RAISING MAXIMUM DESIGN STRAIN ENVELOPES OF FIBER RESIN COMPOSITE PRIMARY STRUCTURAL ELEMENTS SUPPORTED BY A LOAD AND OPERATIONAL MONITORING SYSTEM

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Keywords: Structural Health Monitoring, Operational Monitoring, Fatigue, Damage Tolerance, Misuse, Automobile, Body in White

Abstract
The author describes the motivation for and implications of the introduction of an Operational Monitoring system to the automobile Body in White structure. Consequences on the design strategy and reasons for a possible safe raise in the maximum design strain envelope are given, if Operational Monitoring is used to ensure the safe application of the material. A framework of a suitable solution to cost efficient Operational Monitoring is explained. For the monitoring textile strain sensors can be used. Necessary validation methods and functions and different layers of the Operational Monitoring system are described.

1. Operational Monitoring in the Body in White

Bionic principles work as a motivation for the introduction of Operational Monitoring and Damage Sensing methods. As an example the human body has a central nervous system including the brain and the spinal cord. In addition to this a peripheral nervous system including ganglia and nerves are also available. The human body instantly gives feedback to the user, if the system is suffering from overload conditions or damage, even before damage occurs. The transfer of these bionic principles into technical structures has been part of science during the last 30 years.

In the work of the author the Operational Monitoring principle has been transferred to the automotive Body in White structure (see fig.1). The topic of Operational Monitoring is not by itself new, but few information can be found on the implications of the introduction of such a system into the load bearing structure. It seems that the technical foundation of these lifetime observer systems is generally given, but the benefits of the introduction of such a system are not yet described more specifically in the literature.

The superordinate term Structural Health Monitoring (SHM) divides into the two topics of Operational Monitoring and Damage Sensing. A thorough differentiation between different Structural Health Moni-

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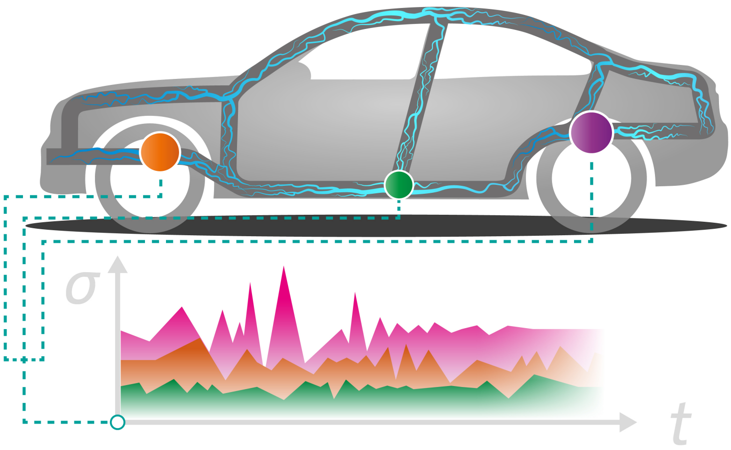

Figure 1. Sketch of a sensing body in white structure, including example local strain measurement in the areas of load application and maximum bending.

toring methods in the context of the aircraft industry can be found in [1]. Some fundamental hypotheses about SHM are shown in [2]. SHM has its heritage in applications in the areas of bridges & buildings, pipelines, wind turbines, railroad tracks as well as military and civil aircraft. In the automotive sector Operational Monitoring can already be found in series production in steering gears. Applications in gearboxes are currently being developed. Up to now in the automotive Body in White no Operational Monitoring method is used, although first ideas, patents and literary description of lifetime observers have been around since the 1990s. One peculiar requirement of the automotive sector is its price sensitivity, if such a system shall be introduced into series production automobiles.

In lightweight design of the Body in White the automotive industry has taken several steps from usage of steel, via aluminum up to multi-material structures (compare fig. 2). As every material and technology shows a final utility over time, beyond which the weight cannot be reduced any more, this is also valid for multi-material-design including the application of fiber resin composite parts. Fiber resin composite components are used e.g. in the BMW i3 and i8 vehicles, or the current BMW 7 series. In extreme lightweight design cases the strategic degrees of freedom in lightweight design are material, optimization and the definition of the degree of utilization of material in the design process.

The latter is the item that the author focuses on in his work. If components of the automobile Body in White structure have an Operational Monitoring system installed, and a proper Damage Tolerance evaluation of the parts has taken place, next steps in lightweight design can be taken. More elaborated and complex monitoring methods are Damage Sensing and the usage of multifunctional structures and adaptronics. The usage of these methods is in the long term the most promising way for lightweight design, but the technology is usually still quite expensive and in early research states. Therefore Operational Monitoring of the Body in White structure can be a suitable intermediate step.

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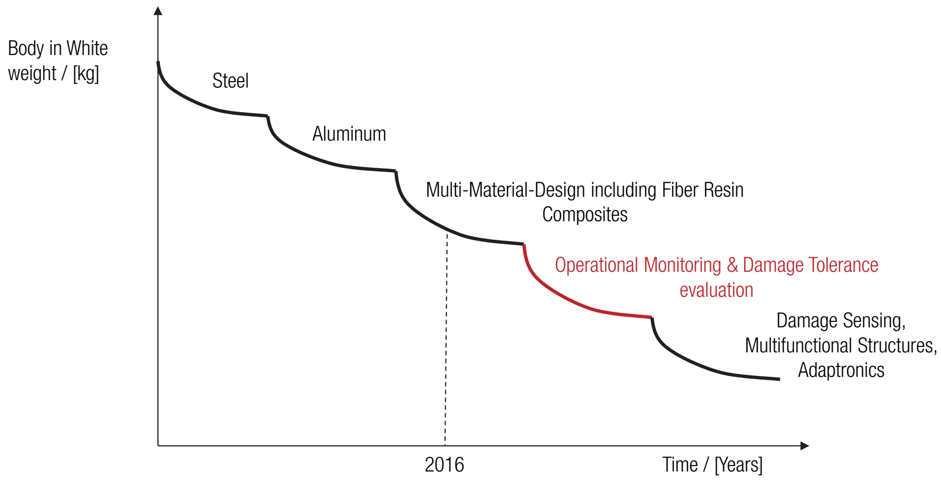

Figure 2. Strategic steps in lightweight design of the automobile body in white structure. Operational Monitoring as an enabler for the next step in lightweight design.

2. Implications of Operational Monitoring to the load and strength distribution

When we consider typical distributions of load and strength in the automobile Body in White structure, we see that the degree of reachable lightweight design is limited by the 1-percent customer and the worst of 1000 parts produced (compare fig. 3). The load requirements of the 1-percent customer usually lie far outside the mean of an assumed load Gaussian bell curve. The safety margin of the new and undamaged structure reduces during the operation of the component due to damage and aging. In extreme lightweight design, the overlapping area of the worst customer with the highest load demand, meeting the worst produced part is dangerous and can lead to catastrophic failure of the component. A study of misuse behaviour through automotive customers can be found in [3]. Typical load assumptions in the automotive industry often rely on [4].

Strategic options can focus on the lowering or narrowing of the load distribution. As this means telling the customer how to operate the car, this can in many cases be judged as a non suitable option. Focusing on the Gaussian bell curve of the load level of the new structure, reliably finding the 1-percent customer through application of an Operational Monitoring system can help when judging the state of the structure.

On the side of the residual strength distribution of the structure, the option is lowering the width of the (residual) strength distribution. As any kind of technical structure can never exist without any faults or defects, this option is limited by the quality of the used production processes and by material science. A study of the effect of defects in Fiber Resin Composites is given in [5]. Another option in the future, which is also currently in research, is the usage of more sophisticated Damage Sensing methods. These methods focus on the direct finding of damage in the component, such as delaminations or cracks. Usually for the introduction of these methods higher quality sensors or more complex sensing principles need to be implemented, which results in a higher cost perspective.

Misuse loadings of Fiber Resin Composite Body in White components, which might have a damaging influence on the component or structure, can nowadays not reliably be recognized. The Fiber Resin Composite material shows brittle behavior and therefore signaling of overload conditions to the user gets necessary. Common metal sheet parts or profiles of the Body in White indirectly send back information to the driver via deformation or changes in the damage chain. Common components are designed for

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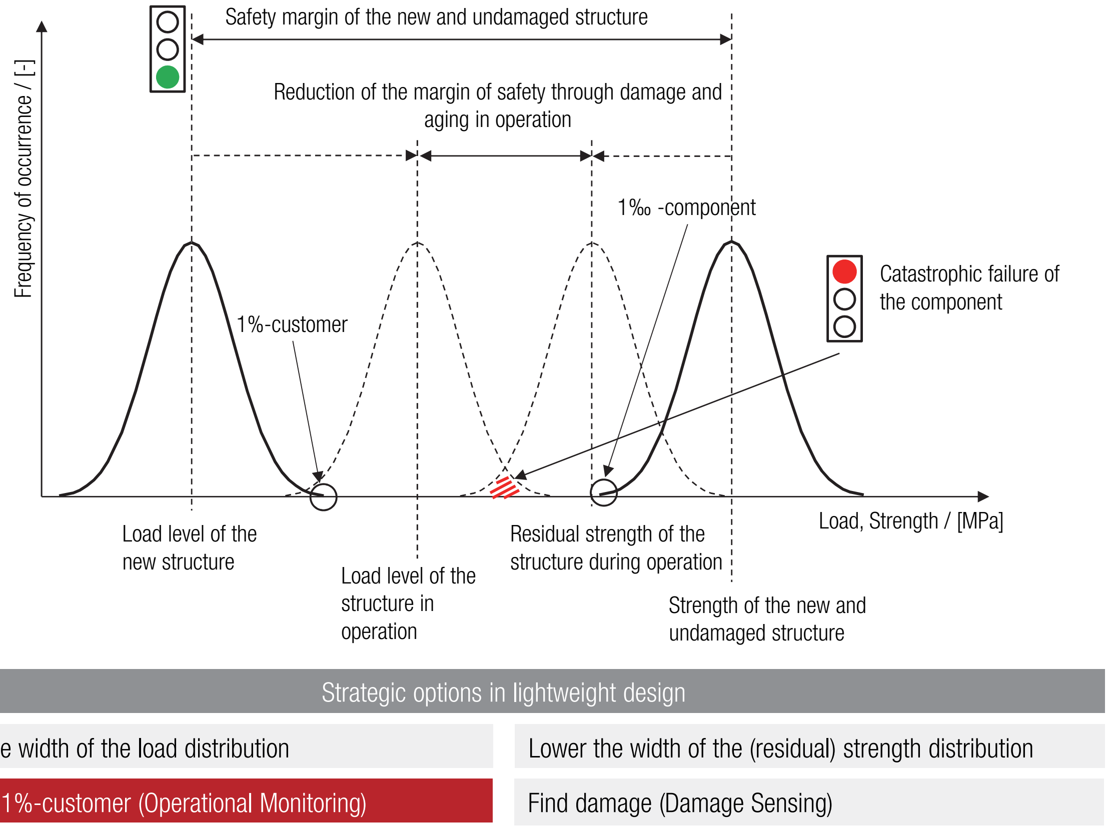

Figure 3. Implications of Operational Monitoring to the load and strength distribution. In the style of [6].

service loadings and special events. In these events no failure may occur, the part is designed in a safe-life philosophy. Further outside in the load distribution misuse events can occur. Here failure is possible, as long as the part fails safely and is located in a predetermined damage chain. In the automobile misuse load cases are handled with force-limiting victim components (rim, axle guide) and a defined chain of defects. Feedback of misuse loading is usually transferred to the customer via a misaligned steering wheel or radial runout of the rim. An Operational Monitoring system can be applied in the automobile with the goal of a higher degree of material usage in combination with a safe application of the Fiber Resin Composite.

Although Operational Monitoring methods have been presented long ago, we do not yet find them in the automotive Body in White. The author's hypothesis for a reason for this is, that the benefits for lightweight design are not yet convincingly understood. The author argues that the introduction of a Operational Monitoring system only makes sense, if the limits of the material are exhausted and a damage tolerant design philosophy (comparable to the aircraft industry) is accepted. In consequence the additional costs of such a system can be outweighed by the saved expenses for the material.

3. Influence of the tolerable maximum design strain on the structural weight

If we examine an example Body in White structure with a weight of $m = 150kg$, which roughly is the structural weight of BMW's current i3 Body in White structure, we can derive the influence of the max-

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imum design strain on the structural weight via Hooke's Law (see fig. 4). As an assumption a part under membrane loading shall be examined. The maximum allowable design strain of Fiber Resin Composite components is limited through the occurrence of First Ply Failure or Inter Fiber Failure in multiaxial laminates. First Ply Failure in a laminate usually occurs around a strain of 0.4%, depending on the specific layup configuration of the laminate and the chosen material. Due to the consideration of damage during the operational lifetime of the component, the usual design strain ends up being comparably low. Depending on the current design strain of around 0.20 - 0.25% weight savings of around 20% of the total weight, or in special cases even more, are possible by introduction of an Operational Monitoring system. This would in the example case translate into material savings of around 30 kg, depending on the existing design baseline. Assuming a current price of around 20 Euro per kg CFRP this can lead to 600 Euro of saved material cost. We see that even small extensions of the design strain envelope have a significant effect on the structural weight. The benefit also is that the same material and same package can be used. How certain is our current assumption that we are utilizing the maximum tolerable design strain reliably in the chain of our part design?

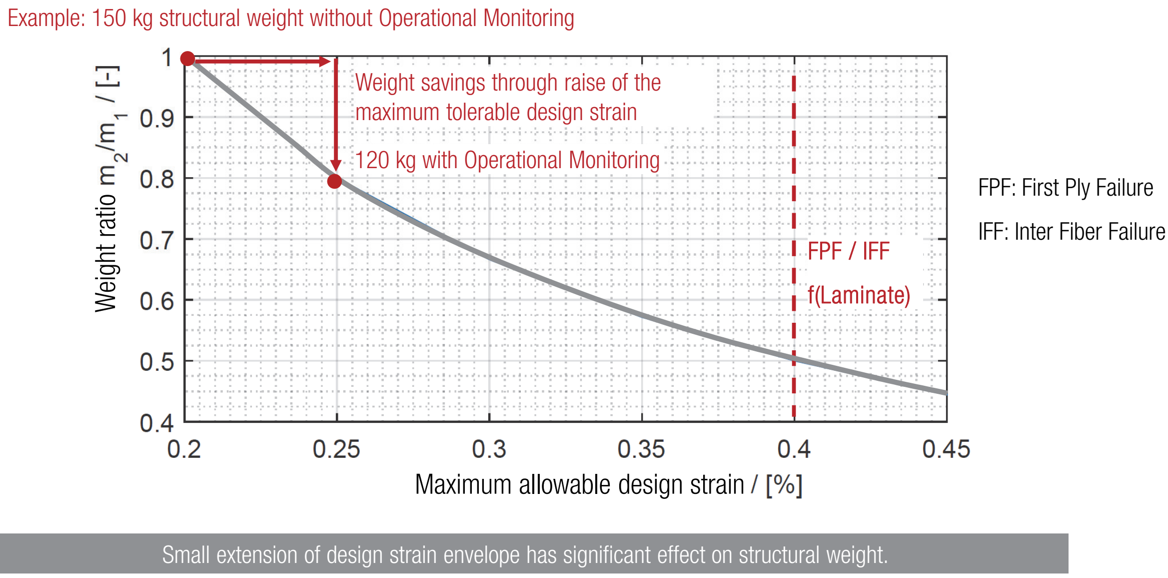

Figure 4. Influence of the tolerable maximum design strain on the structural weight.

Operational Monitoring allows lightweight design without change of material or package, by raise of the design strain envelope. Raising the design strain envelope is possible, as the automobile or the OEM knows how the vehicle is operated. Possible weight savings depend on the specific situation and can be even bigger than 20% compared to the CFRP structure without an Operational Monitoring system installed.

In the component design process one hypothesis usually is: events, which cannot be recognized during operation of the structure, have to be considered by use of additional safety margins. Safety factors have to be added to the usual service loadings, which include special events, to take care of the following events during operation

- crash-design (depending on the specific component, as not all components in the Body in W hite are prone to crash loadings),
- environmental influences such as temperature changes and humidity,

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- impact loads and notch sensitivity, as well as
- scratches and tool-drop.

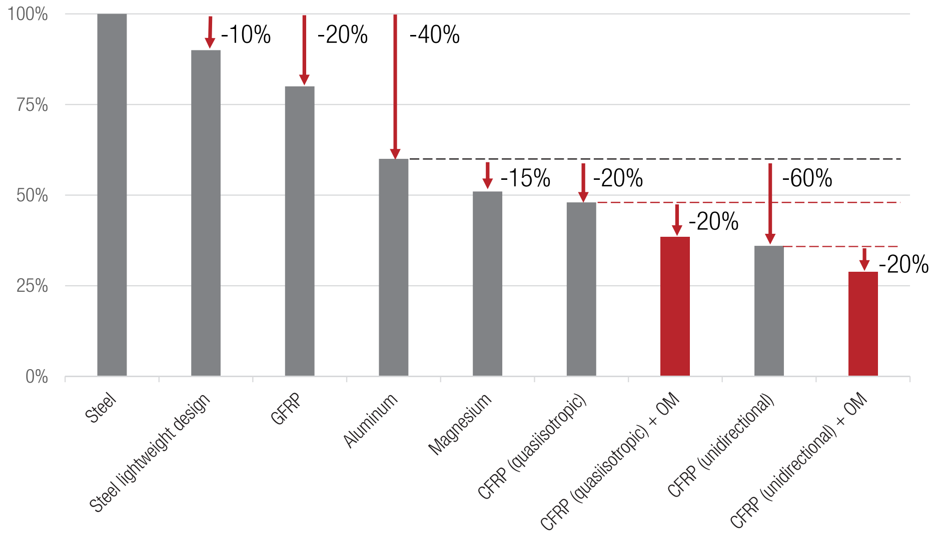

Figure 5. Lightweight design potential through implementation of Operational Monitoring. In the style of [7].

Comparing the design guidelines of the aircraft industry with the automotive industry we see that aircraft industry mostly uses the compression after impact & fatigue (CAIF) criterion in the evaluation of a structure's long term operational durability. Due to the different boundary conditions of the automotive industry it can be argued that in the automotive industry a different criterion can be proposed: *crashworthiness after impact & fatigue*. This criterion might be more suitable to the different needs of the automotive industry compared to the aircraft industry.

Major differences of the automotive context in comparison to the aircraft industry are crash load cases, the lack of a strictly performed maintenance strategy, as well as the operation of the vehicle by untrained drivers. All three of these requirements are hard to be controlled and have to be considered. In sum the maximum design-strain of Body in White components can be increased, if the crash load case can be sustained after material degradation and impact, and if an Operational Monitoring system is used at the same time.

When considering the residual strength of automobile Body in White components (compare fig. 6) we see that the residual strength is determined by discrete, random events (compare [8] and [9]). Depending on the chosen HMI-solution a warning can be given to the driver. Nevertheless the automobile OEM has to be cautious here: the chosen HMI-solution is a very sensitive topic and has to be handled with care. Information about the structural state of the automobile can have negative influences from a marketing perspective. When the crash-design residual strength of the part is reached, which is calculated by the underlying residual strength model in combination with other functions, an Operational Monitoring system can help avoid catastrophic component failure. This happens by giving timely warnings during occurrence of events with crucial influence on the component residual strength.

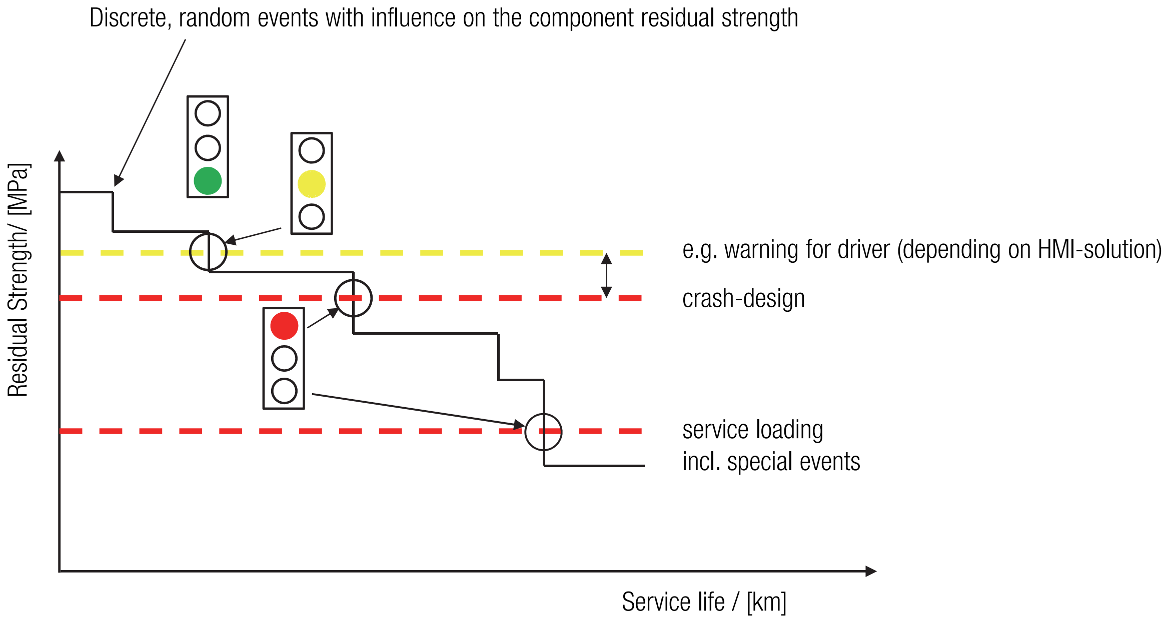

Figure 6. Operational Monitoring considering component residual strength.

4. Framework for Operational Monitoring in the Body in White structure

A typical Operational Monitoring system generally consists of three layers: the input layer, the process layer and an output layer (see fig. 7). In the input layer in our case a so called semi-passive system is used. The term semi-passive is used, as the system itself is not changing or damaging the structure. The used sensors are only passively listening to the load history of the component under supervision. Sensors are only applied on top of the component, to make sure the sensors are not working as voids, which actually might start the deterioration process of the structure. Applied on chosen body in white components we find a low amount of hot spot strain sensors, e.g. cost efficient textile strain gauges. The Operational Monitoring system can be supported by one or more temperature sensors, which are necessary for the consideration of thermal drifts of conventional strain gauges. The system is therefore capable of monitoring mechanical, thermal and (in a limited way) environmental loads. Necessary additional hardware like differential amplifiers and A/D-converters are also well known and cost efficient industrial components.

Operational Monitoring systems have to avoid false-positive and false-negative indications. Therefore the reliability of the system has to be taken care of. The necessary validation of the strain sensor signals can in the automobile context happen by usage of the ESP-sensor system. Available sensor signals for the validation are steering angle, yaw-moment, lateral acceleration, wheel speed and braking pressure. Usage of additional different driver assistance systems for validation of the system, such as camera based systems, GPS or similar is also possible in the future. The full exploitation of all capabilities of a smart combination of different - already available - sensor signals, is still open. The used sensor signals can be merged using Probabilistic Neural Networks, to ensure the necessary predictive quality and avoid false indications.

In the process layer for the function development of the Operational Monitoring system a Rapid Control Prototyping system is necessary. Typical RCP systems are National Instruments CompactRIO or dSPACE MicroAutoBox. As the system works as a model based lifetime observer, the necessary algorithm consists of three steps: preprocessing/signal processing, postprocessing/diagnosis and data storage.

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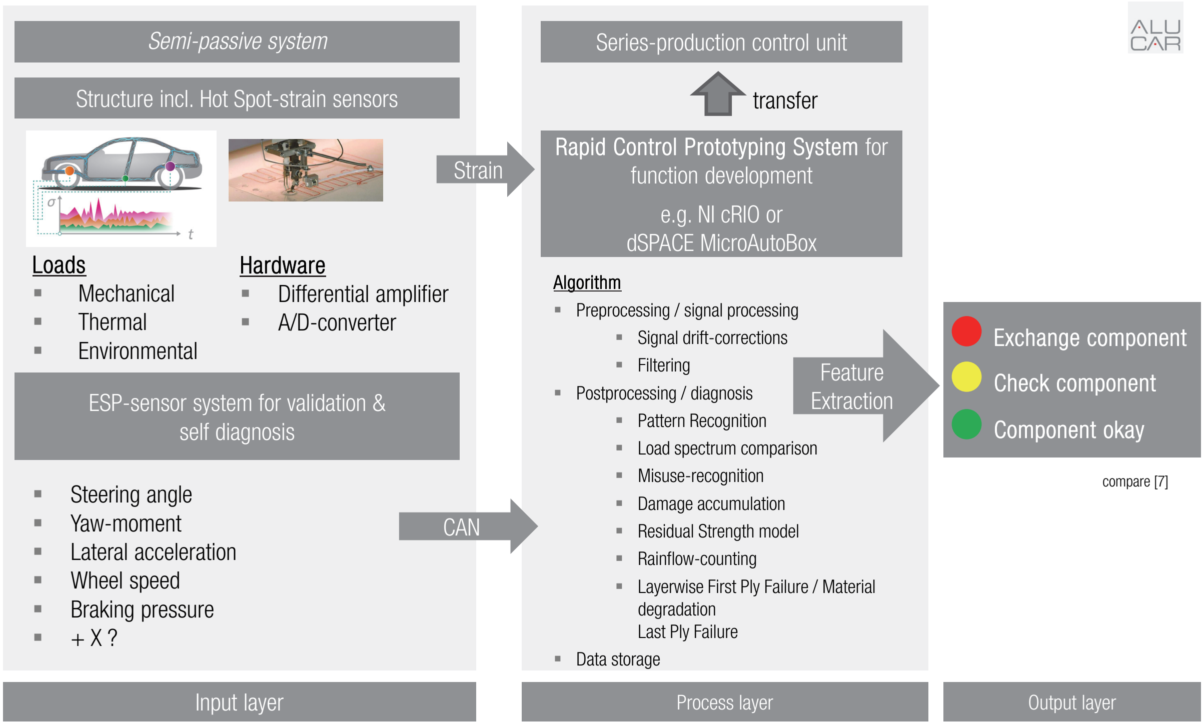

Figure 7. Depiction of different layers of an Operational Monitoring system in the automotive Body in White context.

The goal of the algorithm is the reliable extraction of a feature, that corresponds to damage respectively events, that might lead to damage with a high degree of certainty or high probability. Necessary functions to be included in the Operational Monitoring system are Pattern Recognition, Load spectrum comparison, Misuse recognition, Damage accumulation, Residual strength, Rainflow-counting and layerwise first ply failure & material degradation up to last ply failure.

The behaviour of Fiber Resin Composite structural parts under fatigue loadings in the automotive context has been extensively discussed in [10]. Most important features for the preprocessing of strain signals are the signal drift corrections and the filtering of the signal. Signal drift is a usual phenomenon in strain gauge measurements and can be corrected via usage of temperature polynomes and thermosensors or via algorithm solutions. Regarding the postprocessing of the data different methods for the judgment of a possible impending damage or failure of the component are possible. Usually one differentiates between model based methods that rely on prior teaching and calibration of damaging events, and methods that get along without such prior teaching. For the pure detection of abnormalities during the operation of the vehicle, no prior teaching of the system is necessary.

Considering the output layer different scenarios are possible. The most promising scenario is the pure use of the created data inside the vehicle, without giving information about the structural state to the user. As a goal a very simple depiction of the structural state shall be given, such as the differentiation between the red traffic light (exchange component), an intermediate state (check component) with a yellow traffic light indicator, as well as the green traffic light (component okay) (compare [11]).

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5. Conclusion

The author has presented implications of the introduction of a strain gauge based Operational Monitoring system to the automobile Body in White structure. Weight savings of about 20% or even more can be reached by an additional increase of the maximum design strain of the composite material. The potential is thereby dependent on the existing baseline of the design process. Increasing the design strain of the composite material is only safely possible, when the operation of the vehicle is monitored by a model based Operational Monitoring system. The author has shown different necessary functions and layers of such an Operational Monitoring system in the automotive context. Necessary functions are including a validation of strain gauge signals via usage of the ESP system sensors as well as information given by signals of driver assistance system sensors. Furthermore different preprocessing and postprocessing methods are depicted to reach a conclusion of the current component status, which can be shown in the output layer.

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