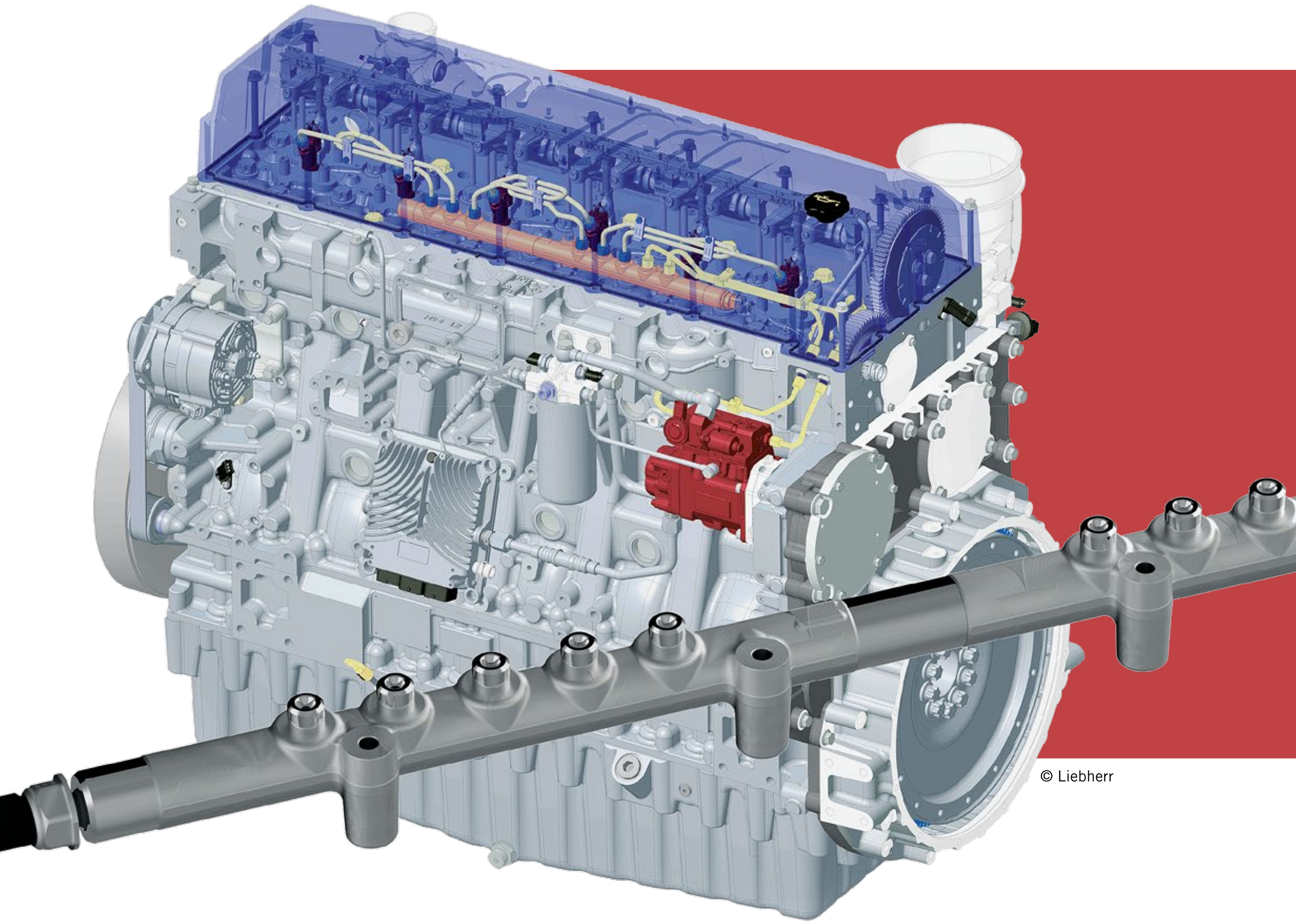

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NEW D976 DIESEL ENGINE

Liebherr is a major worldwide player in the domain of Medium-duty (MD) and Heavy-duty (HD) diesel engines for off-road applications. Diesel engines are renowned for combining high performance and robustness. In recent years, Liebherr has been working intensively on the development of a new range of engines with the aim of continuing to guarantee high performance and robustness and to significantly decrease fuel consumption and polluting emissions. The D976 in-line engine is one of the

Liebherr Diesel Engine D976 with Forged Common Rail

Forged products have always been of great importance in many industries and have found application in a wide variety of areas. Thanks to their application, the performance and robustness of combustion engines have been markedly improved in the past. Hirschvogel Automotive Group and Liebherr Common Rail Systems present the latest results of their cooperation project for the introduction of forging technology in the manufacturing of injection components. The aim of developing a forged high-strength common rail for the Liebherr D976 diesel engine recently launched on the market was a significantly decrease of fuel consumption and simultaneously reduce polluting emissions.

flagship engines of this new range. With a displacement of 18 l and a power range up to 620 kW, it is currently the most powerful in-line engine of the manufacturer. The engine generates a maximum torque of 3650 Nm at 1500 rpm and complies with EU Stage V, Tier 4f and Stage IIIA emission standards. The SCRFilter and SCROnly systems by Liebherr are used to implement Stage V. To achieve the high power, the engine is equipped with the innovative Common Rail System (CRS) by Liebherr, which guarantees a high level of efficiency, precision in fueling timing and accuracy in dosing fuel quantity up to 2500 bar injection pressure.

WORKING PRINCIPLE OF FUEL INJECTION SYSTEMS

When it comes to high-performance engines, the injection system is one of the key assets, subjected to severe requirements. **FIGURE 1** schematically shows a typical set-up of an injection system and its main components. The fuel, stored in the tank, is sucked by the Low-Pressure Pump (LPP) and flows through a pre-filter/water-separator element to filter out the biggest contaminants. The LPP delivers pressurized fuel (approximately 8 bar) to the fine filter where the fuel undergoes the second stage filtration to remove the smallest contaminants and ensure excellent cleanliness before entering the high-pressure part of the injection system. The fuel delivered by the LPP is metered by a Volume Control Valve (VCV) and enters the high-pressure chamber where it undergoes the second compression stage, which brings it to the desired injection pressure. The pressurized fuel is accumulated into the common rail and flows toward the injectors when the injection is trigged by the Electronic Control Unit (ECU). The injector delivers the requested amount of fuel – finely vaporized – directly into the combustion chamber to enable a proper combustion process.

FUEL INJECTION SYSTEM FOR THE DIESEL ENGINE D976

A very compact layout has been adopted for the D976 on account of mounting the high-pressure rail below the cylinder head cover along with top feed injectors. This guarantees minimum distance between fuel pressure accumulator and injectors, hence optimal pressure stability and fuel delivery can be achieved. **FIGURE 2** shows the fuel injection system designed for the engine. The following components from Liebherr must be mentioned:
- Pump LP11.2
- Rail LR60.8
- Top Feed Injectors LI2.9
- ECU3.

To guarantee the accuracy of the injection quantity, the pressure stability, which must be maintained independent of rail position and injection timing, is of paramount importance, especially because of the high power density of the engine (~105 kW per cylinder) and the consequently high injection quantity per shot (up to 500–550 mg for the highest rated power). Beyond that, the correct dimensioning of the accumulator volume appears of great importance as it enables proper dampening of the pressure perturbations due to fuel pumping and injection events. After all, a sophisticated accumu-

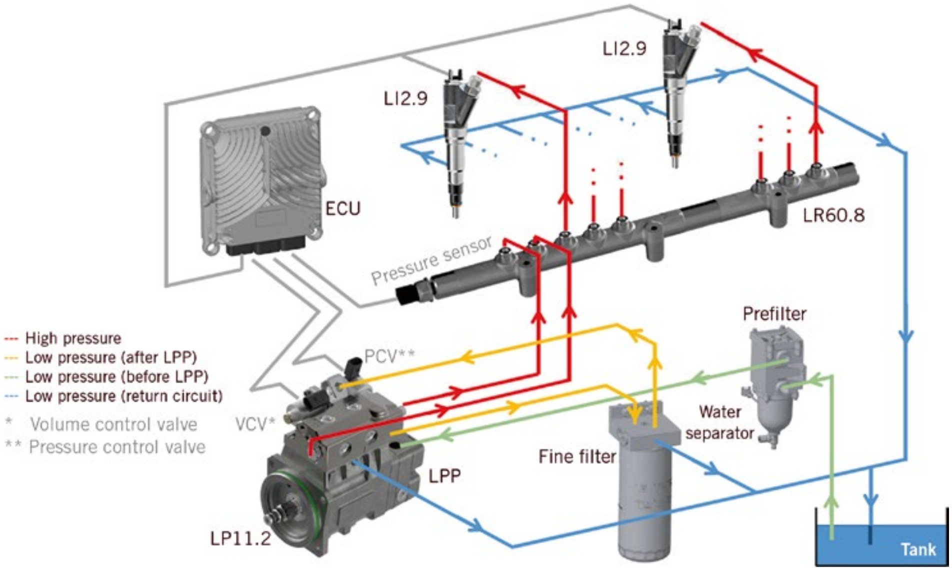

FIGURE 1 Typical functional diagram of a common rail system (© Liebherr)

lator design results in stable pressure conditions cycle-to-cycle and cylinder-to-cylinder, which proved to be beneficial for fueling accuracy, low consumption and emissions.

FIGURE 3 shows an example of the mentioned dampening effect, which originates from the targeted deployment of common rails as pressure reservoir. **FIGURE 3** (bottom left) shows the pressure pulsations measured at the pump outlet. These are extremely discontinuous and rough due to the pumping events. However, thanks to the damping effect of an advantageous rail design, these are transformed into a smoothened pressure gradient at every injector inlet, **FIGURE 3** (top right). The contrast between the two measured pressure signals is evident. Likewise, the beneficial effect in fueling consistency is huge. In summary, a well-dimensioned common rail has a twofold positive effect:

- High-frequency perturbations due to pumping effects and high-pressure valve activations are completely filtered out, which results in higher robustness of injected quantity against injection phasing.
- The amplitude of low-frequency perturbations is significantly damped, which results in lower sensitivity of injection quantity against injector position.

For the engine, a volume accumulator of 60 cc was selected. Because of engine packaging and admissible rail length, the volume requirement leads to an inner diameter of 12 mm. This in turn appears challenging in terms of mechanical stress observed under elevated injection pressure. Accordingly, the material selection is of vital importance to achieve an excellent fatigue strength of the component.

TARGETED APPLICATIONS AND MISSION PROFILES

Thanks to its extended power range and high torque, the engine is suitable for a huge variety of applications: off-highway machines, agricultural and mining machinery, commercial and railways vehicles, marine and power generators application as well as special vehicles. Each application has their own characteristics. This in turn determines the level and the typology of the load on the injection system and particularly on the common rail. An example is given in **FIGURE 4**, which shows the comparison between the injection pressure for an earth-moving machine and for a genset Continuous Power (COP) application. The different application characteristics are well recognizable: highly dynamic working pressure on the earth-moving machine and constant working pressure for the genset. Also evident is the contrast regarding average working pressure: lower in case of the earth-moving machine and extremely high for the genset. Hence, it is of crucial importance to know the future ranges of application in order to predict potential failure modes and application severity. To define a precise target for the life cycle assessment, a special methodology for mission profile analyses has been developed at Liebherr [1]. This methodology consists of three main steps, **FIGURE 5**:

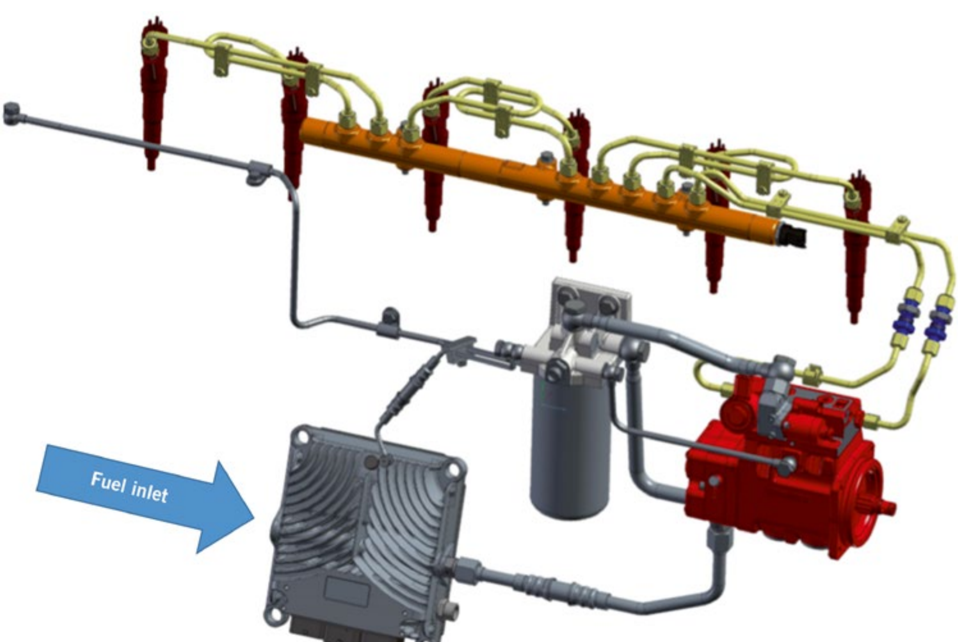

FIGURE 2 Fuel injection system layout for the D976 engine (© Liebherr)

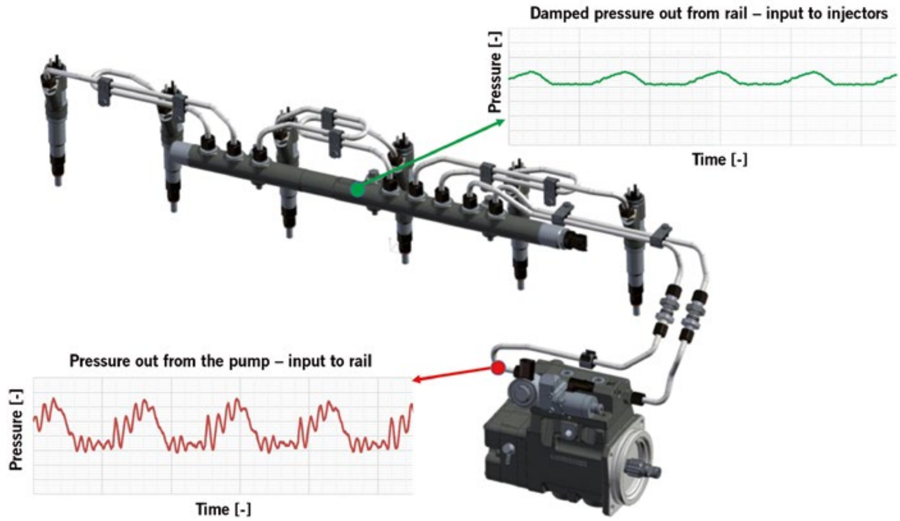

FIGURE 3 Visualization of rail dampening effect (© Liebherr)

– high frequency rail pressure data acquisition on working machines
– frequency analyses and rain flow counting of pressure data
– 3-D load spectrum generation.

The 3-D load spectrum is then consolidated into a typical Wöhler diagram to be compared against the components' Wöhler curves in order to assess the fatigue life robustness. **FIGURE 6** shows a comparison of an earth-moving machine (green) against a genset COP (purple). As expected, the earth-moving machine stresses the rail with pressure pulsations of elevated amplitudes (highly dynamic injection pressure), whereas the genset COP stresses the rail with smaller amplitudes. On the other hand, the cumulated number of pulsations throughout the lifetime is significantly higher for the genset.

DETERMINATION OF MANUFACTURING STEPS

At an early stage of the component development, all the knowledge and experience described in the previous sections are brought together in a specification sheet. This in turn serves as the basis for the virtual component design and for subsequent component tests. Both the development of the component geometry and the selection of material are carried out taking potential manufacturing steps into account. As common rails for diesel engines during operation are exposed to a highly dynamic internal pressure load, most often the hydraulic autofrettage is integrated, as well. In the following this particular process step shall briefly be discussed.

Hydraulic autofrettage as a method to enhance fatigue life has been described in several scientific papers – experimentally as well as computationally via Finite Element Analysis (FEA). In this process step, the component is exposed once to an internal pressure significantly higher than the operating pressure. After the pressure relief, a residual stress field remains, **FIGURE 7**. The introduction of residual compressive stresses into failure-critical locations in turn induces a mean-stress change in the direction of compressive stresses. These residual stresses are superimposed with the later operating stresses and counteract them [2, 3].

VIRTUAL DEVELOPMENT APPROACH

As a failure of common rails may result in engine fire, severe reliability requirements are mandatory and a durable design is therefore imperative. In order to guarantee this, Hirschvogel has established a development procedure as shown in **FIGURE 8**. First, a flow curve generation is carried out via standardized tension-compression tests in order to identify the elastic-plastic material behavior. This serves as a basis for determining the parameters of the Chaboche model implemented in FEA. Furthermore, load collectives are established via combining autofrettage pressure and subsequent cyclic load due to operating conditions. At a later stage, the local (for example node-specific) stress tensors calculated in the FEA are transferred to a fatigue life calculation (for example Finite Element Method Fatigue (FEMFAT)). Among other things, these calculations are based on the definition of a component-specific Haigh diagram. It is of crucial importance to focus on the compressive side

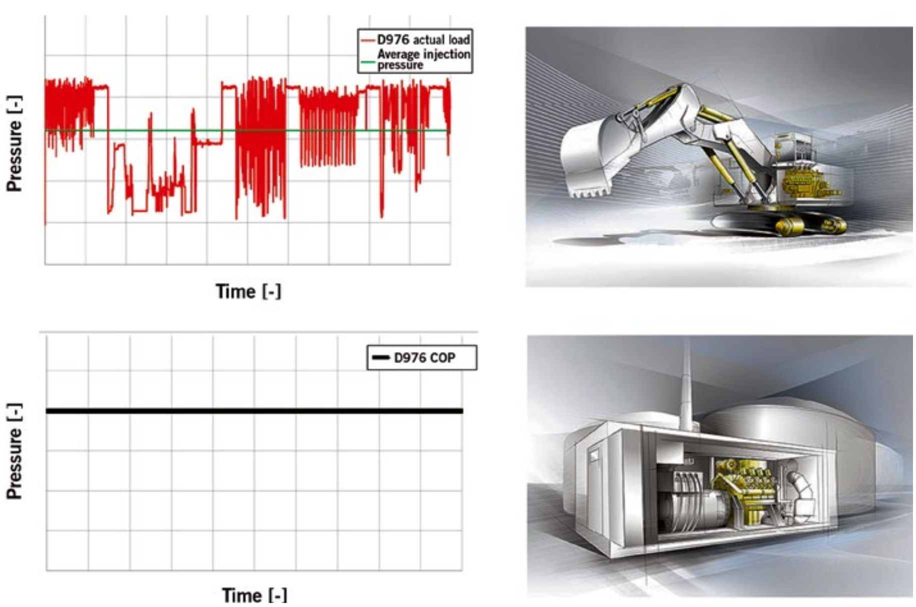

FIGURE 4 Internal pressure of an earth-moving machine and a genset COP (© Liebherr)

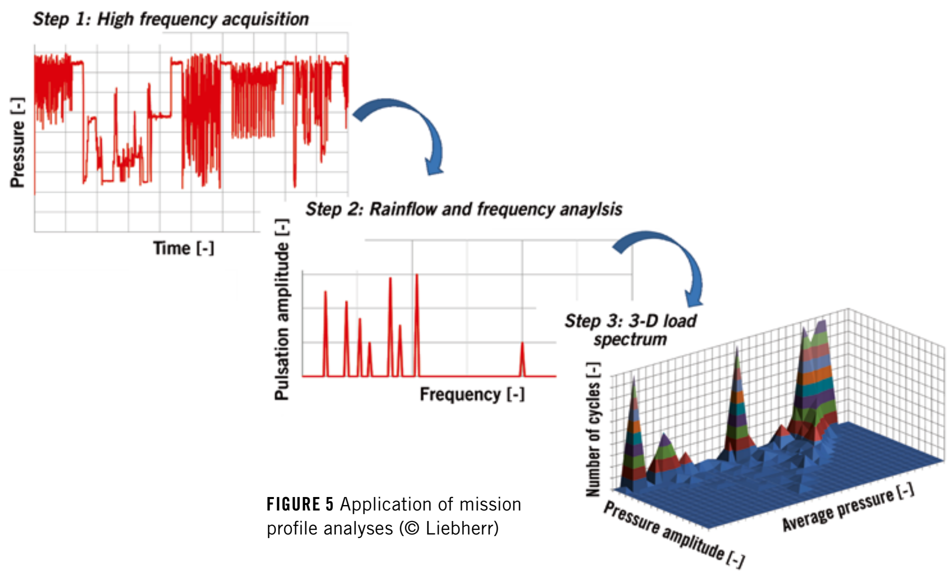

FIGURE 5 Application of mission profile analyses (© Liebherr)

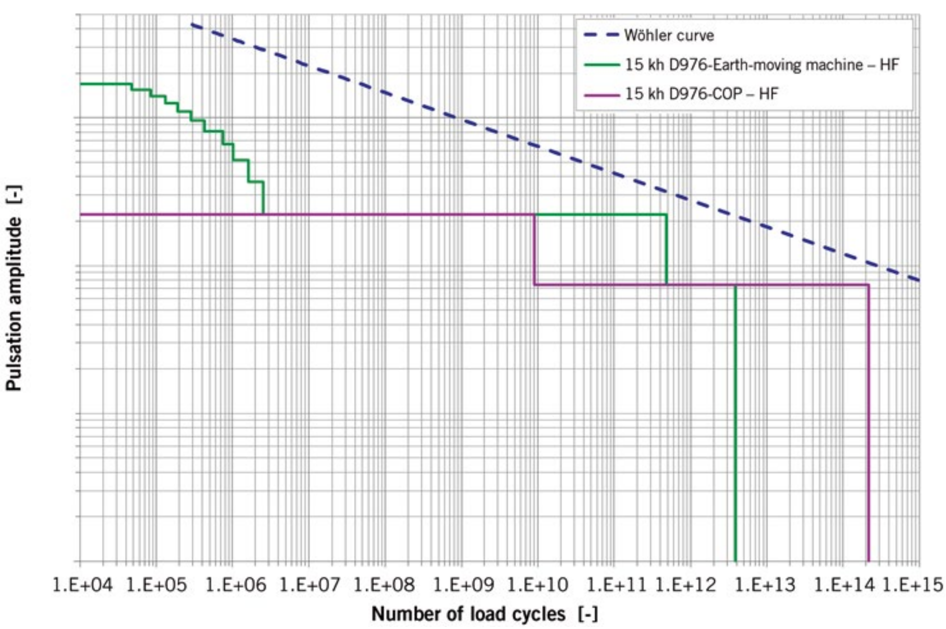

FIGURE 6 Comparison of Wöhler curves of an earth-moving machine and a genset COP (© Liebherr)

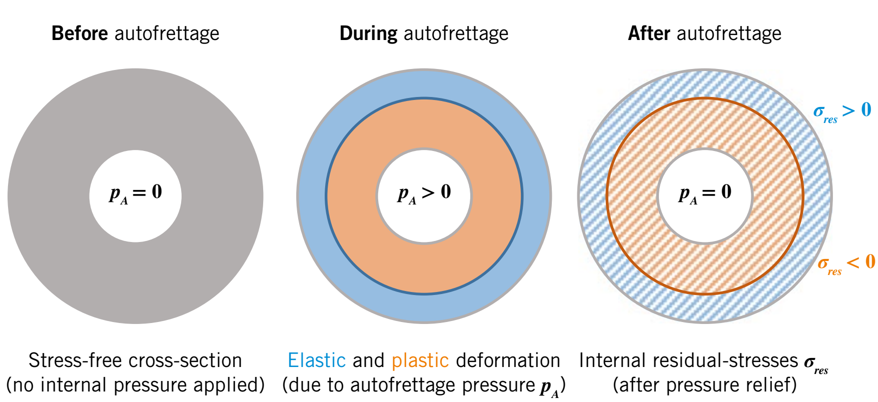

FIGURE 7 Principle of autofrettage on an example of a thick-walled hollow cylinder (© Hirschvogel Holding)

as, due to the high autofrettage pressure, the failure critical points are mainly loaded in the range of negative mean stresses. To obtain significant statements on the accuracy of the calculation results, Wöhler tests are later carried out on prototype components. With the aid of statistical evaluation methods, Wöhler curves are generated and used for durability assessments. Damage investigations on the basis of Scanning Electron Microscopy (SEM) allow to draw conclusions on the failure mechanisms and thus contribute to the verification of existing calculation methods.

FIGURE 9 shows a result of a fatigue life calculation in form of damage distribution using existing calculation methods at Hirschvogel. In this case, the component was autofretted at a pressure of 9400 bar. The subsequently applied cyclic load with a maximum pressure of 3500 bar represents the conditions during component testing. The distribution of damage shows that the critical areas are located at the bore intersection, exactly where the circumferential stresses of the longitudinal and transverse borehole overlap, leading to excessive stress concentration. The reciprocal value of the calculated damages then provides the survivable cycle numbers. Component Wöhler tests have confirmed this failure critical point in the bore intersection.

ONGOING IMPROVEMENTS

Today, software programs are increasingly being used to evaluate the finite/infinite fatigue life of components. These often incorporate the results of upstream FEA. As state of the art, stress tensors determined by means of FEA are transferred to fatigue life calculation. Thanks to the Haigh diagram the influence of the mean stresses on the fatigue strength can be taken into consideration. Following the notch stress concept – in case of a failure – the software stops computing as soon as a technical crack shows [4, 5]. With this approach, numerous development loops can be reduced, which leads to significant time and cost savings. However, this does not mean that development is finished. For example, further development of the design requirements

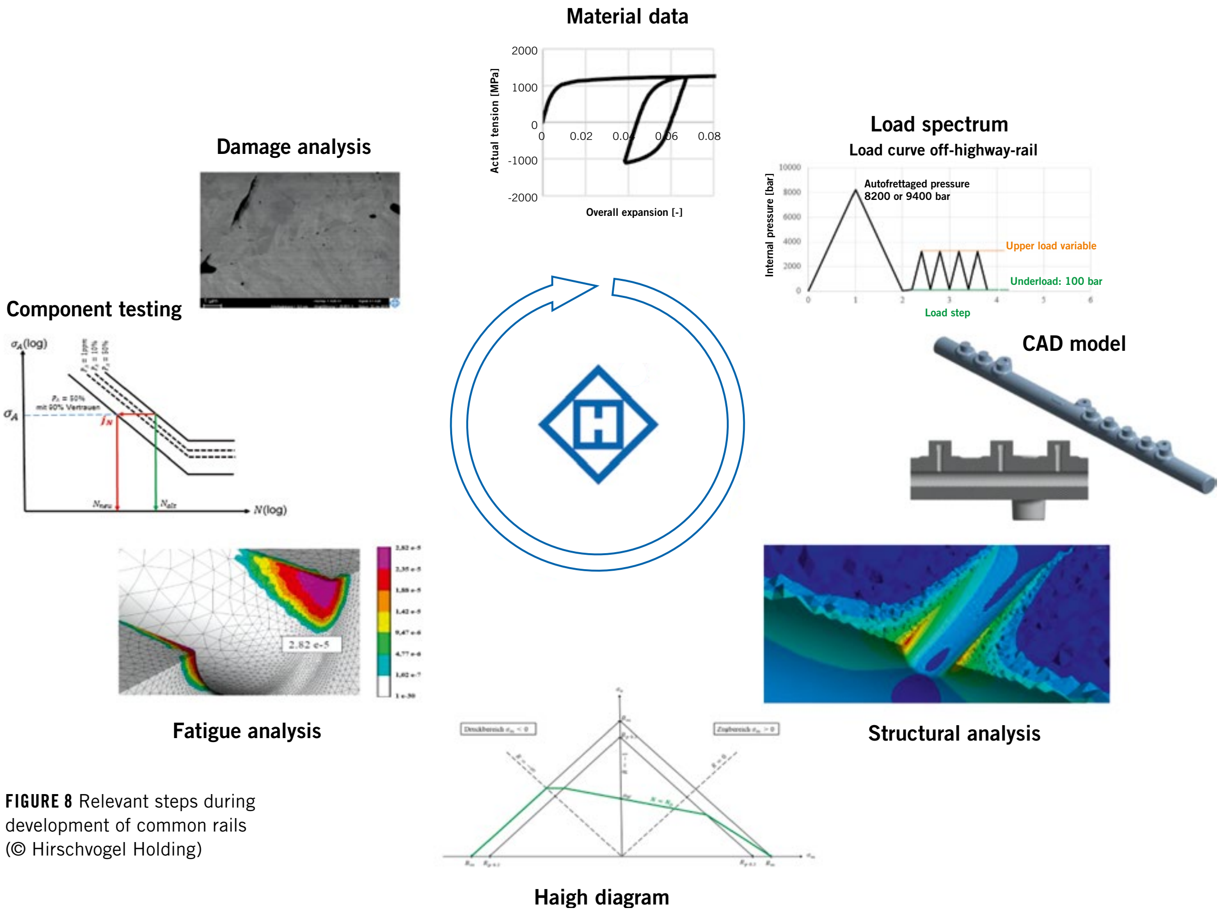

FIGURE 8 Relevant steps during development of common rails (© Hirschvogel Holding)

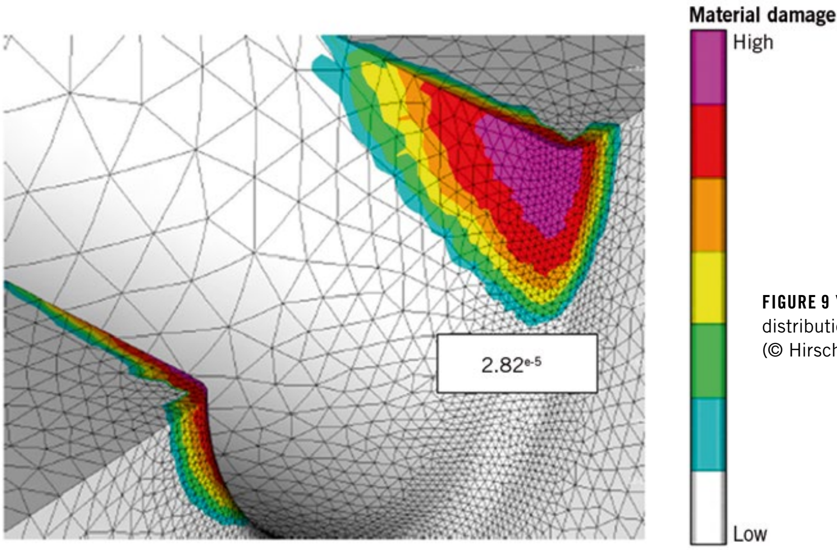

FIGURE 9 Visualization of material damage distribution via FEMFAT postprocessor (© Hirschvogel Holding)

for Haigh diagrams suggests further improvement in the accuracy of computation results.

Regarding the design of the Haigh diagram, FEMFAT has its own design rules [4]. In addition to the static parameters such as the yield strength and the tensile strength, it essentially relies only on the alternating and pulsating strength. Nowadays, the fatigue strength line in the Haigh diagram breaks off at a certain negative mean stress and changes to a horizontal gradient. This assumption leads directly to the fact that in this area, lowering the mean stress does not go along with an increase of the fatigue life. As can be seen from **FIGURE 10** (left), the stress state at the failure critical point (red dot) is clearly in the compressive state for the common rail, so that the design of the Haigh diagram should be as accurate as possible. However, the fatigue limit line for negative mean stresses has been little researched so far. Hence, a revision of the Haigh diagram was carried out together with the software manufacturer. It was agreed to experimentally determine the durability of the material for a stress ratio of R = -10 using a standardized test. Subsequently, the adaptation of the design specification for the Haigh diagram was carried out accordingly.

Within the framework of these investigations, a fatigue strength of 550 MPa results in an R value of -10. This value is above the present fatigue strength and confirms the assumption that the fatigue strength line of the Haigh diagram continues to increase in the compressive range. **FIGURE 10** (right) shows the new Haigh diagram, which was designed with the help of this additionally obtained support point (green cross). The connecting line between pulsating and alternating strength remains intact. However, it will no longer be extended into the compressive area as before. Instead, the alternating strength and the fatigue strength at R = -10 form a new straight line, which is drawn up to the point of intersection with the straight line from the static compressive strength (coming at an angle of 45°). The design of the Haigh diagram in the range of positive mean

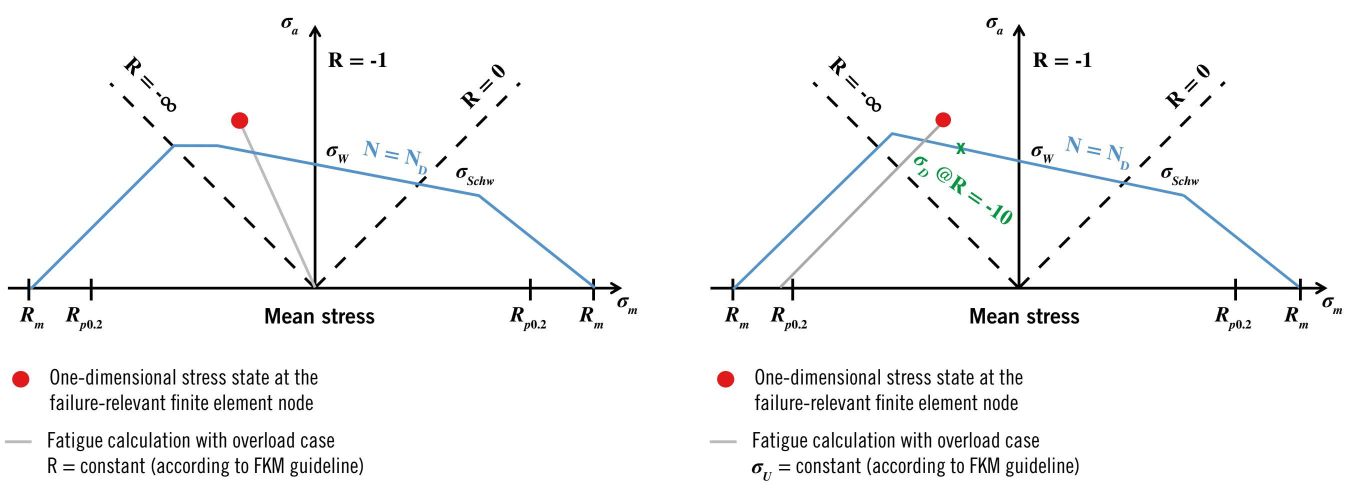

FIGURE 10 Haigh diagram without (left) and in (right) consideration of additional support point (© Hirschvogel Holding)

stresses remains unchanged. Further improvements were achieved by changing the overload case from R = constant to σ_U = constant.

SUMMARY

Among others, the high performance of the recently introduced D976 engine is based on a forged common rail with very high fatigue strength. This was developed by Liebherr CRS and Hirschvogel Automotive Group. To meet the target of this simultaneous engineering project, both parties shared their substantial expertise with each other. On Liebherr's side in particular the know-how regarding design, manufacturing and validation of injections systems is noteworthy. On the other hand, Hirschvogel's contribution lies in the field of designing and manufacturing high strength components as well as the selection of materials. Beyond that, the application of advanced simulation software including sophisticated material models and the generation of reliable material data sets played an important role.

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