STRUCTURAL DURABILITY AND INTEGRITY IN VEHICLE DESIGN

Kurt Pötter
BMW AG, 80788 Munich, Germany

Products with excellent performance to weight ratios and high safety standards along with efficient design and validation processes are, among others, critical factors for success in the Automotive Industry. With regard to structural integrity, the components and systems of a car or motorcycle have to comply with three basic requirements. This is the durability during normal customer operation and the ability of components to withstand special events without any impairment of function or safety relevant damage. Especially important is a visible “deformation prior to fracture” at serious misuse events.
In the case of load assumptions with respect to the structural durability, the differences in driving habits and vehicle usage of customers as well as variations in road characteristics and environmental conditions worldwide have to be taken into account. The structural integrity analysis is based on a statistical approach, considering the variation of component strength and service loads.
Special events are loads which occur infrequently during regular, proper use of the vehicle. Special events must not lead to residual deformation or act as a precursor of fatigue failure. Misuse events by contrast, are permitted to lead to a previously defined and readily identifiable damage although customer’s safety remains paramount.
The design process relies on multi-body and finite element simulation to determine maximum design loads and load time functions for the fatigue analysis. The large variety of the applied materials and manufacturing processes for example; from die-cast to deep-drawn metals, polymers, various kinds of welding processes and adhesive bonding require adequate numerical procedures.
The validation of components and systems rely on hardware prototypes. Custom built test rigs for component and system testing are used. Due to the complexity of the geometry and the assembly of parts, simple failure criteria need to be applied. In general they are based on the first visible, by technical means detectable cracks.
Finally, tests and procedures have to be closely defined to ensure and validate the high quality standards during several years of production.

Keywords: structural integrity; service loads; special events; misuse; simulation; durability test; failure criteria

1 INTRODUCTION

A new vehicle being developed has to comply with an ever increasing number and quality of requirements compared to its predecessor. Main customer oriented design targets like driving pleasure and efficiency are supplemented by regulatory requirements like environmental friendliness or passenger and pedestrian protection for example. Last but not least it has to comply with company goals related to economic targets and sustainability. The development process, starting with the first concept ideas and ranging all the way to the actual use of components in series production, has to enable a best possible compromise between those partially conflicting targets. Therefore, a car maker must follow a very detailed and complex design and validation process. The various functions of a component involve aspects such as acoustic, driving dynamic and aerodynamic behaviour, crash safety and, in particular, structural durability. Each of these disciplines to be fulfilled by the components of a vehicle is part of the complex overall development process.

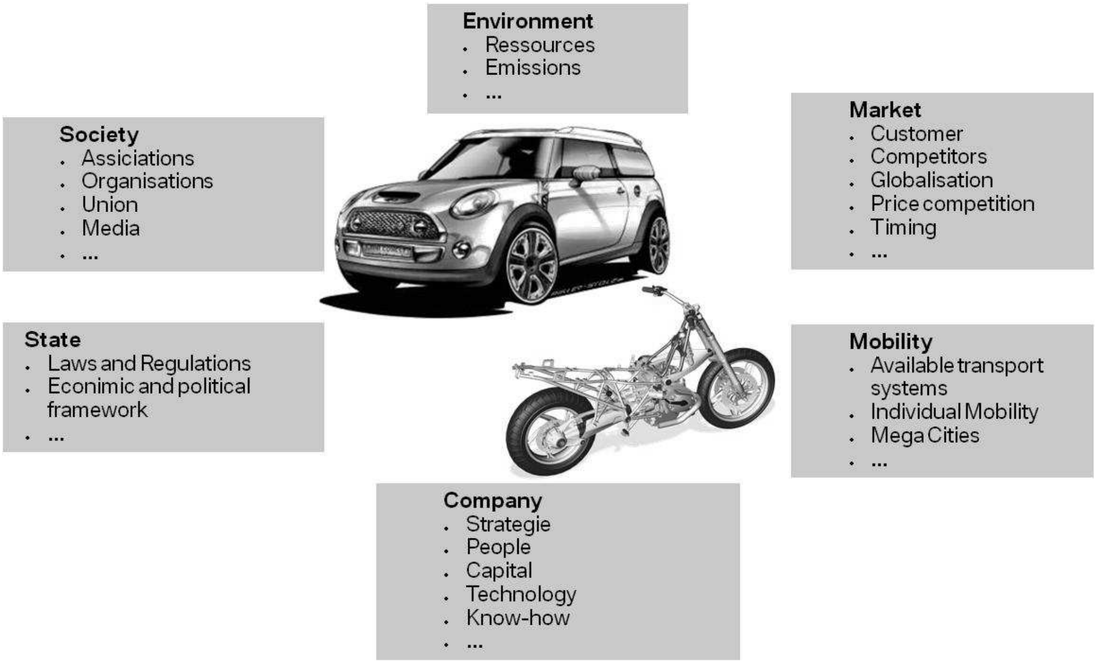


Figure 1: Influencing Parameters for a vehicle concept

Structural durability and integrity has always been a significant highlight in the process of designing and validating a vehicle, making an important contribution to the functional design and configuration of drive train, suspension and body components. By fully utilising the material properties and employing geometrical optimisation, the components can be exploited to their full capability, ensuring an optimum performance to weight ratio. To achieve such a high degree of efficiency in the use of a component, it is absolutely imperative to examine and verify the loads and forces experienced precisely. Therefore, the load spectrum for each component encountered during ordinary customer use must be determined as comprehensively as possible. Besides these service loads special event loads which occur infrequently during regular, proper use of the vehicle have to be considered. These loads must not lead to any impairment of function or to safety-relevant damage. Misuse events by contrast are permitted to lead to a previously defined and readily identifiable damage. The main principle of “deformation prior to breakage” is applied to ensure that the customers’ safety remains paramount [1].

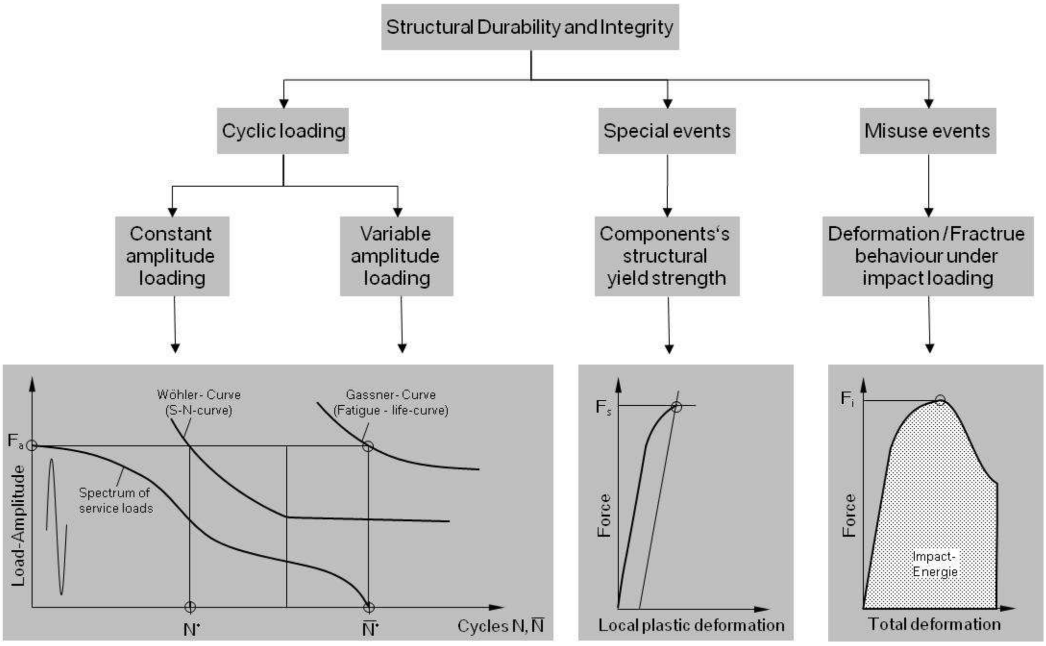


Figure 2: Types of loading that determines structural durability and integrity, [1]

The development process consists of a design and validation phase. Starting with load assumptions the first component designs are analysed by multi-body simulations and finite analysis calculations. The first strength and durability tests are conducted on test rigs on the basis of load assumptions and simulated load data. Especially the influences of the manufacturing process on the component strength need to be evaluated. Finally vehicle tests with close to planned production models are conducted. The focus in this case is the function, interaction and wear of the components. During the design of safety-relevant components, many diverse parameters influencing the service life of a vehicle must be taken into account.

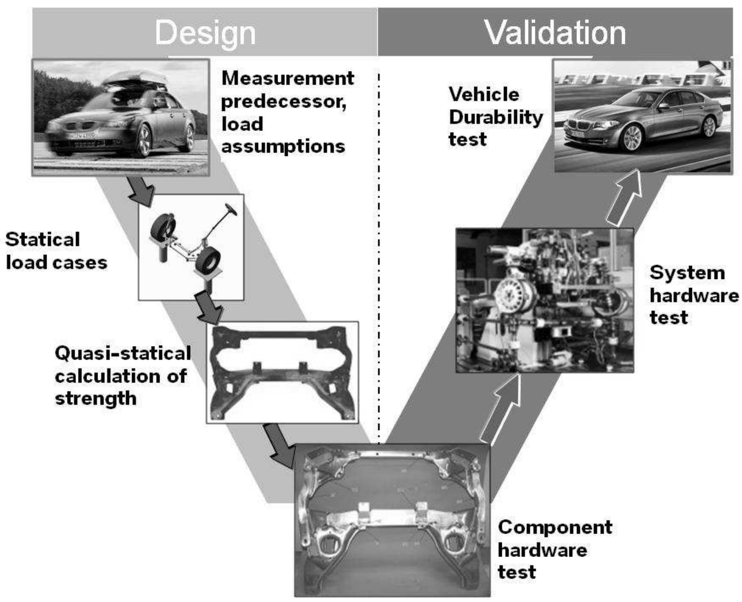


Figure 3: Component development process, [3]

The most important parameters influencing the service life of a vehicle are:

- Loading encountered during service conditions.
- The design of components in terms of their geometry: radii, stiffness, resistance to bending, torsion, etc.
- Surfaces formed in the manufacturing process influencing notch factors.
- The materials with their specific material properties influenced by the manufacturing process (tensile and compression strength, flexural stiffness, etc).
- Characteristic and residual stress generated during the production process, for example during welding or deep-drawing.
- Environmental conditions: e.g. service temperature range and corrosive facilitators.

2 SERVICE LOADS

Cars and motorcycles experience an extremely wide variety of use cases and consequential loads. The use cases are generally influenced by the driver, the road surface and by the properties of the vehicle itself. Driving habits of a customer can vary from ambitious, including e.g. race track training to notably calm. Driving habits, traffic conditions and road surfaces vary significantly for different markets. Some vehicles offer the capability for off road driving or are predetermined for the race track or for comfortable long distance driving.
To determine the service loads and their variation, continuous market observation as well as load measurement with customer vehicles and statistical analysis is carried out. As an example, significant regional differences can be seen in roadway induced loads, like pothole frequency and severity, Figure 4. To achieve high standards of reliability, the design specification with respect to service loads follows a statistical approach that is based on the variation of service loads as well as the variation of component strength and the test procedure. Based on this knowledge a durability test program is compiled, that consists of measured load time histories from different tracks on the proving ground of the car manufacturer. The intensity and frequency of the occurring loads are representing the most stressful operating conditions for the vehicle.

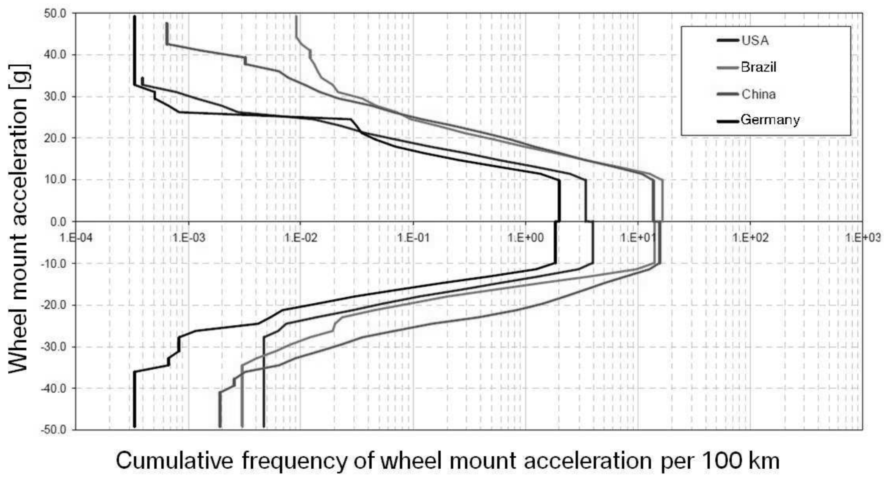


Figure 4: Load spectrum of road surface induced vertical wheel mount acceleration in different regions

The proving ground offers the opportunity to measure service loads on pre-production vehicles and prototypes under reproducible conditions to compile a database. This database is used for the design and configuration of a new vehicle and also to compare measured data against load assumptions and virtual load data. Depending on the type of vehicle, parameters such as wheel load, acceleration, temperature, engine performance, drive torque, local stress and displacement, are measured.
The need to shorten development periods and cut costs as well as the increasing number of vehicle variants lead to a reduction of hardware prototypes and encourages the use of simulation tools to determine design loads. Applying multi-body simulation, the loads acting on components are determined from the external loads acting on the wheel, taking the spring/mass system and the component interface into account.

3 DESIGN AND TEST FOR STRUCTURAL DURABILITY

The process of designing and validating a component in terms of the requirements made and the service life anticipated has changed significantly in recent times. In the past the design and validation processes in terms of a vehicle's service life were based largely on the use of specific hardware requiring significant expenditure and taking up a relatively long period of time in their production and examination.
The process started by determining the design and configuration loads for the vehicle to be developed. This was generally based on data measured on the former vehicle appropriately adjusted to the new vehicle on the basis of existing experience. Such load data was used to carry out the first quasi-static strength and stability calculations for chassis and body components. Once positive results were available, the next step was to build the first test components. Durability tests carried out on components and systems such as a complete front axle served to detect and eliminate weak points, with new test components then being built as a result. These development loops were repeated consistently until all the requirements made were duly fulfilled.
Today virtual configuration of components by means of multi-body simulation and the fatigue life prediction method is already a firmly established and confirmed procedure. The iterative optimization process is therefore now conducted largely in the virtual world. It is only when the virtual components simulated meet the demands made that test components are actually built as hardware serving first and foremost to confirm the results of the simulation process.
This paradigm change causes great efforts to enable the simulation methods for the needs of the design and optimization process. In the early phase of the design process it is sufficient to assess the pertinent material data, unless cyclical data determined by way of experiment is available for the materials to be examined. Appropriate factors are sufficient to consider the influence of the production process in calculation programs, and the demands made in assessing fatigue life by a fine finite element mesh of components geometry are relatively small in the early phase, with no great need for high-quality results or data [3].

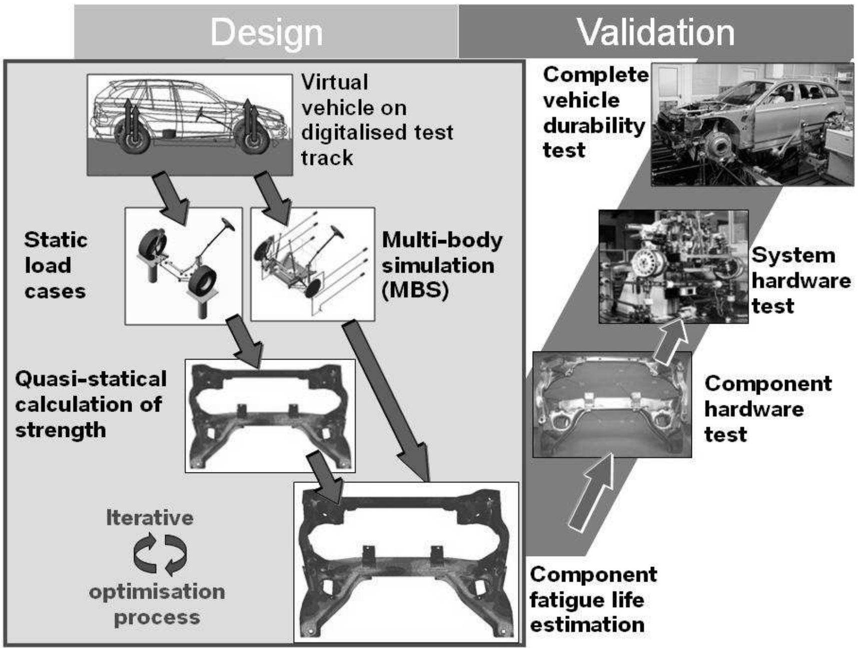


Figure 5: Component development process with the use of simulation [3]

The need for precise design and validation and, accordingly, the demand for exact data in calculating fatigue life increases significantly in series development. This clearly calls for methods with a higher standard of quality and better input data for determining the fatigue life of a component or module. In the case of the finite element size for example the pure size of the components sometimes causes a challenge. Figure 6 shows the length of adhesive flange in a body in white. 160 meters of adhesive joint with an average element size of 4 mm makes a detailed fatigue analysis of a visco-plastic material nearly impossible.

Depending on the manufacturing process, the geometry of a component will change the properties of the material – for example the thickness of a metal panel in the deep-drawing process – possibly pores inside die castings made of aluminium or generating residual stresses within the material itself during the process of welding, deep-drawing and casting. Programs currently available for the simulation of manufacturing processes in some cases already provide the input data required for the assessment of fatigue life.

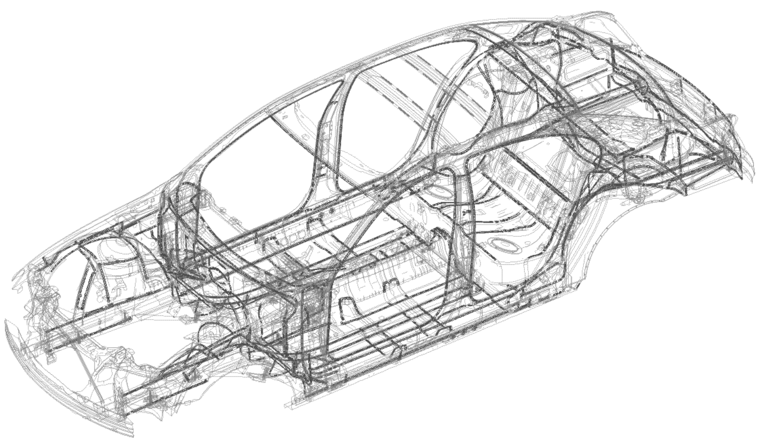


Figure 6: BMW 7 Series: 160 meter flange of adhesive joint

3.1 Fatigue test

To verify the simulation results, a systematic experimental validation of the respective components and modules is necessary. The test engineer is able to apply diverse testing and measurement methods so that:

- Virtual or experimental methods are applied to determine the local forces acting on a specific component. In particular, thermo graphical measurements are used, supplementing strain gauges and optical methods.
- Quasi-static tests serve to analyse deformation behaviour and calculate buckling and fracture loads.
- Constant amplitude and service load simulation tests are conducted to assess dynamic durability.
- Failure criteria need to be defined appropriately for the laboratory environment. Therefore, visual inspection or dye penetration is typically used.

It is important to choose the most appropriate test method to confirm the service life experimentally. For example, which test is most appropriate to determine the structural durability of a chassis component: a constant amplitude test, a service load simulation test on a complete axle, or a road endurance test with an entire vehicle? Hence, the process of conducting a meaningful strength and durability test always requires an optimum balance of the work involved with consideration of cost and time factors.
Figure 7 illustrates the relationship between engineering values and the complexity of various testing methods. It highlights the advantages and disadvantages of the individual processes.

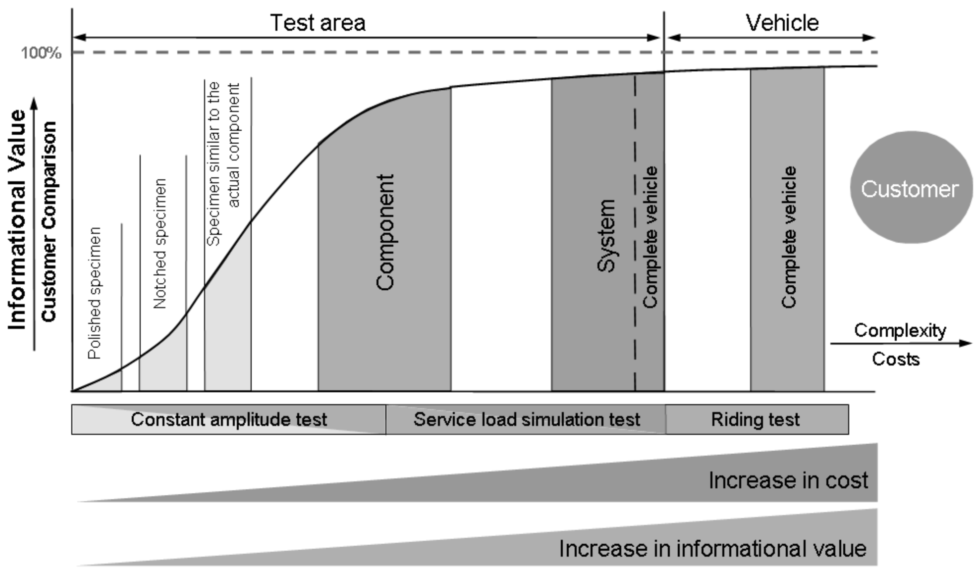


Figure 7: Informational value of various tests [2]

Uni-axial constant amplitude tests are a fast low-cost option to determine the structural durability of components. However, since the loads acting on suspension components of a vehicle are usually multi-axial, it is essential to ensure that the strains acting in the critical area of the component are correctly reproduced. This can be assessed by conducting measurements with strain gauges or by means of finite element analysis.

During development of a motorcycle, component tests on the Paralever swing arm of the rear wheel system were carried out, Figure 8. The Paralever swing arm is an aluminium die casting and carries all loads acting on the rear wheel. One particular point of the swing arm is subjected to very high dynamic loads. The loading occurring at this point during riding was accurately reproduced employing a simple constant amplitude test.

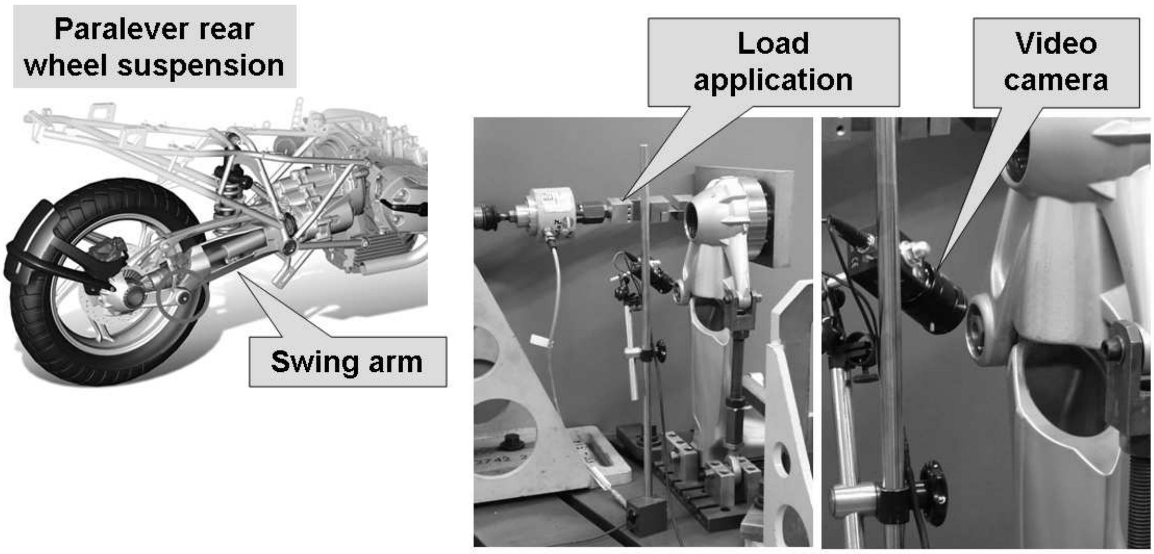


Figure 8: R1200 GS swing arm component test, [2]

During the test, the critical fracture spot was monitored by a time delay video camera. This enabled better observation of the crack formation and propagation and allowed the test engineer to evaluate the influence of surface porosity on the service life of the component [2].

Figure 9: Complete vehicle test-rig simulation

Compared to uni-axial constant amplitude tests a service load test-rig simulation with a complete vehicle is expensive and time consuming, though this test comes closest to a vehicle riding test at a proving ground. Custom made test rigs with 20 degrees of freedom including the simulation of environmental influences like temperature and UV-radiation (e.g. for carbon fibre reinforced components) are used for this validation test, Figure 9. Though these tests allow for complex multiaxial loading conditions, the test procedure and the inspection of possible damage sites often demand for well trained staff members and a good anticipation of weak spots for example based on previous finite element simulation.
Especially tests with a complete vehicle or assembly group like a suspension or a complete drive train, call for simple failure criteria. In general they are based on the first visible, by technical means detectable cracks. Often the test is continued after the first fatigue crack in a component is identified without exchanging the part due to the necessity of a weak point analysis by monitoring the damage propagation.
The root cause analysis by means of metallurgy or x-ray radiograph after completion of the test offers some basic information for the assessment of the test result and the optimization of the component. In the case of prototype components with flaws or manufacturing defects the analysis can lead to changes of the production process and to the adaption of quality standards for the subsequent series production.

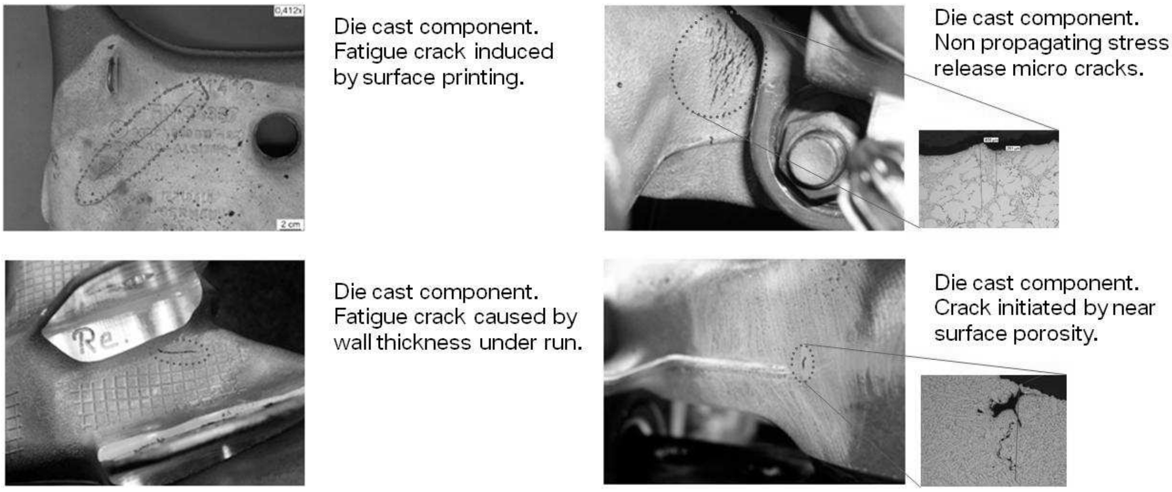


Figure 10: Typical weak points for die cast components

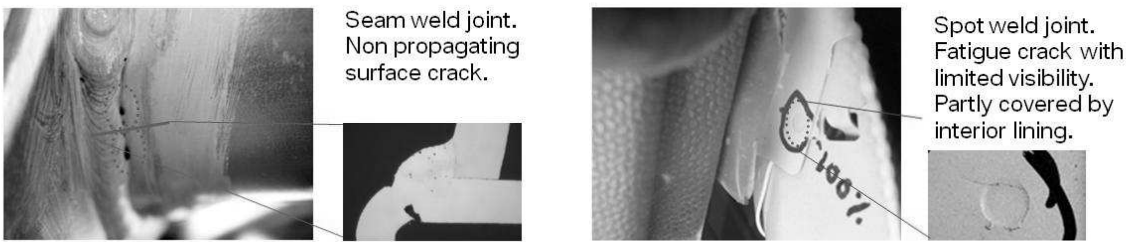


Figure 11: Typical weak points for seam and spot welded joints

4 SPECIAL EVENTS

In addition to the service loads, it is also necessary to consider special event and misuse loads typically occurring during service life to determine the structural durability.
It is therefore essential to observe the specific features and characteristics of a vehicle carefully and to apply the knowledge gained in field tests. A typical special event encountered on a motorcycle is the “wheelie”. Here the rider accelerates with full power in low gear and pulls up the handlebar resulting in the motorcycle running only on its rear wheel. The rider then abruptly removes engine power while simultaneously applying the rear brake and the front wheel then impacts the road, causing high vertical and longitudinal forces in the front suspension, Figure 12.
The motorcycle must be able to withstand a certain, defined number of such manoeuvres and the high loads generated without the service life of the components being reduced or being damaged in any way. This is ensured by applying such special event loads prior to the usual service load simulation tests on a specially developed “wheelie” test rig [2].

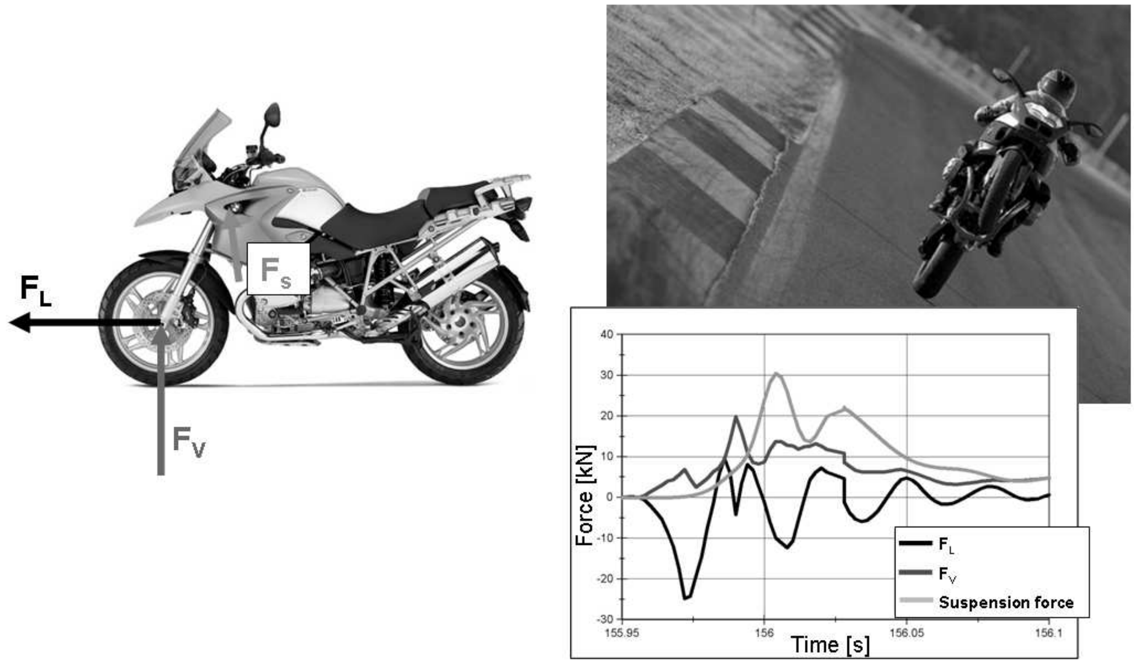
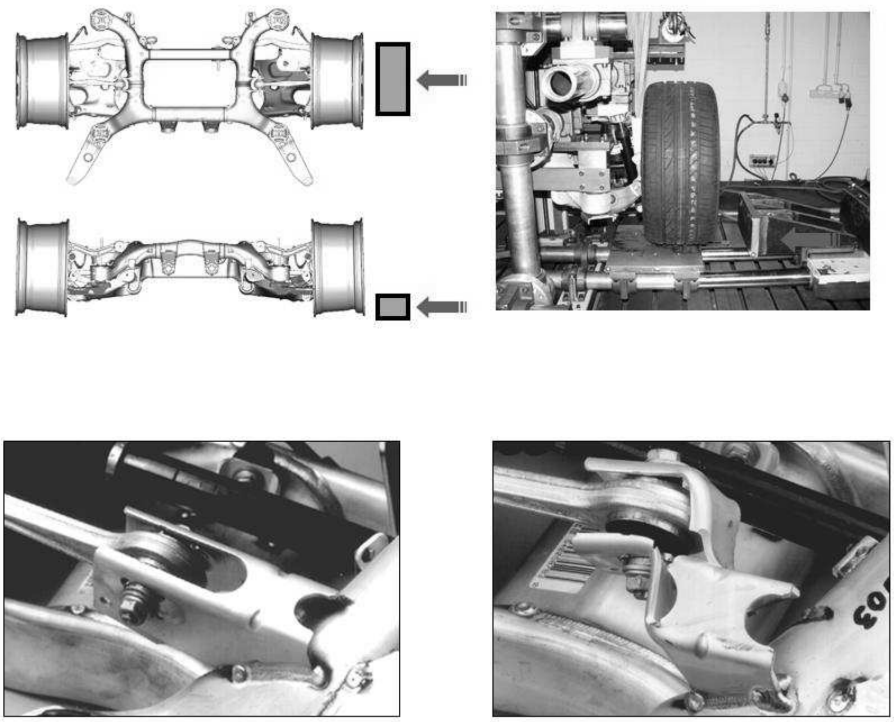


Figure 12: Time history of a “wheelie” special event, [2]

5 MISUSE EVENTS

Vehicles can undergo a number of different misuse events during service life. The most prominent misuse event is probably the unintended passing over significant road obstacles. Also the lateral sliding against a kerbstone due to a low friction coefficient of the road at below zero temperatures or intense rain has to be mentioned. In case of a motorcycle falling over at a standstill or while manoeuvring is the foremost event.
To ensure appropriate customer safety despite the appearance of such events, it is essential to maintain a clearly defined “damage chain” ensuring that deformation occurs prior to fracture. Hence, it is imperative that the customer can clearly identify that the structure of the

vehicle has been damaged and over-exposed to adverse forces following such misuse. Concealed damage which could impede the proper functioning of a part during the ongoing use of the vehicle is not permissible. In the interest of low-cost repair, it is also essential to limit the damage to components which are both inexpensive and easy to exchange.
Impact tests are performed by the use of a test rig with the complete front or rear axle. Different impact directions and energies of the pendulum are used to verify the pre-defined “weakest link” of the structure where the impact energy is converted into plastic deformation. In general an axle guide or bearing support is preferential to act as a “weakest link” component due to their high deformation capability which results in an obvious necessity for a workshop repair.
In order to enable harmonious and robust structures and concepts, the load assumptions and associated damage chain must be determined at the beginning of the design stage in the development of a new vehicle.



Bearing support prior impact   Bearing support post impact

Figure 13: Rear axle impact test

6 SUMARY AND OUTLOOK

Before a vehicle can be released and approved for production, each safety relevant component must be fully tested to ensure that it can withstand the load conditions expected during the course of the vehicle’s entire service life.

The use of new materials and material compounds as well as the use of standardized systems and components throughout several model series presents an additional challenge in ensuring adequate structural durability and integrity. Experimental validation of structural durability alone is no longer sufficient to meet such complex requirements. Hence, optimised virtual methods must also be applied to an increasing extent in order to determine the anticipated service life. To ensure optimum lightweight construction it is crucial to apply and maintain a consistent design, calculation and validation process in product development during the entire process.

To further reduce the weight, magnesium alloys and plastics, including carbon-fibre-reinforced plastics, will be used for load-bearing structures to an increasing degree. In this case the experimental validation tests conducted must also take the special properties of such materials into account, for example by simulating environmental conditions in an appropriate manner.

References

[1] C. Berger; et.al.
Betriebsfestigkeit in Germany – an overview
Int. Journal of Fatigue 24 (2002) 603-625

[2] L. Krüger; G. Greim
Structural durability and lightweight design in motorcycle development
Proc. 2nd Int. Conf. Material and component performance under variable amplitude loading, DVM, ASTM, 03/09 Darmstadt

[3] M. Brune; H. Oppermann
The process of design and validation from the perspective of structural durability – close interaction of testing and calculation
Proc. 2nd Int. Conf. Material and component performance under variable amplitude loading, DVM, ASTM, 03/09 Darmstadt

e-mail: kurt.poetter@bmw.de