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SHAPE OPTIMISATION BASED ON LIFETIME PREDICTION MEASURES

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1 Introduction and Objective

Modelling and simulation software have become popular tools in almost all industries to predict the behaviour of components and structures. In sophisticated companies even the step beyond simulation - the structural optimisation - has become part of the daily work. Key drivers of these changes in the product development process are the need to reduce time-to-market and the money spent for the development process.

Usually the dimensioning of components using FEA is done by the evaluation of stresses and strains. The resulting component loading is then compared with reference values (e.g. material data, engineering experience) to come to estimates of the components lifetime:

$$\sigma_{FEA} \leq \frac{R}{S} \tag{1}$$

where σ_{FEA} is the component stress calculated with FEA, R is the data from the material testing (material's resist) and S is the safety factor.

As mentioned shape optimisation is more and more used to increase the components lifetime. Therefore the shape of the component is varied to minimize or maximize an objective function with respect to boundary conditions.

In CAOSS [1] the variation of the shape is managed by displacing the nodes of the FEA mesh. This results in a decrease of the local surface curvature. Today mostly stress measures (e.g. equivalent stresses) are used to determine the amount of shape changes:

$$\Delta U_n = \alpha \left| \sigma_{eq} - \sigma_{eq,r} \right|^{\kappa} sign\left(\sigma_{eq} - \sigma_{eq,r} \right) \tag{2}$$

Reducing the stresses and strains on the surface in some cases leads to an enhancement of the lifetime. The main drawback of this way dealing with the components life is that neither the load time history nor the fatigue behaviour of the material can be considered during the optimisation process.

This can be avoided using lifetime estimation methods. In general these methods are based on numerical computations and are used as post processing tools that evaluate local strains within the component. The time until a crack is initiated on a surface is predicted by the sum of partial damages over the load time history:

$$\sum D_i = \sum \frac{n_i}{N_i} \geq 1 \tag{3}$$

By using this data the comparison or assessment of different design stages regarding lifetime is possible. These methods consider the load time history of different load cases as well as the fatigue behaviour of the material.

The CAE/Optimisation Group of the Institute of Machine Design at the University of Karlsruhe/Germany is working in the area of structural shape and topology optimisation for almost ten years. Besides own research the Institute contributes to the development of the structural optimisation software CAOSS from the company FE-DESIGN which is distributed worldwide by MSC.Software as MSC.Construct [2]. For that reason the group has extensive experience with industrial demands in the field of structural optimisation.

In this context the above described single methods (structural analysis, lifetime estimation and optimisation) are combined to a structural optimisation process based on lifetime calculations. By doing so, an isolated view on only the component stresses and strains neglecting lifetime effects, which are nowadays of major interest, can be avoided.

The homogenisation of the spatial lifetime distribution of the component is now directly the objective of the optimisation. Instead of optimising stresses and strains in order to get lifetime improvements, the lifetime is considered explicitly (resulting vice versa in better stress distributions):

$$\max N(x) \rightarrow \min \sigma(x) \tag{4}$$

With this extended approach it is possible to regard the load time history as well as the fatigue behaviour of the material during shape optimisation. Due to this fact it is now also possible to consider constraints during the optimisation that result from the manufacturing process like the surface roughness.

2 Methods

The above explained procedure is realised coupling the optimisation software CAOSS with the lifetime prediction software MSC.Fatigue (which is FE-Fatigue from nCode). For the structural analysis MSC.Nastran is used (Figure 1).

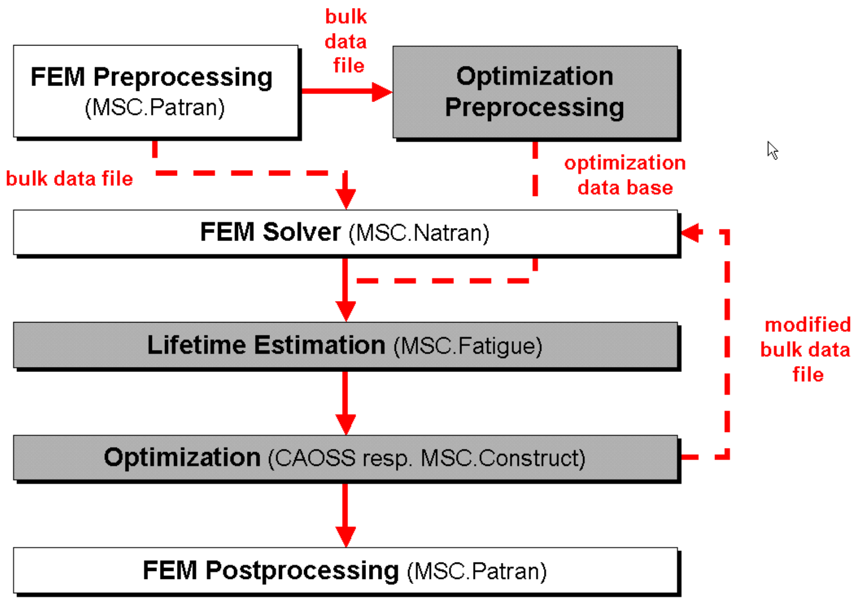

Figure 1. Data Flow

Within the optimisation loop the lifetime estimation software requires the nodal strains of the FE-calculation to predict the lifetime. The calculated lifetime quantities are used as input values for CAOSS. The optimiser modifies the nodal coordinates and creates a new FE input file with the updated shape of the component.

The values of the lifetime quantities are distributed over a different range compared to a conventional optimisation based on stresses and strains. Using them directly would lead to a different behaviour of the optimiser and, as a consequence, the conventional optimisation and the optimisation based on lifetime quantities would not be comparable because of a different characteristic of the result input [3].

For this reason the input quantities of the optimiser are recalculated with the Manson Coffin relationship:

$$\varepsilon_t = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f (2N_f)^c \tag{5}$$

Assuming only elastic stresses and strains the plastic strain component can be neglected. With this an equivalent lifetime stress σ_{eq} can be defined:

$$\sigma_{eq} = \sigma'_f (2N_f)^b \tag{6}$$

3 Example

A comparison of a conventional optimisation based on equivalent stresses and an optimisation based on equivalent lifetime stresses is presented on the basis of a cylinder loaded with a single moment.

3.1 Modelling

The cylinder shown in Figure 2 (length = 20mm, diameter = 4mm) is modelled with 16,000 3d solid elements. It is fixed on side B at the middle node in all degrees of freedom. The remainder of the nodes on that surface are fixed in circumferential direction and in z (all nodes are given in a cylindrical coordinate system).

The cylinder is loaded with a moment of M_x = 2 Nm at the reference node on side A. This node is coupled with a rigid body (RBE2-) element in all degrees of freedom with the corresponding surface nodes.

The model was generated with MSC.Patran V9. The linear static analysis (Sol101) was run with NASTRAN V70.7 on an HP J5600.

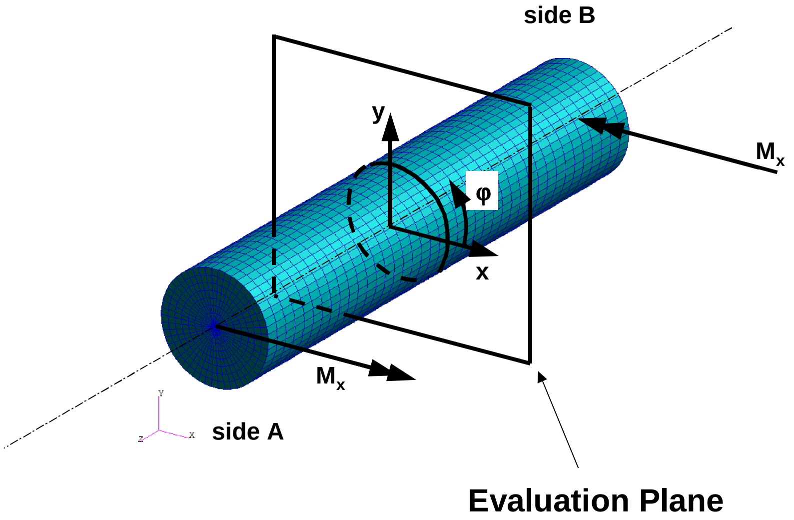

Figure 2. FE-model of the cylinder

The material used in this example is a St52 (BS4360-50D) with the material parameters shown in Table 1. The moment M_x is assumed to be loaded with a frequency of 10Hz (completely reversed). The given load is scaled by the load time history.

Table 1. Material Parameters [4]

Yield Strength $R_{p0,2}$ (MPa)	355
Ultimate Tensile Strenght R_m (MPa)	510
Fatigue Limit σ (MPa)	255
Young's Modulus E (MPa)	210,000
Poisson's Ratio ν	0.3
Fatigue Strength Coefficient σ'	1,036
Fatigue Strength Exponent b	-0123

3.2 Lifetime Estimation

The crack initiation method is chosen as analysis type [5]. Within the lifetime calculation local strains (maximum absolute principle strains) which are calculated from nodal results are used. Neither surface finishing nor surface treatments are considered in the calculation.

3.3 Optimisation

The nodes on the circumference of the cylinder represent the optimisation area. A mesh smoothing of all elements is allowed after each iteration step. Along the cylinder-axis all nodes are fixed. As a further boundary condition a constant volume during optimisation is chosen. The optimiser CAOSS determines the objective value itself. This means that the aim of the optimisation is the homogenisation of the optimisation criteria. After 10 iterations the optimisation converged.

3.4 Results

In the following the optimisation results of the above described model are presented.

Lifetime optimisation

The recalculated lifetimes are the input data for the optimisation. Thus the optimisation objective is the homogenisation of the lifetime. Figure 3 (left) shows the damage D, which is reciprocal to the lifetime N:

$$D = \frac{1}{N}, \tag{7}$$

and the equivalent lifetime stress at the circumference in the evaluation plane (see also Figure 2) of the cylinder before optimising it (Iteration Step 0) .

The strain life method does not differ between compression and tensile stresses. This is the reason why we get the highest damage and thus the highest equivalent lifetime stress in the area of the highest load at the upper and lower side of the cylinder (Φ=90° and Φ=270°). This load is induced due to the moment.

Because of that maximum in 90° and 270° it can be expected, that during the optimisation the component will grow in these areas. To keep the volume constant, the component has to shrink in the lower loaded areas. On the right side of Figure 3 one may see the development of the cylinder shape during the optimisation process in the expected manner.

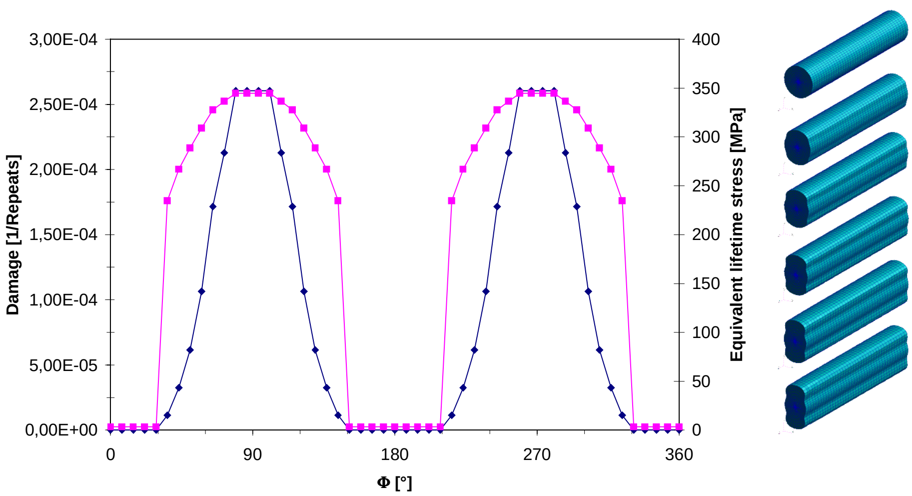

Figure 3. Damage and equivalent lifetime stress at the circumference at the evaluation plane (left). Shape of the bar after different optimisation iterations (right).

In Figure 4 (left) the development of the cylinder's cross section in the evaluation plane during the optimisation is displayed. During the optimisation the cylinder tends to become an I-beam. Figure 4 (right) shows the damages for the iterations at that circumference. During the optimisation the damage is reduced by 91% and thus the expected lifetime increases by 91%.

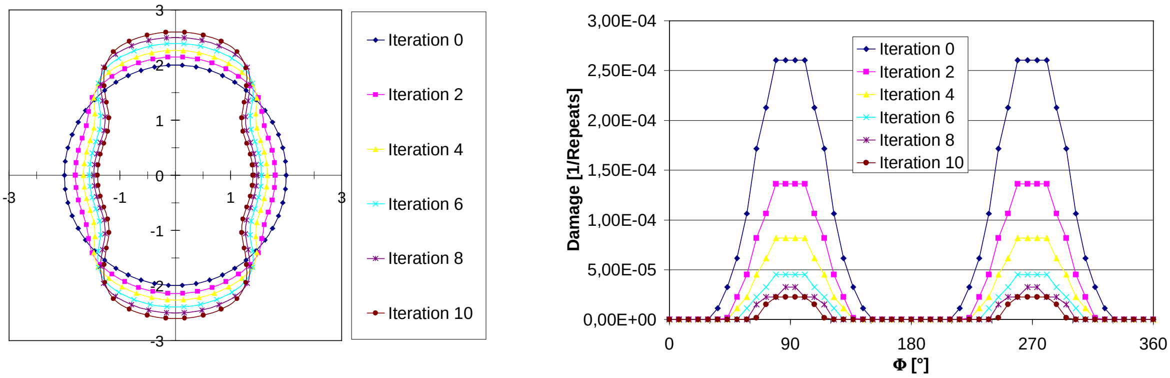

Figure 4. Development of the shape at the evaluation plane (left) and the effect on the damage along the circumference after different iteration (right). Optimisation based on equivalent lifetime stresses.

Conventional Optimisation

The objective of the conventional optimisation is to homogenise the von Mises stresses:

$$\sigma_V = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \tag{8}$$

In Figure 5 the stress distribution is shown at the circumference in iteration 0. As for the distribution of the lifetime and equivalent lifetime stresses in Figure 3 the diagram shows maxima in the area of the highest load of the cylinder (Φ=90° and Φ=270°).

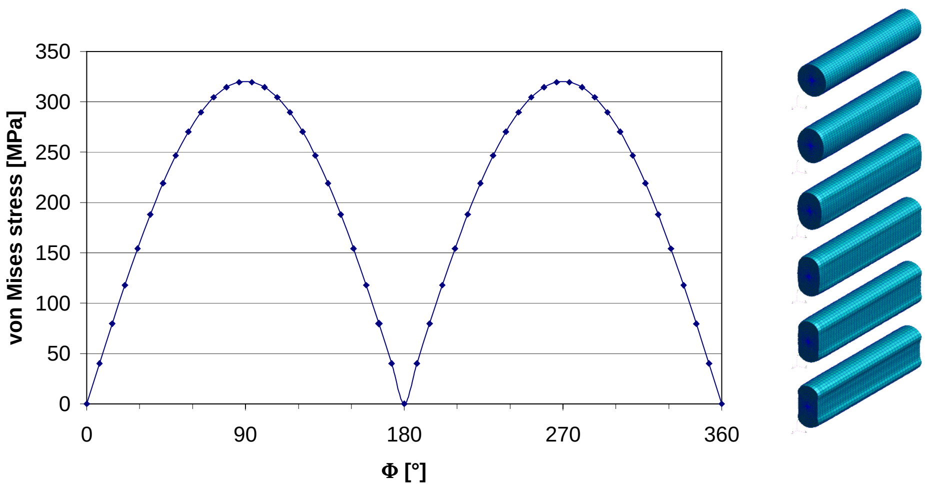

Figure 5. Von Mises stress along the circumference at the evaluation plane (left). Shape of the bar after different optimisation iterations (right).

Due to a similar distribution of the von Mises stresses (Figure 5) and the equivalent stresses (Figure 3) at the circumference of the evaluation plane the shape of the conventional optimisation develops rather similar to the optimisation based on lifetime measures (Figure 6 left). Thus the development of the damage during the optimisation shown in Figure 6 (right) is quite similar to the optimisation based on the equivalent lifetime stresses. The damage is reduced by 91% over 10 iterations either. Thus the lifetime improvement is 91%

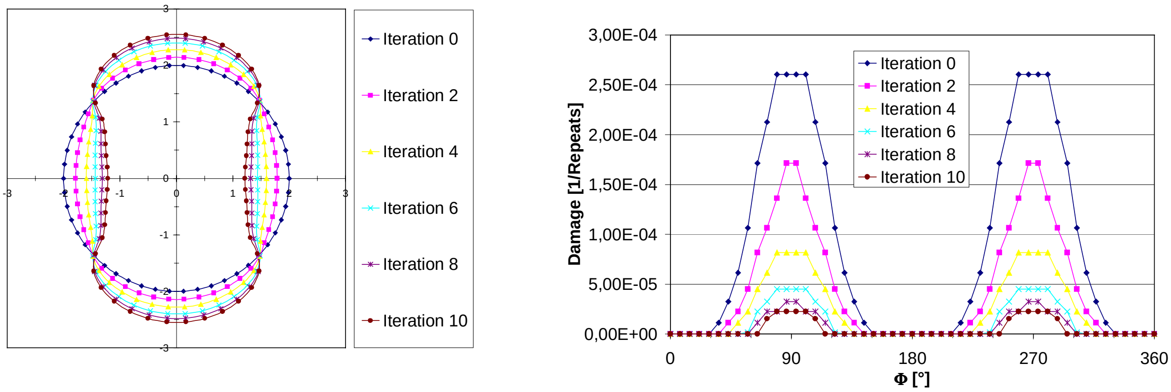

Figure 6. Development of the shape at the evaluation plane (left) and the effect on the damage along the circumference after different iterations (right). Optimisation based on von Mises stresses.

4 Conclusion

The paper presents the comparison of automated shape optimisation based on lifetime quantities with conventional optimisation based on the von Mises Stress hypothesis. The application of both methods show a lifetime improvement of 91%. Comparing the development of the damage for each iteration step during the optimisation (Figure 7), both methods show a similar overall behaviour.

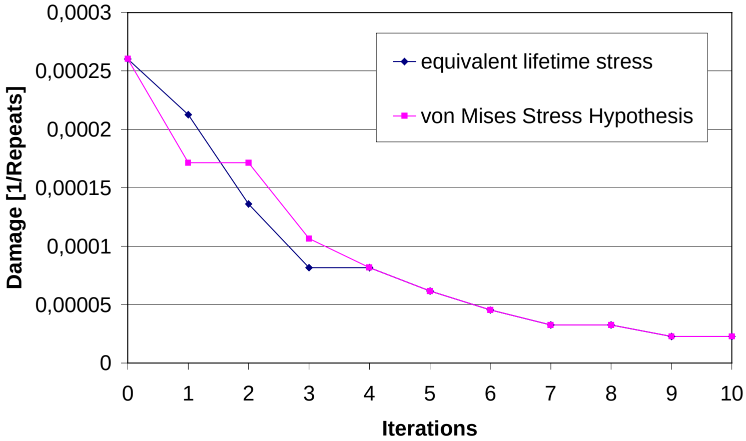

Figure 7. Development of the maximum damage during the optimisation

In this example the feasibility of the optimisation based on lifetime quantities is shown. But there is no improvement of lifetime for this elementary example.

Generally the advantages of this optimisation method are:

- Considering the load time history during the optimisation

- Load cases with a high damage quota are considered in an adequate manner during the optimisation
- Optimisation based on lifetime estimation allow the consideration of surface conditions (surface treatment, surface roughness etc.) during the optimisation

At that time no experimental results exists. The true impact to real structures will be subject of further studies. In addition this work supplements the approach described in [6], where multi body simulation is used to generate load data from virtual models.

5 Acknowledgement

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