood) and the crash management system. In addition a lot of experts think that in future the roof could be made from aluminium. Further components that are mentioned by some experts are longitudinal beams, package trays and strut towers. Even the application of aluminium in the rearwall or in the supporting structure of the seats is possible.

In the next step the experts are asked to describe the advantages and the disadvantages of aluminium as material for a vehicle body. The main advantages of aluminium in comparison to steel are the high weight reduction caused by the low density and the good energy absorption behaviour. On the other hand there are some disadvantages concerning the usage of aluminium in the body. Beneath the economic disadvantage of the high raw material price, there are technological challenges to realise a material-mix. One challenge is the selection of an adequate joining technology. Spot welding of aluminium and steel is not possible because of the different melting points of the materials. To optimise the joining process of the body in the factory, it would be positive to use only one joining station for aluminium and steel. Additionally, the joining of these materials is influenced by contact corrosion and different thermal

expansion coefficients. Another challenge is the forming of aluminium sheets. Because the ductility of aluminium is with 10 to 15 % lower than that of steel (50 % to 60 %), shaping freedom of the sheets is lower (in the meaning of the interviewed experts). So aluminium components have larger draw radii and a thicker sheet thickness. Therefore a material substitution always comes along with changes in the geometry. One way to improve the design freedom of aluminium components is to use die-casting components, but the experts expect these parts to be brittle. Finally, the application of a surface coating on an aluminium sheet is considered to be more difficult than on a steel sheet.

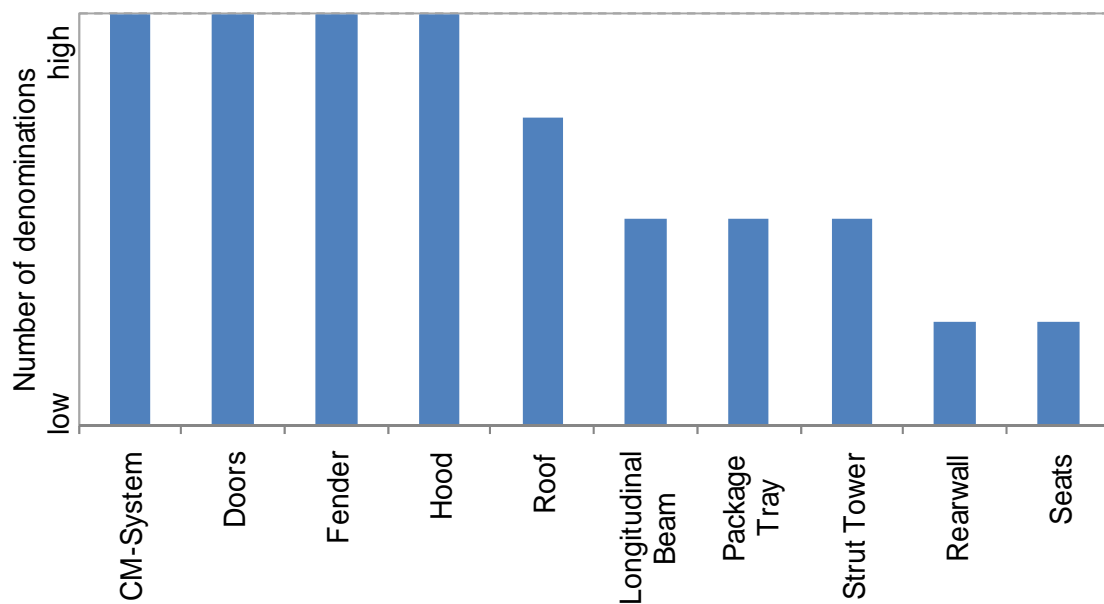


Fig. 5-6: Components with high potential for aluminium usage

Because fibre reinforced plastics (FRPs) might be an alternative to aluminium (see Fig. 5-5), the experts are asked to describe the advantages and disadvantages of FRPs in comparison to aluminium. The advantages of FRPs in comparison to aluminium deep-drawn sheets are the lower costs for the tools and the possibility to have more parameters for designing the components. Die-casting of aluminium also enlarges the freedom of design, but the application of this technology is generally limited to non-visible parts and smaller series volumes. The disadvantages of the usage of FRP are the costs for the components (especially if carbon fibres are used) and the higher process time. Therefore this material is not meaningful for medium and high volume vehicles. The costs of glass fibres are much lower than that for carbon fibres, but glass fibres have no clear advantage concerning its performance in comparison to aluminium. Additionally the models of FRP-components are much more difficult to handle in dynamic FE-simulations. High forces can only be transferred in parallel direction to the fibres. Because of this unidirectional behaviour of FRP-components, an aluminium component is able to handle multidirectional forces in a better way (e.g. subframe).

In the next question the experts are asked to classify body components in the three areas “high stiffness & low strength”, “high stiffness & high strength” and “low stiffness & high strength”. The conformity of the experts’ answers with the classification of components resulting from the FE-simulations (see Fig. 4-4) is shown in Fig. 5-7. Therefore the experts’ answers for each area are compared with the expected area resulting from this study. For each expert who named the component to be found in the same area as in this study figured out, the component gets one evaluation point. The percentage of these points for each component is transferred into the evaluation of the conformity.

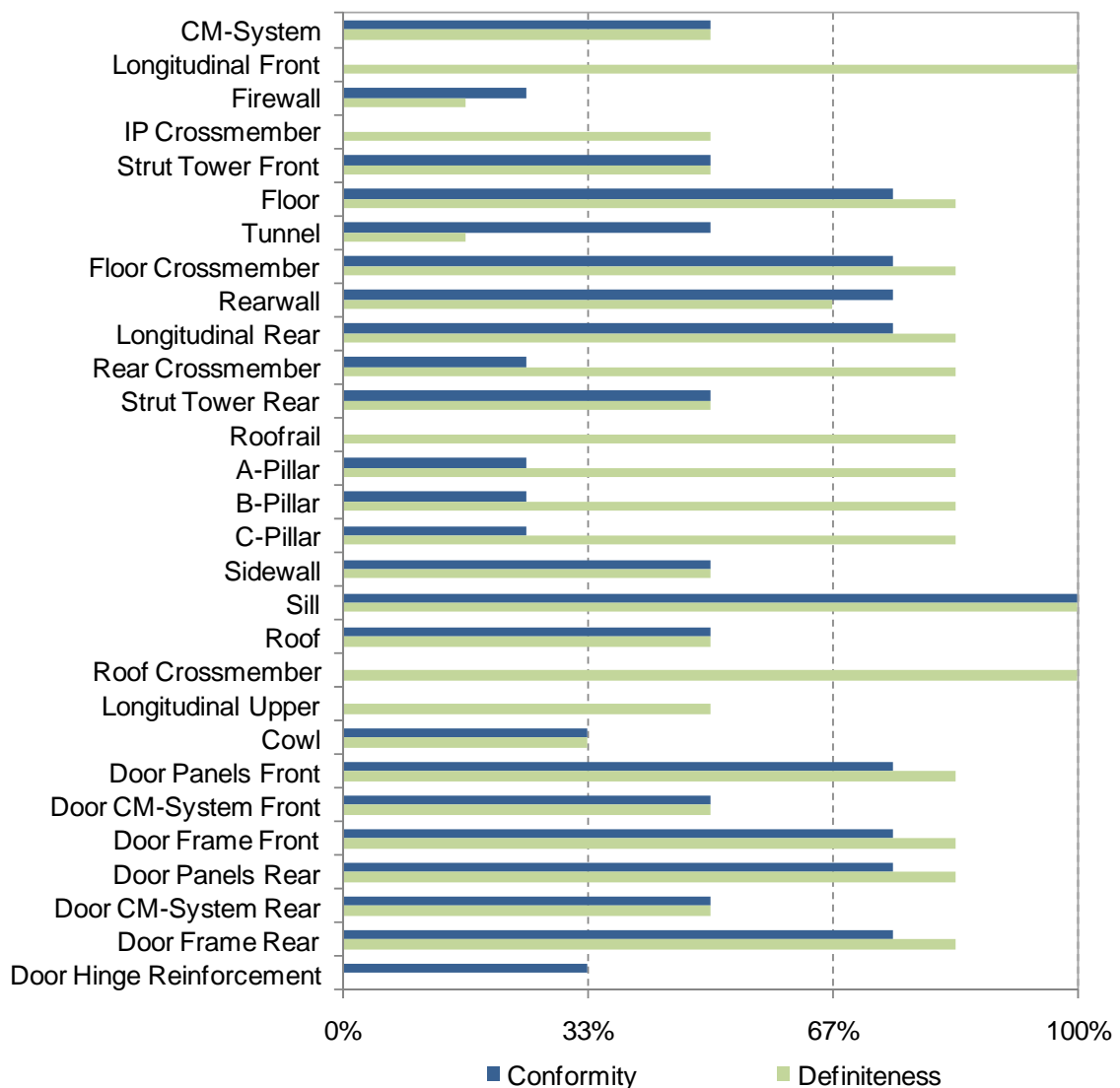


Fig. 5-7: Classification of body components and definiteness of the expert's answers

All components with conformity $\geq 50\%$ are evaluated with an acceptable conformity. About 59 % of all components have conformity $\geq 50\%$. The only components that do have a conformity value of 0 % are the longitudinal front, the IP crossmember and the longitudinal up-

per. For these components the study and the experts are not in the same opinion. In addition the experts have another opinion about the role of the roofrail and the roof crossmember. Probably this results from the fact, that this study does not regard the influence of a rollover crash test. For this reason it is not possible to show the correct values for the roofrail.

The values for the conformity shown in Fig. 5-7 are calculated for the maximum achievable conformity. It is reached, if the values at which the area limiting lines for area II ends are transferred from 0.8 to 0.6 for stiffness and for strength relevance (Fig. 5-8). Hence area II is becoming larger. For that reason the classification of the C-pillar and the sill changes from high stiffness and low strength relevance (area I) to high stiffness and high strength relevance (area II). In addition the floor changes its classification from high strength and low stiffness relevance (area III) to high stiffness and high strength relevance (area II).

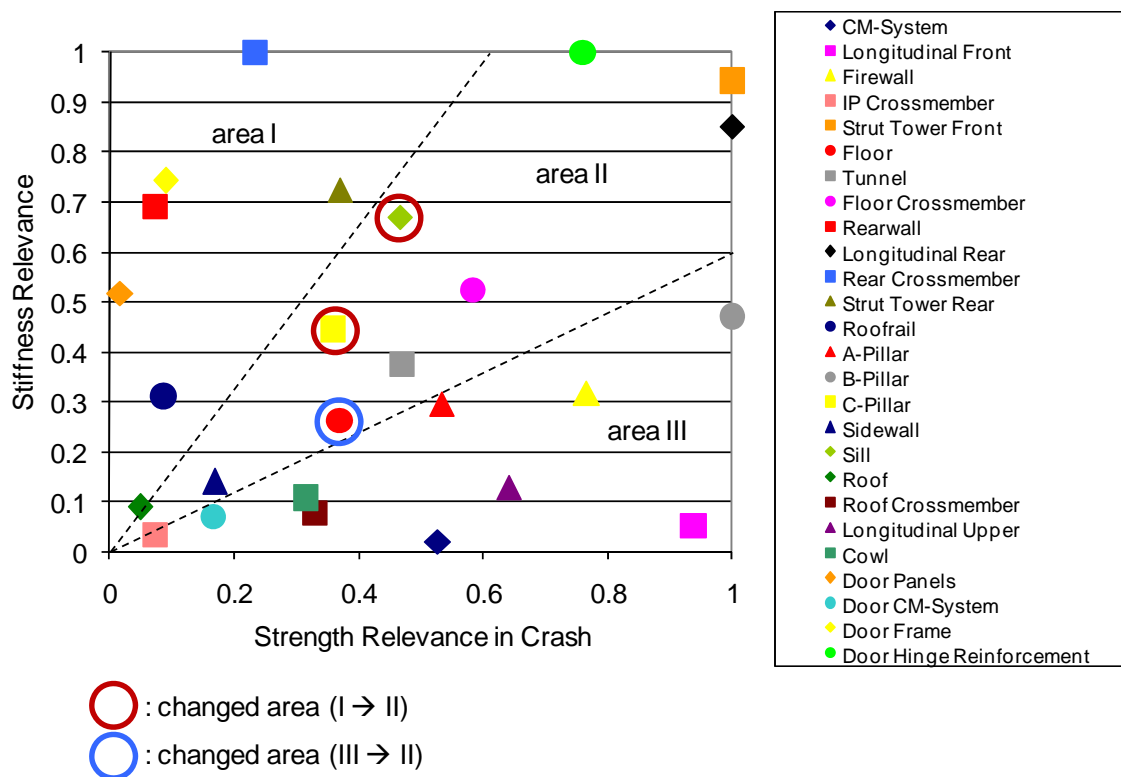


Fig. 5-8: Adjusted evaluation of the components

To evaluate the quality of the experts' answers, the definiteness of these answers has to be considered. Therefore this parameter is also included in Fig. 5-7. The definiteness is divided in seven classes, depending on the similarity of the expert's answers, as shown in Fig. 5-9. For the classification the sequence of the number of expert answers is not mandatory, but the distance between the maximum and the minimum area. E.g. if three experts think a component should be located in area I and one expert says the component is in area II, the component is classified as class 6. If three experts think it is located in area I and one expert says it is in area III, the component is classified as class 5, because there is area II between. Therefore the definiteness of this answer is lower. The results of this evaluation scheme

| Classi- fication | no absention | | | 1 absention | | | 2 absentions | | | 3 absentions | | |
|---------------------|--------------|----------------|--------------|--------------|----------------|--------------|--------------|----------------|--------------|--------------|----------------|--------------|
| | Max. area | Medium area | Min. area | Max. area | Medium area | Min. area | Max. area | Medium area | Min. area | Max. area | Medium area | Min. area |
| 7 | 4 | 0 | 0 | | | | | | | | | |
| 6 | 3 | 1 | 0 | 3 | 0 | 0 | | | | | | |
| 5 | 3 | 0 | 1 | | | | | | | | | |
| 4 | 2 | 2 | 0 | 2 | 1 | 0 | | | | | | |
| 3 | | | | 2 | 0 | 1 | 2 | 0 | 0 | | | |
| 2 | 2 | 1 | 1 | | | | 1 | 1 | 0 | | | |
| 1 | 2 | 0 | 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |

Fig. 5-9: Methodology for the classification of the definiteness

Fig. 5-7 shows, that the longitudinal front, the roofrail and the roof crossmember have a low conformity but a high definiteness. The longitudinal front was expected to be found in the area for high stiffness and high strength in crash by the experts, but the evaluation from the FE-simulations located this component in the area for low stiffness and high strength in crash. In addition the expert's were not sure if the longitudinal upper should be located in the area for high stiffness and low strength or in the area for high stiffness and high strength. The study identified this component to be located in the area with high strength and low stiffness. An example in that the low definiteness of the experts' answers influence the conformity is given for the firewall, the cowl and the door reinforcement. They have a conformity < 33% because the definiteness of the experts' answers is very low. But there are also assessments like for sill, floor, floor crossmember or longitudinal rear corresponding well with the study.

6 Summary

In the project “Stiffness and Crash Relevance of Car Body Components” quantitative values for the strength relevance in crash and the stiffness relevance of typical components of a compact class car body were determined for selected global crash and stiffness load cases. Using these values the resulting weight reduction potential of intensive high-strength steel usage was assessed to be approximately 11 % for a state-of-the-art reference car body including closures. Further assessment showed that if for the same reference car aluminium is substituted for steel the weight reduction potential is approximately 40 %.

For the determination of the strength relevance in crash and the stiffness relevance the body-in-white and the door of the reference vehicle were subdivided into 26 typical components. In numerical simulations the elastic modulus or the material strength of these components respectively were reduced and the effect on the static stiffness and the intrusions in crash were analysed. In comparison to the stiffness of the unmodified reference vehicle and its intrusions in crash these results could be transferred to values between 0 and 1 that define the stiffness and strength relevance for each component. For most of the components the results are according to the expectations. The exceptions are the longitudinal beam, the IP crossmember, the door hinge reinforcement and the firewall. Compared to the expectations the analysed stiffness relevance of the longitudinal beam is lower, the analysed strength relevance of the IP crossmember is lower, the analysed strength relevance of the firewall is higher and the analysed stiffness and strength relevance of the door hinge reinforcement is higher. The low strength relevance of the roofrail is comprehensible, since the roof crush test where the roofrail fulfils a dominant strength function was not considered in this study.

The expert interviews carried out to validate the results of the analyses showed that there is a certain scatter among the experts opinion regarding the relevance of components. However, for about 60 % of the components there is a good conformity of the global expert opinion with the results of the analyses. For only 5 of the 26 components analysed the experts disagreed with the results of the analyses. Those are mainly identical with the components that showed unexpected results. Except for the IP crossmember the unexpected results could be explained.

The numerical analyses showed that about 38 % of the components are highly relevant for global stiffness but have low strength relevance in crash. These components are not suitable for efficient weight reduction using steel grades with higher yield strength. A systematic approach was developed to assess the achievable weight reduction for steel components by material strength increase based on the stiffness and strength relevance and the current yield strength of the component. The application of this approach for the reference vehicle showed that the remaining weight reduction potential of high-strength steel (including TWIP steel) in modern car bodies can be estimated to be about 11 %. A similar approach was also developed to assess the weight reduction potential when substituting aluminium for steel. Using this approach, the weight reduction potential, when designing the reference car body and the closures in aluminium (including 7000 alloy), was estimated to be 40 %. In addition

to components where aluminium is an established material already the longitudinal beam, the roof, the strut tower, the floor and the sidewall were identified as interesting components for future aluminium applications in a multi-material body-in-white. Another interesting result of the approach was, that for most of the components strength still is not the limiting factor when substituting aluminium for steel.

In addition to the numerical analyses and the assessment of the lightweight potential of future material concepts the current material application in the body-in-white was analysed. Therefore the analysed vehicles were divided into the classes "Subcompact", "Medium", "Crossover" and "Small MPV". The most intensive usage of steel with average yield strength higher than 600 MPa was identified in the CM-system, the door CM-system and the B-pillar of subcompact class vehicles. In the other classes the average yield strength is lower. Typical components with low average yield strength in all classes are the strut towers, firewall, cowl, floor, roof and the sidewall.

An additional target of this study was to identify the opinion of experts from the automotive industry concerning future aluminium applications. Concerning the reduction of fuel consumption, most of the interviewed experts thought, that engine-driven measures are the most important ones. Lightweight design is not so important for the reduction of fuel consumption, but for the improvement of driving dynamics. The most important vehicle areas for lightweight measures are the front, roof and closures. In these areas components like the CM-system, doors, fenders or hood promise to keep the highest lightweight potential. As future materials ultra high-strength steels and aluminium were expected to have the highest potential for a more intensive usage in vehicles. Concerning the results from FE-simulations in this study, a sufficient conformity between the stiffness and strength analysis and the experts' answers was identified with conformity of 59 %.

This study forms an initial step on the way to determine quantitative values for the strength relevance in crash and the stiffness relevance of car bodies. The results can change if the number of load cases considered is increased. Therefore, future research should be carried out considering additional load cases and a number of different reference vehicles.

7 Literature

- [AST07] AST, G.; OBERLE, M.
The new DaimlerChrysler C-Class Car Body
Daimler AG
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [AUG08] AUGSTÍN, X.
Die Karosserie des neuen Seat Ibiza
Seat S.A.
Aachen Body Engineering Days 2008, Aachen, Germany, 2008
- [BEN08] BENEDETTO, A.
The new Toyota Avensis
Toyota Motor Europe
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [CAR07] CARBIT, J.; ERNAULT, H.
The new Renault Laguna III Car Body,
Renault SAS
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [COR08] CORDES, H.
The Passat CC
Volkswagen AG
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [FUR09] FURRER, P.
Comments
Novelis AG
Zürich, Schweiz, 2009
- [LEF08] LE FLOCH, B.; BARBIER, M.
The new Citroen C5
PSA Peugeot Citroen
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [LIE08] LIESENFELDER, B.; GALL, C.
New Ford Fiesta
Ford Motor Company
EuroCarBody 2008, Bad Nauheim, Germany, 2008

-
- [MAN06] MANNS, K.P.; ZIELKE, S.
The new Opel Corsa Body
Adam Opel GmbH
EuroCarBody 2006, Bad Nauheim, Germany, 2006
- [MIC07] MICHIURA, Y.; MOSS, D.; POLLOCK, T.
The new Nissan Crossover Qashqai Car Body
Nissan Motor Co. Ltd.
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [NED08] NEDIC, S.; LJUNGQUIST, H.; HOLLANDER, E.
The new Volvo XC60 Car Body
Volvo Cars
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [NIS08] N.N.
Teana
Nissan Motor Co. Ltd.
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [OST92] OSTERMANN, F.
Aluminium
Werkstofftechnik für den Automobilbau
Expert Verlag, Ehningen, 1992
- [PAT07] PATOIS, C.; GAULLIEZ, G.
The new Citroen C4 Picasso
PSA Peugeot Citroen
Tag der Karosserie 2007, Aachen, Germany, 2007
- [PED09] PEDERSEN, R. H.
Weight Reduction Chart
(document based on internal study)
Hydro Aluminium
Raufoss, Norway, 2009
- [PIN07] PINN, C.
The new Opel Antara
Adam Opel GmbH
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [RAB07] RABE, M.
Leichtbaustrategien für den Karosserieleichtbau bei Volkswagen
Volkswagen AG
Tag der Karosserie 2007, Aachen, Germany, 2007

-
- [SAS07] SASAKI, M.; ICHINOMYA
The new Honda Accord Car Body
Honda R&D Co. Ltd., Honda Engineering Co. Ltd.
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [SCH07a] SCHENN, A.
Der neue BMW X5
BMW Group
Tag der Karosserie 2007, Aachen, Germany, 2007
- [SCH07b] SCHMELEV, E.M.; GALKIN, E.A.; ZUCHKOVA, M.
The new Lada 2116 Sedan Car Body
Avtovaz Inc.
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [SIM06] SIMON, P.; SENKYR, P.
The new Skoda Roomster Car Body
Skoda Auto a.s.
EuroCarBody 2006, Bad Nauheim, Germany, 2006
- [SIM08] SIMON, P.
Skoda Superb
Skoda Auto a.s.
EuroCarBody 2008, Bad Nauheim, Germany, 2008
- [SUE09] SÜNKEL, R.
Opportunities and Risks for steel manufacturers in the European automobile market
ThyssenKrupp Steel
Strategic Questions in Car Body Engineering, Bad Nauheim, Germany, 2009
- [TOR07] TORELLI, A.; TAGLIANI, M.
New 500: B.I.W. Design
Fiat Auto S.p.A.
EuroCarBody 2007, Bad Nauheim, Germany, 2007
- [WHI07] WHITE, M.; BLACK, S.
The new Land Rover Freelander 2 Car Body
Jaguar & Land Rover Cars
EuroCarBody 2007, Bad Nauheim, Germany, 2007