Coupling of Simulation Tools for Obtaining Local Fatigue in Combination with Experimental Data

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Abstract. Cast iron components have a good ratio between strength properties and weight. This leads to a frequent use in the wind industry. The design of cast iron components is currently based on the use of individual simulation tools and material data that is uniform across the components. In order to better exploit the lightweight potential of cast iron components, it is necessary to link the simulation tools and thus take local material properties into account already in the design phase. This is described in the present work using the example of a large casting from the wind industry.

Introduction

Designer of castings components increasingly using simulation tools. There are typically three steps involved: (1) The design engineer creats a geometry based on the requirements and calculates the stresses resulting from the applied static operating loads and inertia forces by means of an FEM simulation using a structural analysis. In an optimization loop, component optimization can be performed in which the stresses are minimized under certain restrictions. (2) The casting process simulation is preformed, based on the 3D CAD model. There, the complete casting process from the pouring process to the solidification of the melt is analyzed in the form of a CFD simulation and the casting system (feeder, material allowance, etc.) is defined. (3) Based on the CAD data and, if necessary, the local material properties, the fatigue life is assessed and potential local weak spots in the component are identified. Until a final design is achieved, sub-steps have to be run through several times.

The use of simulation programs for the casting process, structural and fatigue analysis is currently still carried out independently. An exchange of all relevant data takes not place when several calculation tools does are used, also due to the lack of software interfaces. A holistic view of the simulation data is missing.

Cast iron components are frequently exposed to high mechanical loads. To ensure safe operation of plant and machinery, the fatigue life of the component must be guaranteed under the assumed operating conditions over the planned service life. New or expanded areas of application and increased safety requirements increase the demands on detailed service life determination. From this point of view, the following question arises: What contribution can make the casting process simulation and structural analysis to the fatigue life calculation?

In addition to simulation-based fatigue analysis, the component's fatigue life can also be determined experimentally, although the corresponding tests are time-consuming and expensive. They also require extensive laboratory equipment. In addition, component tests of this magnitude are hardly feasible experimentally. Therefore, this route is only taken in a few cases, and experimental validation of simulation results is also too costly in most cases. In the present work, an attempt is made for the first time to take into account the experimental data determined at great expense in the simulation-based fatigue analysis. These data were determined on samples taken from large cast components.

1 Simulative Determination of Local Fatigue Limits

The following chapter presents two different approaches from a methodological point of view. The first approach describes the calculation of fatigue limits based on a homogeneous material definition, i.e., the material definition is identical for the complete component. Locally varying material parameters are not considered. The second approach describes the integration of data from the casting process simulation into the fatigue analysis. Here, the definition of the local material properties is performed on a shared FE mesh. Both approaches have already been mentioned in [1, 2, 3]. In this paper, the data-technical realization is described in detail on the basis of an example.

1.1 Procedure with Global Material Data

FEMFAT is the world's leading solver for FE-based fatigue analysis and calculates structural durability of statically and dynamically loaded components on the basis of FE calculation results. FEMFAT as FE post-processor requires not only the data from the structural analysis (FE mesh and loads) but also the material data (strength values). Figure 1 shows the typical procedure for the calculation of local fatigue limits in FEMFAT.
The example of a large casting of a wind turbine below explains the procedure in more detail. The *poll end* or *canister* (cast iron box on the end of the windshaft through which the sail stocks pass) of a wind turbine has to withstand high cyclic loads. It is therefore extremely important to ensure fatigue limits in areas of high stress.

The determination of the fatigue limits starts with the import of the component geometry into the pre-processor of the structural analysis in order to generate an FE mesh from it. This step was performed in VisPER, a component of the structural analysis tool PERMAS 18.00.404.

The simulations to calculate the static stresses were performed in the FE solver PERMAS. For the poll end, the resulting stresses for the different rotor positions were investigated for a complete poll end revolution at a distance of 45°. For the resulting 8 positions, the mechanical stresses were determined with PERMAS (Figure 2).
The TransMAX module from FEMFAT was used to calculate the locally endurable stresses. This provides the user with a functionality to analyze structural durability based on load-time histories. Prior to this, a material had to be defined for the fatigue analysis model. Typically, the option of a homogeneous material definition from the FEMFAT internal database is used.

A material class is selected from the material

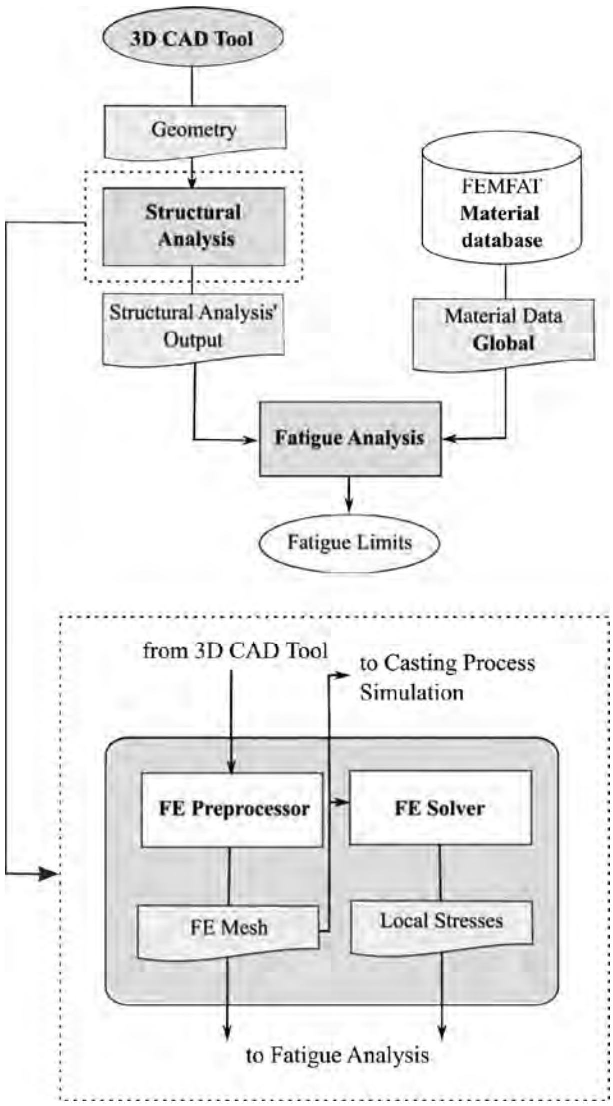

Figure 1: Calculation of fatigue limits with global material data

database. Based on preprogrammed ratios, the following missing material parameters are added to a predefined tensile strength for the calculation are automatically generated:

- Young's modulus
- Yield strength
- Elongation at break

At the FE node, local fatigue limits are calculated from material parameters, which are additionally influenced by local component properties (e.g. notch effect) and loads. The basic procedure for calculating

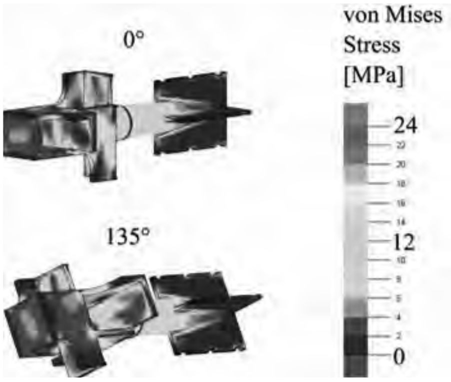

Figure 2: Simulated distribution of mechanical stresses at two different angular positions

fatigue limits is based on the influencing factors with which the fatigue strength is increased or decreased. The FKM (Forschungskuratorium Maschinenbau) standard descirbes these factors [4].

1.2 Integration of a Casting Process Simulation

The casting process simulation determines the local microstructure formed by casting. A microstructure is formed in the course of metal solidification and consists of the different microstructural phases with different shape, size and distribution (grains, dendrites, lamellae, pores) [5]. Figure 3 illustrates the distribution of a microstructural phase - pearlite - on the poll end.

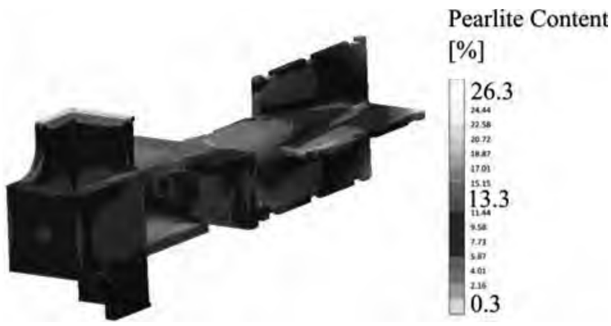

Figure 3: Simulated microstructure fraction in the component at room temperature

With regard to requirements on the accuracy of today's simulations in the casting industry, local material differences must be taken into account in the fatigue analysis. One way to deal with this is to use the local material data from the casting process simulation. From the microstructure, the casting process simulation can determine local material values (tensile strength, Young's modulus, yield strength, elongation at break) in the casting in the next step (Figure 4).

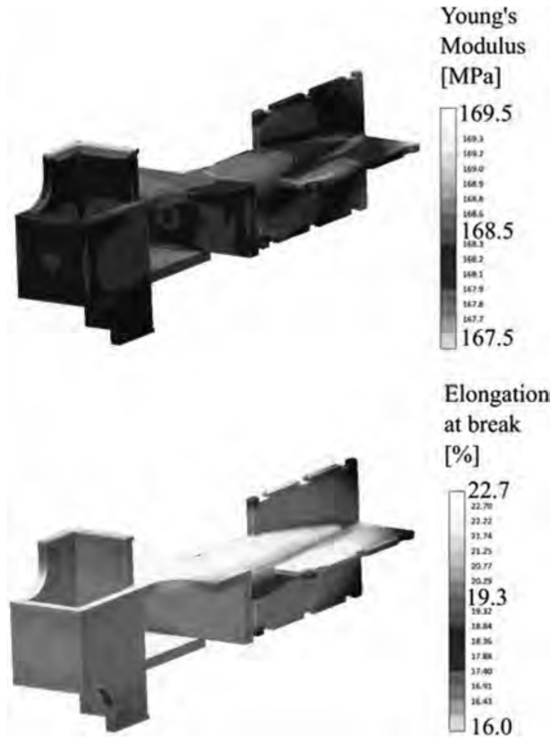

Figure 4: Simulated local material properties in the component at room temperature

Figure 5 shows the schematic description of the approach for calculating the local fatigue limits with integration of the local material data from the casting process simulation

For the calculation of the local material data of the poll end, the casting process simulation was carried out in the commercial software package MAGMAsoft 5.4.

The discretization for the numerical solving algorithm in the casting process simulation on the one hand and in the fatigue/structural analysis on the other hand is different: in MAGMAsoft the discretization is based on the finite volume method (FVM) and in the fatigue/structural analysis on the finite element method (FEM). There is a need for mapping the results from the casting process simulation to the FE mesh generated in the structural analysis. The mapping is realized by MAGMAlink, a module of the casting process simulation. This makes the results of the casting process simulation usable for further processing in the fatigue

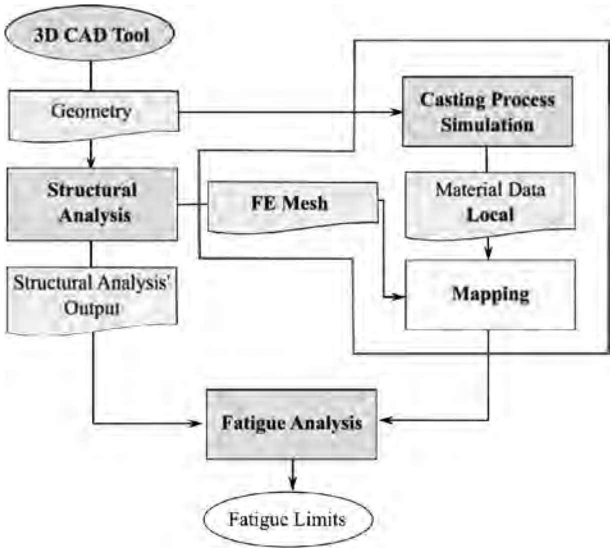

Figure 5: Calculation of fatigue limits with local material data from casting process simulation

analysis.

According to the state of the art, FEMFAT can read in the local material data from casting process simulation and use the output from structural analysis (FE mesh and local loads) to calculate the fatigue limits for each FE node. Comparing the two approaches (Figure 6), it can be seen that when the casting process simulation is included, the fatigue limits are on average between 10 % and 20 % higher. The difference at the edge of the poll end is significantly larger, up to 50 %.

2 Consideration of Experimental Data

The described simulative approaches start from the component geometry and the determination of the fatigue limits is computer-aided. However, the fatigue life analysis tool FEMFAT also offers the possibility to directly import already existing local fatigue data in order to perform a more specific calculation.

In various publications, it has already been shown that the microstructure has an influence on the fatigue life [6, 7, 8, 9]. In particular, the ratio of pearlite to ferrite and nodularity have been shown to be important microstructural parameters. In this context, a high pearlite content and a high nodularity have a positive effect on the endurable stresses and thus on the component fatigue. However, nodularity is not calculated by

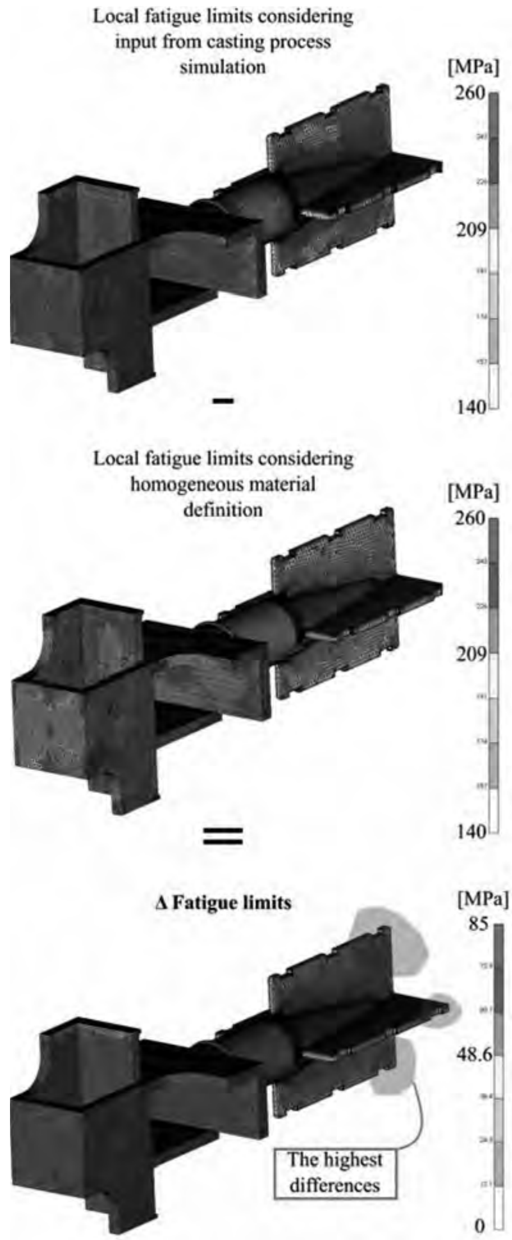

Figure 6: Fatigue limits with homogeneous material data and taking into account data from casting process simulation

the casting process simulation and is consequently not considered further.

From the casting process simulation, at this point not the local mechanical properties are required, as in the purely numerical approach, but the local microstructure. If experimental data on the microstructure and the associated fatigue limit are now available in a material database, the microstructure resulting from the casting process simulation can be used to generate local fatigue limits (Figure 7).

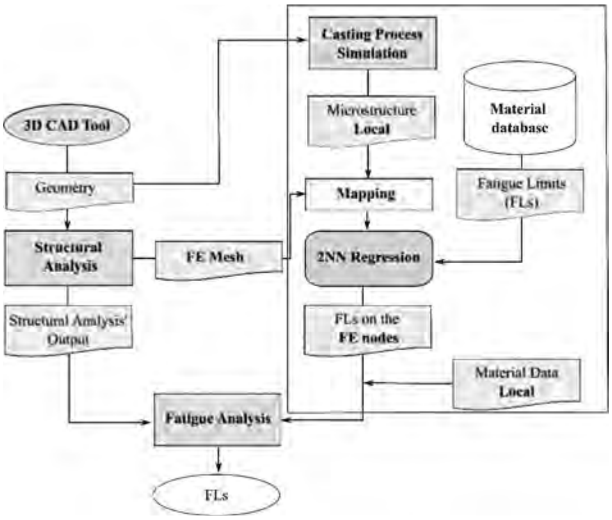

Figure 7: Calculation of local fatigue limits using experimental data

Since the experimental determination of microstructure/fatigue limits data involves a great deal of effort, only a few data sets are available. In order to determine the associated fatigue limits for all microstructure data from the casting process simulation, these must be determined approximately on the basis of the available experimental data.

Using the k-nearest neighbor algorithm (kNN) as a regression method [10], an individual fatigue limit can be generated for each FE node (Figure 8). Here, the value at a FE node is weighted by the distances d of the 2-nearest neighbors proportional to their distance. In the present work the regression method is implemented in form of the in-house developed MATLAB code.
The fatigue limit $FL(x)$ for a node x from the experimentally determined fatigue limits of the two nearest neighbors x_1 und x_2 (both come nodewise from casting process simulation) is determined according to equation 1:

$$FL(x) = \frac{d(x,x_1)}{d(x,x_1)+d(x,x_2)} FL(x_1) + \frac{d(x,x_2)}{d(x,x_1)+d(x,x_2)} FL(x_2) \tag{1}$$

In the equation 1 the $d(x,x_1)$ and $d(x,x_2)$ represent the distances from the FE node to the next two neighbours (experimental data) in two-dimensional space that con-

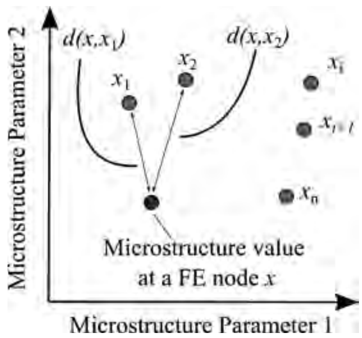

Figure 8: 2NN regression of fatigue limits from microstructure values

sists of two positive real numberss, the values for microstructure parameter 1 (x-axis) and microstructure parameter 2 (y-axis).

Finally, the obtained fatigue limits are modified via the FEMFAT internal algorithm using the stresses from the structural analysis. This allows a comparison of the fatigue limits from the three approaches described.
Compared with the calculation using the local material properties from the casting simulation, the fatigue limits with the regression from the microstructure data increase again by between 10 % and 20 %. Figure 9 shows the areas with the highest differences between the approach based on experimental data and the approach based on the local material properties. The differences are located at the blade bearings and contact vials to the shaft.

Conclusion and Outlook

In this article, three possibilities for the simulative determination of fatigue limit were shown on the basis of a large casting component from wind turbine technology. The integration of experimental data represents a new possibility to combine information from simulation and experiment. It is shown that the determined fatigue limits are lower with the purely numerical approaches than with the consideration of experimental data, which supports the application of the purely numerically determined fatigue limits in industrial practice.

The purposeful coupling of not connected software tools in the foundry industry explains the complexity of the study for numerical determination of local fatigue limits. In order to combine the different software modules, a number of interfaces are required. Table 1 shows the formats of the respective interfaces used in the three

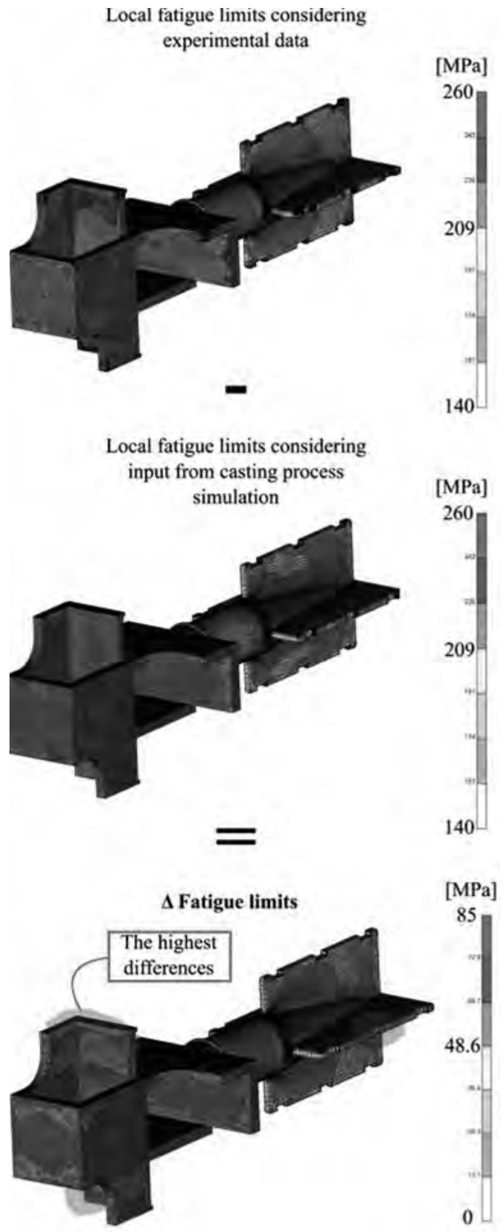

Figure 9: Fatigue limits considering data from casting process simulation and considering experimental data

#	Interfaces between software tools	Transmitted data	Format (file extension)
1.	3-D CAD tool → Structural analysis	Geometry	(STL)
2.	Structural analysis → fatigue analysis	Stresses	PERMAS (POST)
3.	Structural analysis → fatigue analysis	FE mesh	PERMAS (DAT)
4.	Casting process simulation → fatigue analysis	Local material data	(UNV)
5.	Casting process simulation → regression	Local microstructure	PERMAS (DAT)
6.	Material DB → regression	Microstructure-dependent fatigue limits	(XLSX)
7.	Regression → fatigue analysis	Local fatigue limits and material data	(UNV)

Table 1: Overview of the used file formats

approaches for the calculation of fatigue limits.

The integration of experimental data into the numerical process chain could be realized by a 2NN regression. Since the acquisition of experimental data on fatigue limits is very time-consuming, the algorithm is currently based on very little data. The incorporation of more experimental data will improve the prediction accuracy. These should also cover significantly more microstructure classes with the associated fatigue limits. An evaluation of the method presented here is only possible if the fatigue limit of a component is determined both experimentally and numerically.

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