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Structural durability of forged automotive aluminium chassis components submitted to spectrum loading and salt-corrosion by the example of a tension strut

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Abstract

The structural durability design of a tension strut of forged aluminium (EN AW 6082 T6), which is a safety component of the automotive chassis, is described. The first step of the structural durability design is the knowledge of the mechanical and environmental loadings. The mechanical loadings are the spectrum loading for the designated normal driving conditions and unintended special event loadings by e.g. braking over road bumps, which are introduced into the component through the wheels. The local stresses imposed on the component are also influenced by kinematics, stiffness, axle mass, dampers, bearings, bump geometry etc. The environmental loading is the corrosion caused, in winter-time, by salty water on the roads. For design according to the local stress concept, the knowledge of Woehler-curves without and with salt corrosion effects is necessary. On this basis, cumulative fatigue under spectrum loading, which also comprises the special events mentioned, is assessed for a standard configuration and for an optimized one. The numerical results are verified by experimental proofs on the component in the laboratory and on the proving ground as well as by field tests with vehicles.

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1. Introduction

As chassis components belong to the category of safety components, which must never fail, their structural durability design has to be carried out through a consideration of all possible types of service loadings, Fig. 1.

These are service spectrum loading including special events and corrosion resulting from salty roads in winter. The methodology for the consideration of these effects for aluminium components has already been studied and proposed on behalf of the German automotive industry [1] and will be summarized in the next section. The proposed paper will demonstrate using the example of a forged aluminium (AlMgSi1 T6 (EN AW 6082 T6)) tension strut, Fig. 2, a safety component of the BMW 3-series, how the design must be carried out and verified. Details on the loading of this component are given in [2 - 4].

In the following, a short overview will firstly be given of the state of the art in considering salt corrosion and spectrum loading in the structural durability design of automotive aluminium safety components, the loading conditions and the parameters influencing the stresses of the forged aluminium tension strut will then be compiled, and finally the structural durability will be assessed, using the specific material data and derived spectra.
2. Short State of the Art in Considering Salt Corrosion and Spectrum Loading Effects on Aluminium Chassis Components

Independently of the manufacturing mode, i.e. cast, forged or welded, fatigue strength due to salt corrosion under constant amplitude loading decreases in the high-cycle regime (N \(> 10^6\) cycles) with increasing lifetime, as displayed in Fig. 3. However, under spectrum loading, the decrease of fatigue strength due to corrosion is significantly lower [1, 5].

This knowledge was obtained for a corrosion cycle 20 to 25 minutes dry and 5 minutes spraying with 5\% NaCl solution during continuous mechanical cyclic loading [1, 5]. Under these conditions, within typical chassis frequencies (1 to 100 \(\text{s}^{-1}\)), an additional frequency effect on fatigue life is not observed. This corrosion cycle, recommended for testing purposes of automotive components, is considered to be sufficiently severe and consequently conservative, because the corrosion conditions are intensified [1].
The following design recommendations for aluminium alloys of the 5000 and 6000 groups of the international alloy register were derived from this knowledge [1]:

- The SN-line for corrosion is determined by reducing the fatigue strength in air at $5 \cdot 10^6$ cycles by 50%. Through this corrosion fatigue strength, the SN-line for corrosion is drawn with a slope of $k_{corr} = k_{air} - 1$. This SN-line has no knee point because of the influence of corrosion. If experimental data are not available, the SN-line in air can be drawn up to a knee point at $1 \cdot 10^6$ to $2 \cdot 10^6$ cycles with a slope of $k_{air} = 5.0$ and continued beyond the knee point with $k^*_{air} = 22.0$, and the SN-line for salt corrosion can be drawn with a slope of $k_{corr} = 4.0$.

- If a Gassner-line is experimentally obtained in air for a given spectrum, the Gassner-line for salt corrosion can be estimated by reducing the fatigue strength in air by 20-25%.

- For a cumulative fatigue life calculation and numerical determination of Gassner-lines according to the Palmgren-Miner rule, the allowable damage sum for noncorrosive applications is $D_{air} = 0.3$ and, for salt corrosion, $D_{corr} = 0.5$, as long as the load-time history does not reveal significant mean-load fluctuations. If mean-load fluctuations result in a difference of more than a factor of 3 in the most damaging parts of spectra obtained by level-crossings and range-pair countings [6], then the additional damaging influence by the fluctuations must be considered by applying lower allowable damage sums, 0.1 and 0.3 respectively. For the cumulative damage calculation, the SN-line in air is continued beyond the knee point with $k'_{air} = 2k_{air} - 1$, while, for the SN-line for salt corrosion, the slope $k_{corr}$ is not changed.

- The failure criterion for automotive safety components is the initiation of a visible surface crack with a length of 1 to 2 mm. This is allowed when the design life is exhausted, e.g. 300,000 km for automotive components, and a spectrum loading with an occurrence of $P_o = 1\%$. Crack propagation is excluded.

The application of these recommendations will be presented in the section, which focuses on the structural durability assessment of the tension struts.

3. Design, Material and Loading of the Tension Struts

3.1. Design and material

In Fig. 4, the design and dimensions of the tension strut and its maximum stressed and fatigue critical cross section are shown. The tension struts are mounted by one ball bearing and one elastomeric bearing into the suspension structure and are submitted only to longitudinal forces introduced over the attachment points. With reference to the quality of the struts, any surface defects must be excluded through application of the dye penetrant method according to DIN EN 571-1. A fine-grained, homogenous and defect-free macrostructure along the component is required. After forging, the struts are shot blasted with aluminium granules for surface cleaning. The surface roughness is $R_z = 10-35 \mu m$. The conventional mechanical data of the alloy AlMgSi1 T6 (EN AW 6082 T6) are $E = 72$ GPa, $\nu = 0.33$, $R_m \geq 340$ MPa, $R_{p0.2} \geq 300$ MPa and $\epsilon = 10\%$.

Fig. 4. Geometry of the forged aluminium tension strut and critical cross section
3.2 Special events and spectrum loading

Special events [7 - 9] experienced by the tension strut are e.g. caused by braking over road bumps. To consider such events, a standardized bump geometry was developed, Fig. 5, for the sake of reproducibility of measurements and for non-arbitrary numerical simulations. Fig. 6 displays the wheel behaviour during such an event and the measured longitudinal load-time history.

Fig. 5. Geometry of standardized road bumps

Fig. 6. Load-time history of the load due to braking over a road bump

Fig. 7 demonstrates how, for example, the variation of kinematic conditions, here the standard configuration versus best (optimized) and worst cases, may influence the longitudinal loading of the tension strut by driving at 120 km/h and braking over a bump with a defined geometry.

The variation of the connection points of a tension strut is shown schematically in Fig. 8. In addition to the standard position, the best (optimized) and worst cases are displayed.
Further parameters that influence the maximum load of tension struts and the ranking of these parameters, with regard to the size of the occurring loads, are given in Fig. 9. The loads were determined by multi-body systems simulations through variation in both directions (best (optimized) and worst case) of the parameters given in Fig. 9. Details on the applied model are presented in [2-4]. The optimization of the influencing parameters, with regard to the reduction of the loads introduced into the tension struts, is carried out by design of experiments.

The number of times that a special event may be allowed in the design and the corresponding proof is a decision for the vehicle manufacturer. In the case of the tension struts, 100 occurrences of the maximum load is considered [2].

For the structural durability assessment, as well as the unintended special event loads, the load spectrum under designated normal driving conditions, i.e. for the design life, must also be known. These loads are obtained from measurements at a BMW proving ground for a driving distance of \( L = 10,000 \) km. The intensified driving conditions on this proving ground correspond to a driving distance under normal conditions of 300,000 km, resulting in a spectrum with a probability of occurrence of \( P_o = 1\% \). Therefore, the spectrum obtained on the proving ground is damage equivalent to the design spectrum for 300,000 kms. Due to the multi-body systems simulation model, the spectrum obtained can be transmitted to any chassis configuration. Fig. 10 illustrates, in addition to a cut-off of the load-time history, the spectra obtained from the numerical simulations for the standard configuration and the best (optimized) case. From the rainflow-countings, the spectra for level crossings and range pairs are derived.
For the assessment of the structural durability of the tension struts, the mentioned special event loads must also be superimposed on these spectra. This will be performed in next section.

4. Structural Durability Assessment

The statistically-based safety consideration of a component or of a structure is expressed by a theoretical probability of failure $P_f$. This comprises not only the probability of occurrence $P_o$ of the spectrum, but also the probability of failure for the design SN-curve (fatigue strength) $P_{f,SN} = (1 - P_{s,SN})$, which is a complementary value to the probability of survival. When the scatter of service loading is higher than the scatter of fatigue strength, which is usual for automotive safety parts, then the theoretical probability of failure is determined by $P_f \leq P_o \cdot P_{f,SN}$ [10]. This probability of failure is given when the matching of the spectrum with the design SN-curve results in the allowable damage sum. If the design life (spectrum size, e.g. 300,000 km) or the allowable damage sum is exceeded, then the probability of failure increases.

For the tension struts, the design SN-curve, for the failure criterion of a first technically detectable crack with a surface length of $l = 1\text{-}2 \text{ mm}$, was derived from fatigue tests in air for a probability of survival of $P_{s,SN} = 99.9\%$. This results, when combined with the probability of occurrence of the spectrum $P_o = 1\%$, in the theoretical probability of failure $P_f = 10^{-5}$, which is usually applied for various automotive chassis components. This value signifies that, as long as no harder spectrum will occur during the designated design life and as long as the defined quality of the tension struts will not be lower than the determined one, practically no failure will occur.

Based on these prerequisites, the particular spectra for the standard and best case configurations of the tension struts and the design SN-curves for $R = -1$ are as presented in Figs. 11 and 12. Also, the displayed spectra are valid for $R = -1$; amplitudes with mean stresses in the rainflow-matrices were transformed to $R = -1$ by the use of a Haigh-diagram for the mean-stress sensitivity of $M = 0.3$ for the forged alloy used [1, 2]. The damage increments, resulting from the unintended special events with the assumed occurrence of $n = 100$, are so small ($D < 0.01$) that they have no importance in the following discussion.
The cumulative damage is evaluated using the allowable damage sums $D_{\text{air}} = 0.3$ and $D_{\text{corr}} = 0.5$, without any reduction to account for mean-load fluctuations. This is justified by the fact that the maximum difference of cycles between the level-crossings and range pair countings does not exceed the factor 3 mentioned in the section describing the state of the art, Fig. 13.

The spectra for the standard configuration and optimized case, shown in Fig. 11, result, for a noncorrosive environment, in damage sums of $D = 0.109$ and $0.028$, respectively. These values are lower than the allowable damage sum $D_{\text{air}} = 0.3$, i.e. the theoretical probability of failure is much lower than $P_f = 10^{-5}$ or this probability would be reached after a driving distance larger than the design distance by a factor of $D_{\text{air}} / D = 3$ and 11, respectively. The ratio between the calculated damage sums 0.109 and 0.028 results, for the best configuration, in a higher durability than for the standard one by a factor of 3.9.
Fig. 13. Comparison of level-crossings and range-pair countings

Under a corrosive environment, the design SN-curve for salt corrosion, Fig. 12, is shifted to a lower fatigue strength level and therefore results in higher damage sums compared to those under air, $D = 0.622$ and 0.249, respectively. The optimized configuration of the struts results in a value lower than the allowable $D_{corr} = 0.5$, but the standard configuration exceeds this allowable damage sum by a factor of 1.24. However, this issue is not critical and deserves no further consideration because the recommendations for deriving the design SN-curve for salt corrosion are overly severe as they are based on intensified spraying cycles (see section on the state of the art), which never occur in this way in service. Also, the fact that the calculated Gassner-curve for corrosion lies in a fatigue strength range more than 20 to 25% below that of the Gassner-curve for air, Fig. 14, underlines the conservatism of the performed cumulative damage calculation. Proving ground and field experiences confirm this. The obtained fatigue life improvement from the optimized strut configuration in the corrosive environment is a factor of 2.5 compared with the standard one. This is lower than the calculated improvement in air, but still offers a significant opportunity for lightweight design.

Fig. 14. Calculated Gassner-curves of tension struts in air and under salt corrosion
5. Summary and Conclusions

Using the example of forged aluminium tension struts of AlMgSi1 T6 (EN AW 6082 T6) for the BMW 3-series, a structural durability assessment was carried out. During this assessment, not only was the spectrum loading inclusive of special event loadings due to braking over bumps considered, but also the environmental loading by salt corrosion in winter time. Therefore, recommendations with regard to the reduction of fatigue strength by salt corrosion as well as for cumulative damage calculations were applied. The results are compiled in Fig. 14 and were verified by proving ground and field experiences.

Furthermore, the mechanical loading of standard tension struts can be reduced significantly by optimizing the interaction between kinematics, component stiffness, axle mass, dampers, bearings and bump geometry. This enables a significant improvement of fatigue life, as displayed in Figs. 11 and 12. This life increase can certainly be compensated by a reduction of dimensions offering a considerable opportunity for lightweight design, provided that a buckling of the strut does not occur.

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