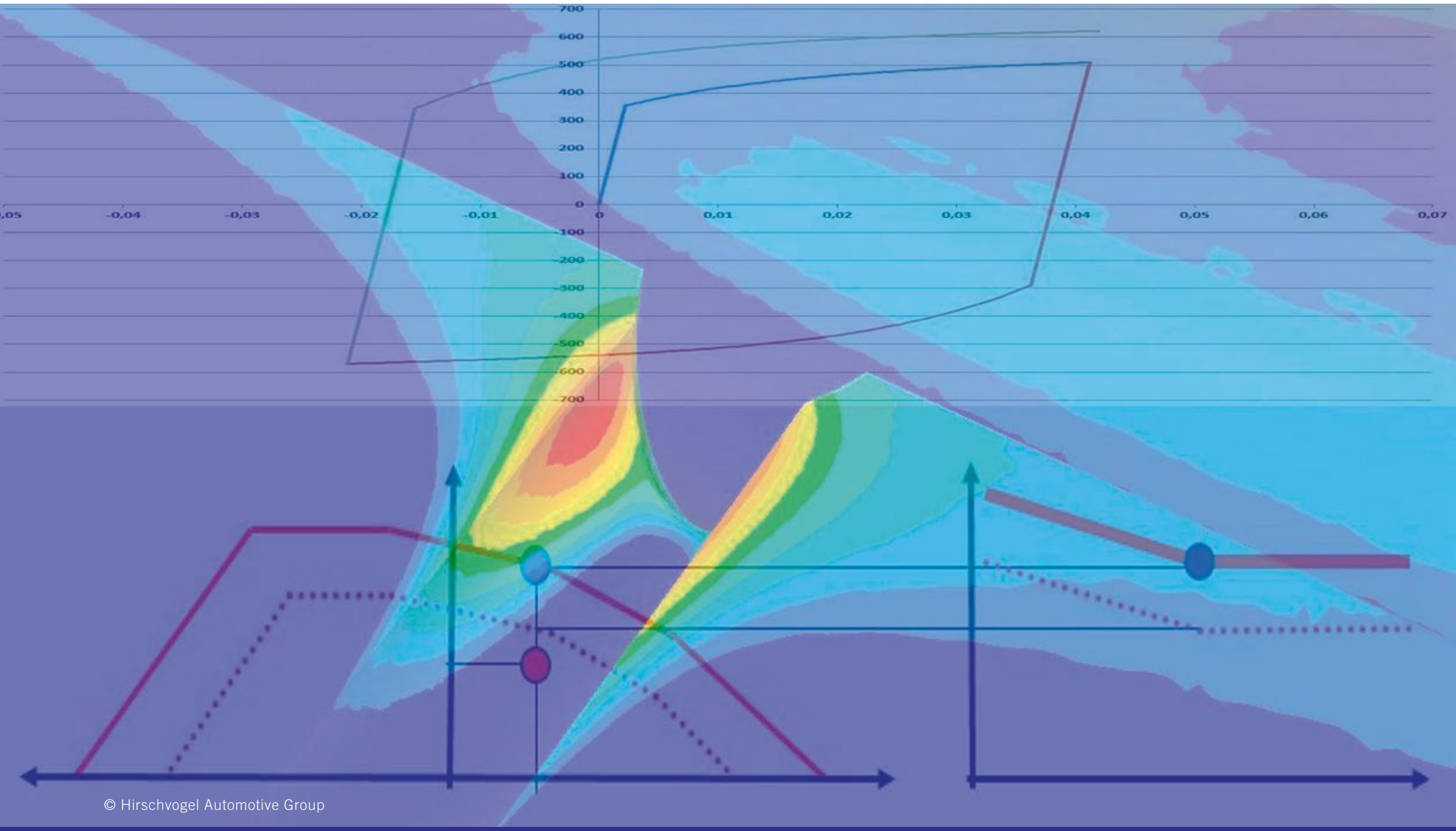


© Hirschvogel Automotive Group

Layout of Highly Stressed Injection and Motor Components

Hydraulic autofrettage as a means of increasing fatigue life of components charged with internal high-pressure (for example common rails for Diesel-injection systems) is establishing itself progressively in the field of off-highway engines. During computational layout of this process step, consideration of anisotropic material behaviour is of primary importance. So far, local quite possibly directional component-strength (such as due to prior autofrettage) has not been taken into account among standards to evaluation of durability for forged components. In the context of a joint development project this gap has been closed by Hirschvogel Automotive Group, Engineering Center Steyr and Transvalor.

AUTHORS

Jochen Heizmann, B.A.
is responsible for the development of new business areas at Hirschvogel Automotive Group in Denklingen (Germany).

Dr.-Ing. Hans-Willi Raedt
takes responsibility for the Advanced Engineering Department at Hirschvogel Automotive Group in Denklingen (Germany).

Dipl.-Ing. Patrice Lasne
is Senior Engineer in the Development of Transvalor S.A. in Mougins (France).

Dipl.-Ing. Helmut Dannbauer
takes responsibility for Analysis Services and Software Products of the Structural Analysis Department at Engineering Center Steyr GmbH & Co. KG in St. Valentin (Austria).

PRINCIPLE OF HYDRAULIC AUTOFRETTAGE

Injection pressures beyond 2000 bar contribute significantly to a more efficient exploitation of fuel in prospective engines. The so-called autofrettage method ensures, that hydraulic tubes and pipes are able to withstand ever-increasing alternating loads [1]. Autofrettage is a means of generating residual stresses in pipes, in order to improve its load-bearing capacity as well as fatigue-life [2]. In the course of hydraulic autofrettage thick-walled metallic cylinders are subjected on the inner diameter to a high internal pressure. At present, the level has been recorded at three to four times the nominal working pressure. Thereby material at the inner diameter is expanded under tensile loading above its elastic limit, **FIGURE 1**, whereas deformation in outer sections still remains in the elastic area of the material. After release of the autofrettage pressure the outer zone of the cylinder will relieve elastically. Material in the area of the inner diameter, particularly at the bore-intersection will undergo plastic deformation again, this time under compressive loading. After achieving the state of equilibrium, plastically deformed sections will end up in a condition of compressive residual stresses. Later, under impact of internal working pressure this will have a positive effect, as compressive residual stresses resulting from autofrettage compensate tensile stresses: during operation reduced equivalent stresses as well as shifted local mean-stresses can lead to higher admissible amplitude stresses [3].

OPTIMISATION OF FORGED HIGH STRENGTH COMPONENTS

Technical systems of modern times – both for automotive and off-highway applications – contain forged high-strength components, many times. Its key role particularly can be explained by the massive load-bearing capacity, which is the crucial point whenever it comes to transmission of exalted forces, torques or pressures. Increasing requirements regarding power density necessitate more intense component optimisation, which takes painstaking tuning of material, component-geometry as well as numerous parameters along the entire development- and process-chain for granted.

In the course of full utilisation of mechanical-geometrical potentials at ideally lowest costs, vigorous application as well as continuous development of advanced design tools gains great importance. Thanks to long-standing know-how and software-tools as CAD, topology- and shape-optimisation as soon as linear-elastic FEM simulation the Hirschvogel Automotive Group is in a position to reliably design components on the basis of requirements and design-rules of customers. Furthermore, the company recently has acquired numerous further competences and refined these together with for instance industrial and academic partners (such as regarding understanding of micromechanical material-mechanisms). Such as application of elasto-plastic forming-simulation in combination with advanced materi-

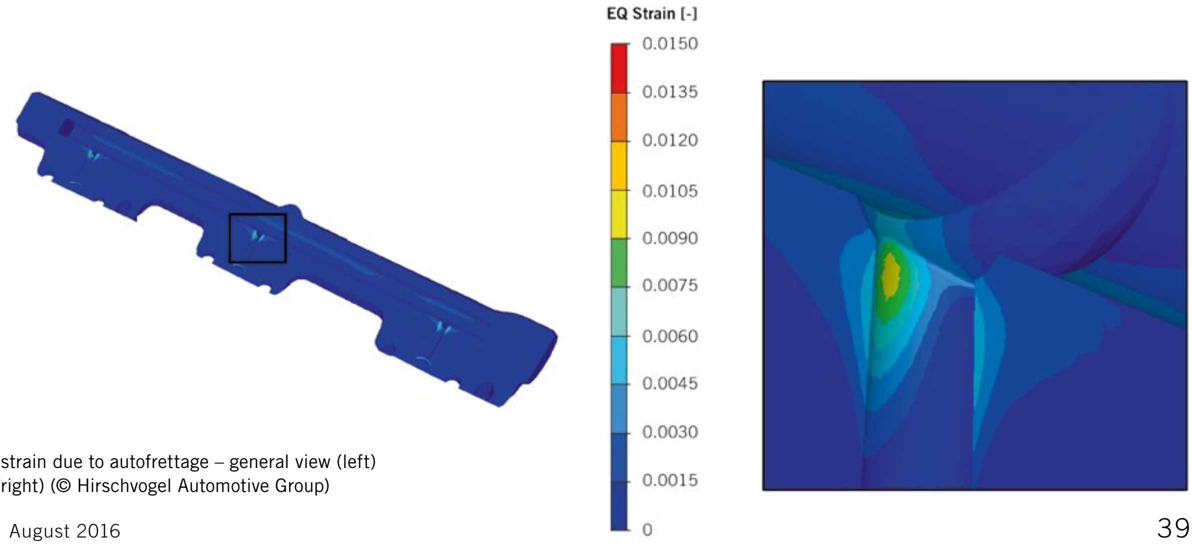


FIGURE 1 Plastic strain due to autofrettage – general view (left) and detail view (right) (© Hirschvogel Automotive Group)

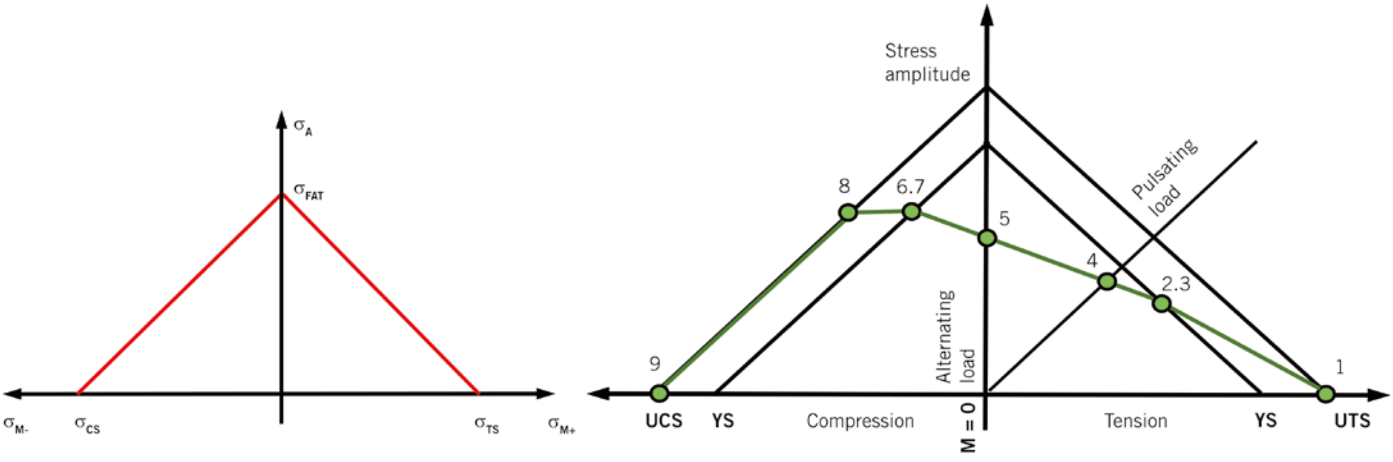


FIGURE 2 Goodman Diagram (left) and Haigh diagram (right) (© Hirschvogel Automotive Group)

al-models creates the possibility, to not only compute least plastic deformations precisely adjusted during autofrettage, but also to post process resulting residual stresses. Generally, whenever it comes to classical forming simulation in combination with metallic materials, isotropic hardening is assumed. In the case of minor plastic deformation and particularly in combination with cyclic material loading, as a rule kinematic hardening dominates. These will now by means of suitable models in combination with material-specific parameters be taken into consideration during FEM simulation of the autofrettage-process followed by a fatigue analysis.

PREVIOUS APPROACHES ADOPTED TO ASSESS FATIGUE LIFE OF COMMON RAILS

In cases where autofrettage does not come to fruition or whenever one chooses conservative approaches during layout of common rails, engineers are tempted to regard empirical values related to diameter ratios. If FEM software good for linear-elastic analysis of operating states (without prior autofrettage) is available, various geometry-proposals can be assessed via empirical formula which take material strength (for example YS or UTS) and von Mises equivalent stress into account at the same time. In the event of deploying formulations of material science and fatigue, the Goodman diagram, **FIGURE 2**, may be applied, in order to quantify the relation of mean stress and alternating strength with respect to durability of the material. The area underneath the graph indicates, that at given stresses the material should not fail. The area above the curve represents potential failure of the material. Thereby σ_A stands for stress amplitude, σ_M for mean stress, σ_{FAT} represents fatigue limit for exclusively alternating load and σ_{TS} stands for ultimate tensile strength, respectively σ_{CS} for ultimate compressive strength of the material. The general trend, shown by the Goodman diagram for example provides decreasing sustainable stress amplitudes with increasing tensile mean stress [4].

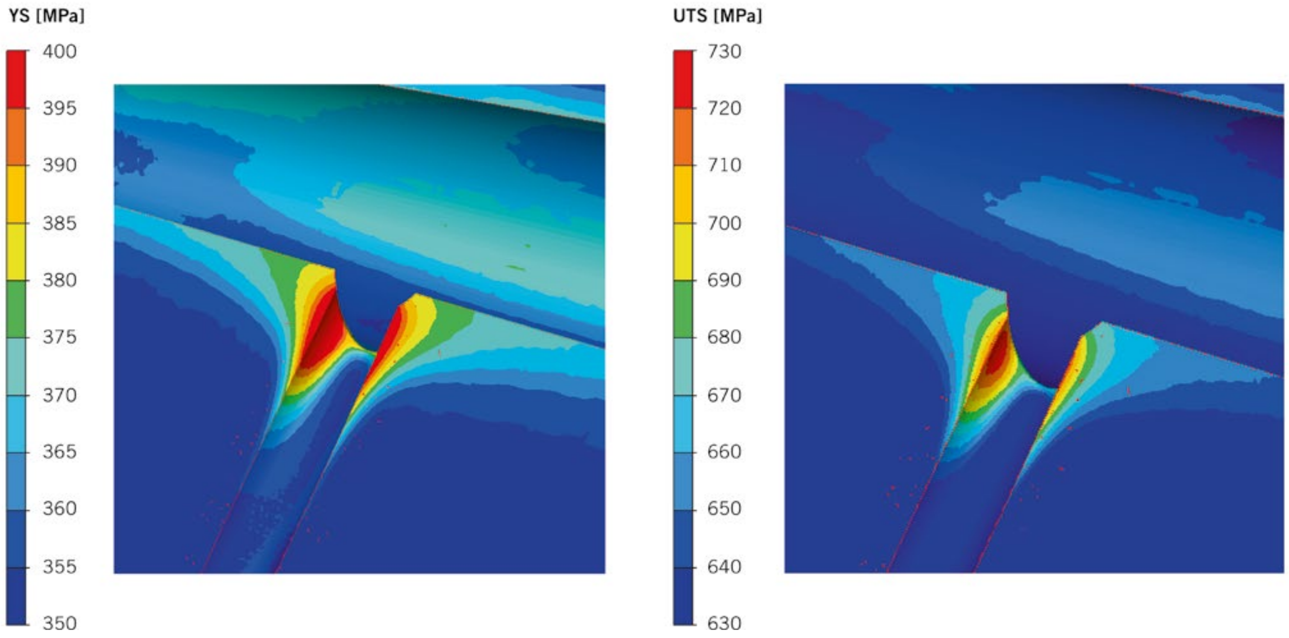


FIGURE 3 Local increase of yield stress (left) and ultimate tensile strength (right) due to autofrettage (© Hirschvogel Automotive Group)

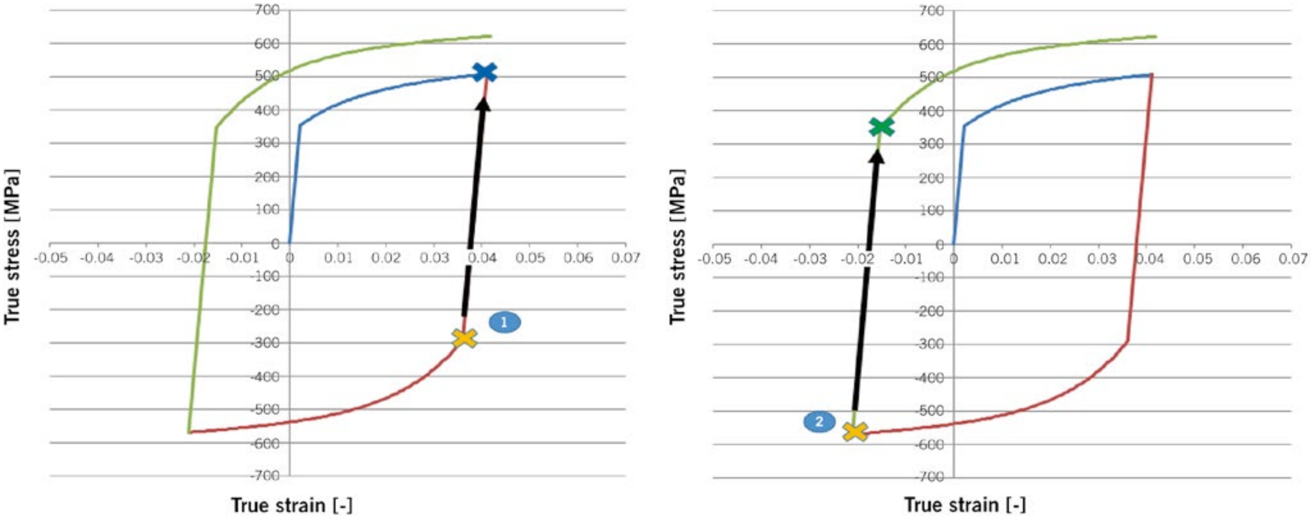


FIGURE 4 Consideration of isotropic (left) and kinematic (right) material behaviour (© Hirschvogel Automotive Group)

In the course of fatigue-life assessment (such as common rails) taking autofrettage into consideration, while following advanced approaches, as a rule elasto-plastic FEM software (for example FORGE) is applicable. Simultaneously the so-called Bauschinger effect in terms of kinematic hardening models is included in the computations, so that a realistic distribution of residual stresses can be transferred from a prior autofrettage simulation to the subsequent fatigue-life analysis (for example FEMFAT). Thanks to the description of the material-characteristic by Haigh diagrams, compared to the Goodman diagram mean stress sensitivity of the material can be considered at a higher level of detail, **FIGURE 2**.

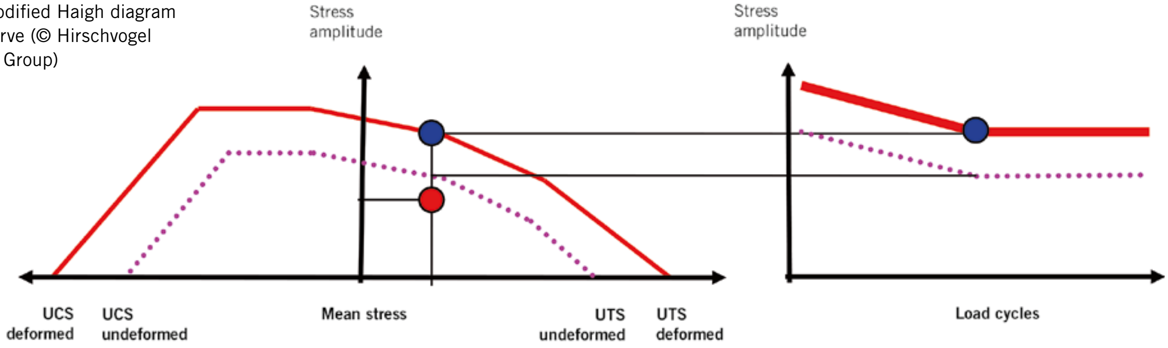
NEW ACCOMPLISHMENTS QUALIFIED FOR FATIGUE LIFE ASSESSMENT OF COMMON RAILS

Due to joint further development of models suitable for fatigue life assessment, in the future local strain hardening as well as softening effects related to plastic deformation can be integrated in terms of yield stress as well as ultimate tensile strength – as a result of a preceded elasto-plastic forming simulation – into the subsequent fatigue analysis, **FIGURE 3**. This is ensured by making a distinction between isotropic and kinematic material behaviour during transfer of local parameters to durability analysis. As a rule, for the latter behaviour directional dependency of ultimate tensile strength and yield stress due to deformation during autofrettage plays a crucial role, **FIGURE 4**.

This in turn means that fatigue life analyses do not only operate on the basis of local Haigh diagrams, beyond that these are adapted due to present variations of strength. Whenever impacts on the material properties (such as fatigue strength) are being calculated in the FEMFAT software, the associated Haigh diagram changes. Positive impacts lead to an expansion of the diagram, whereas negative ones would entail a reduction of material properties, simultaneously the loading capacity would decrease. Any individual adaptation shall be made proportionally in accordance with existing local specifications for ultimate tensile strength. As a consequence, any node of the finite-element-mesh can carry a customised Haigh diagram and therefore also can evince a varying local s-n curve – due to dissimilar material properties and boundary conditions (temperature, notch, surface roughness etc.). Furthermore, one has not to assume homogeneous material properties anymore, because the accuracy of the material description via individual data on material strength at any finite-element-node can be transferred from forming simulation to fatigue life analysis, **FIGURE 5**.

As a general rule, engine components are designed to have fatigue strength. As a consequence, during fatigue life analysis of common rails focus is solely placed

FIGURE 5 Modified Haigh diagram and S/N-curve (© Hirschvogel Automotive Group)



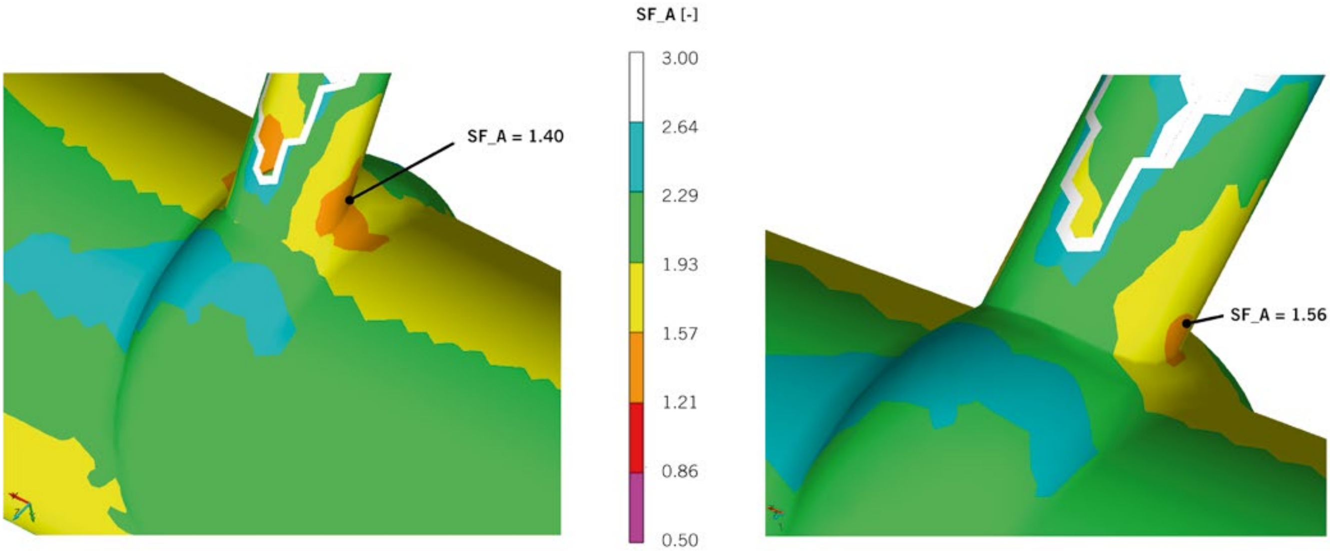


FIGURE 6 Safety factor without (left) and in (right) consideration of local parameters (© Hirschvogel Automotive Group)

on the two critical load cases. Considering that, the locally present safety factor will be determined - in accordance with scatter range, survival probability of the material to be investigated and the targeted survival probability. The calculated safety factor enables the development engineer to assess, whether durability can be expected for the analysed component or not. **FIGURE 6** illustrates, that the increase in ultimate tensile strength and yield stress in the critical area of the bore intersection have a significant positive impact on the respective safety factor (increase from SF_A = 1.40 to SF_A = 1.56) - hence in the present example durability can be anticipated.

SUMMARY

Consideration of kinematic material behaviour can increase precision of the layout of components charged with internal high pressure (for example common rails for Diesel-injection systems) markedly. In case one wants to particularly assess the anticipated fatigue life of the component as well, it seems appropriate, that residual stresses computed in the course of autofrettage-simulation as well as respective local strain hardening of the material should be taken into account during a subsequent fatigue life calculation. Furthermore, new accomplishments facilitate a significant increase in the predictive quality of durability analysis. These are premised on generation and transfer of further parameters applicable for characterisation of local material strength (for the time being limited to the successful implementation of local ultimate tensile strength and local yield stress of the strain hardened component).

REFERENCES

[1] N.N.: FELSS – Shortcut Technologies. www.felss.com/verfahren-maschinen/autofrettage, access 04.06.2016
[2] Carlucci, D.; Jacobson, S.: Ballistics – Theory and Design of Guns and Ammunition. Boca Raton: Taylor & Francis Group, 2014.
[3] Narayanan, R.; Dixit, U.: Advances in Material Forming and Joining. New Delhi: Springer, 2015.
[4] N.N.: Wikipedia: Goodman Relation. https://en.wikipedia.org/wiki/Goodman_relation#cite_ref-6, access 04.06.2016

THANKS

The authors would like to thank Dipl.-Ing. Axel Werkhausen, FEMFAT-Sales- and Support-Manager, and Dr.-Ing. Christian Gaier, Team-Manager of the FFEMFAT Development Department, both at Engineering Center Steyr GmbH & Co. KG in St. Valentin (Austria), as well as Dipl.-Ing. Olivier Krafft, Sales Engineer Northern Europe at Transvalor S.A. in Mougins Cedex (France) and Dipl.-Ing. Angela Kotte, Development Engineer for Material & Technology in the Advanced Engineering Department at Hirschvogel Automotive Group in Denklingen (Germany), for their contribution during the implementation of the development project.