Geometrical optimization for notches based on multi axial fatigue criterion

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ABSTRACT. Shape optimization of components subjected to multiaxial fatigue is studied. The application of static optimization algorithms, generally based on Von-Mises stress, is no more applicable in these cases. In this paper an optimizing routine for multiaxial fatigue is developed on the basis of the CAO technique proposed by Mattheck. According to a criterion for fatigue strength estimation of notched specimens made of ductile materials and subjected to mutiaxial fatigue: Liu-Zenner. Abaqus 6.8-1is used as the commercial software to develop finite element simulation and Python 2.4 and Matlab2007 are used as the subroutine programs.

INTRODUCTION

Fatigue failure is the most experienced failure in many fields such as automobile and aerospace industry. It is possible to avoid fatigue failures by simple over dimensioning the dangerous notches which afflict the components, but the global weight and the performances of the components will as a result become worse. Another, more attractive way to improve the fatigue behavior of machine elements is the definition of procedures able to lead toward the optimum design of notched parts. In the present study, computer aided optimization (CAO) [1] is used as an optimization method to increase the fatigue life in notched components. Previously, Peng et al. [2] have tried to optimize the notches based on other methods for uniaxial loading. Wilczynski [3] has tried to optimize the shape under multiaxial fatigue loading for crack propagation.

The present approach is composed of five steps. Roughly speaking, it is based on simulating the stress field in the notch zone namely "Growth Zone" with temperature and simultaneously decreases the elastic module in that zone. Abaqus 6.8-1[4] is used as commercial software for finite element simulations. In the original CAO method which is developed by Mattheck [1], the Von-Mises stress is the criterion for calculating the stress concentration factors and also the stress which should be transformed to temperature. In the present study Liu-Zenner is the chosen criterion [2] due to the fact that based on the literature [6, 7] the fatigue prediction of this method in different types of loading is reasonable. In this paper, Papadopoulos definition [8] of the amplitude and mean values of the shear stress acting on the plane is used. The space, obviously, should be divided into several planes; the division should be implementable on numerical software. The Webber [9] method which deals with the way to obtain a homogeneous distribution of planes having almost the same area and also the determination of the smallest circle surrounding the loading path is implemented. At the end, an example based on the developed method is represented.

OPTIMIZATION PROCEDURE

The paper is based on a method introduced by Mattheck [1] which is derived from the natural phenomenon of adaptive growth in trees. The CAO method [1] is briefly described in the following steps. The flowchart is also illustrated in Fig. 1.

1. A finite element model of the structure representing the desired appearance of the component is produced by Abaqus 6.8 [3].
2. Based on the FEM results the Liu-Zenner [5] stress for each node will be calculated by using the routine developed in Python 2.4 [10].
3. The computed stresses are then substituted by a virtual temperature distribution. Moreover, the modulus of the elasticity in the upper layer is set to only 1/400 of the initial value. This will result in a fictitious soft layer with particularly high temperature at original overloaded zones and rather cold layers in the unloaded region.
4. In the next FEM computation which considers just the thermal loads, the previous mechanical load (tension) is set to zero. Only the soft upper layer will have a thermal expansion factor $\alpha>0$. All the procedure is controlled by Matlab 2007 [11].
5. The structure improved by growth in computation step 4 is already shape-optimized to some extents, and occasionally one such growth cycle is sufficient. This is checked by again setting the elastic modulus of the soft layer to the value of the basic material and starting at step 2 with a new FEM computation under purely mechanical loading, which will deliver a more homogeneous stress distribution with greatly reduced notch stresses. The computation loops 2-5 are run through repeatedly, till the stress concentration factor stops changing due to fact that construction conditions forbid further growth.

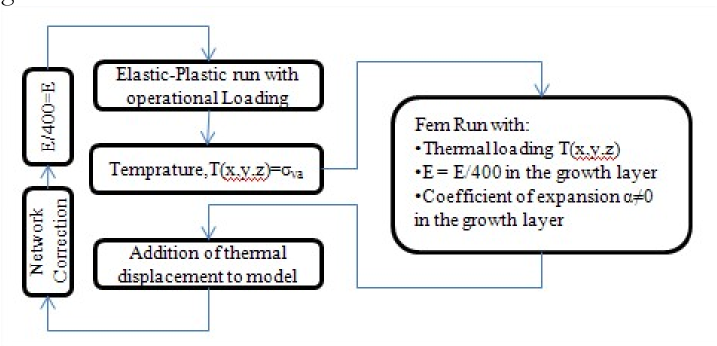


Figure 1: Flowchart of the proposed CAO method

MULTI AXIAL FATIGUE CRITERIA

Finding fatigue limit under multiaxial loading has been one of the most controversial issues in the last century; due to the fact that, without omitting and simplifying the problem condition, most of the structures in real life, which are under the cyclic load, suffer from the multiaxial fatigue damages. There are many different criteria from dissimilar categories which have been proposed to find the fatigue limits. The Liu-Zenner is the chosen criterion which is going to be described briefly in the following section.

Liu-Zenner criterion

The Liu-Zenner [5] multiaxial criteria of integral approach and of the critical plane approach can be derived as special cases from the general fatigue criteria. Based on the literature [6, 7], the estimated life time according to this criterion shows appropriate results in different loading conditions. The Liu-Zenner multiaxial criteria of integral approach and of the critical plane approach can be derived as special cases from the general fatigue criterion. The formulation of Liu-Zenner shows that it works only for the materials with the following condition:

$$\frac{2}{\sqrt{3}} \leq \left(\frac{\sigma_W}{\tau_W}\right) \leq \sqrt{3} \tag{1}$$

For calculating the failure condition the values of fatigue limit for pure bending σ_W, fatigue limit for pure torsion loading τ_W, fatigue limit $s_{W(R=0)}$, $t_{W(R=0)}$ are necessary. The fatigue limit under pulsating tensile stresses $\sigma_{W(R=0)}$ is evaluated by assuming a mean stress sensitivity factor equal to 0.2 and for fatigue limit under pulsating torsion stress the same assumption in [7] is made.
Finally the failure condition is formulated directly by combination of all the equivalent stresses:

$$\sigma_{va}^2 + m\sigma_{vm,\tau}^2 + n\sigma_{vm,\sigma} = \sigma_W^2 \tag{2}$$

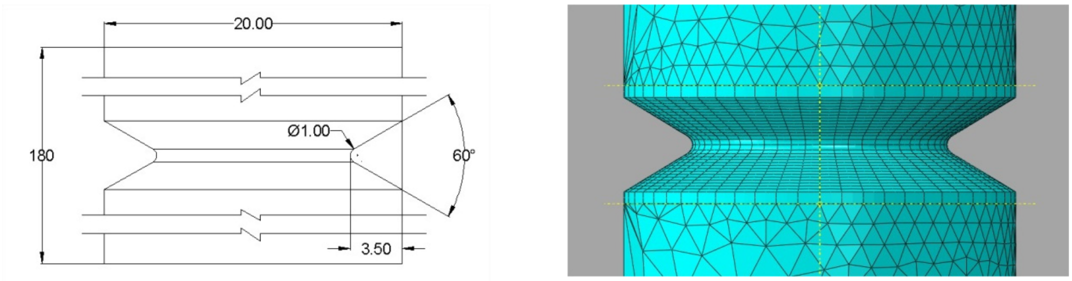
$$m = \frac{\sigma_W^2 - \left(\frac{\sigma_W}{\tau_W}\right)^2 \left(\frac{\tau_{W(R=0)}}{2}\right)^2}{\frac{4}{7}\left(\frac{\tau_{W(R=0)}}{2}\right)^2} \quad n = \frac{\sigma_W^2 - \left(\frac{\sigma_{W(R=0)}}{2}\right)^2 - \frac{4m}{21}\left(\frac{\sigma_{W(R=0)}}{2}\right)^2}{\frac{5}{7}\left(\frac{\sigma_{W(R=0)}}{2}\right)^2}$$

$$M = \frac{\sigma_W - \sigma_{W(R=0)}}{\sigma_{W(R=0)}} = 0.2\tau_{W(R=0)} = \frac{4\tau_W}{1+\frac{2\sigma_W}{\sigma_{W(R=0)}}} \tag{3}$$

AN EXAMPLE OF IMPLEMENTATION

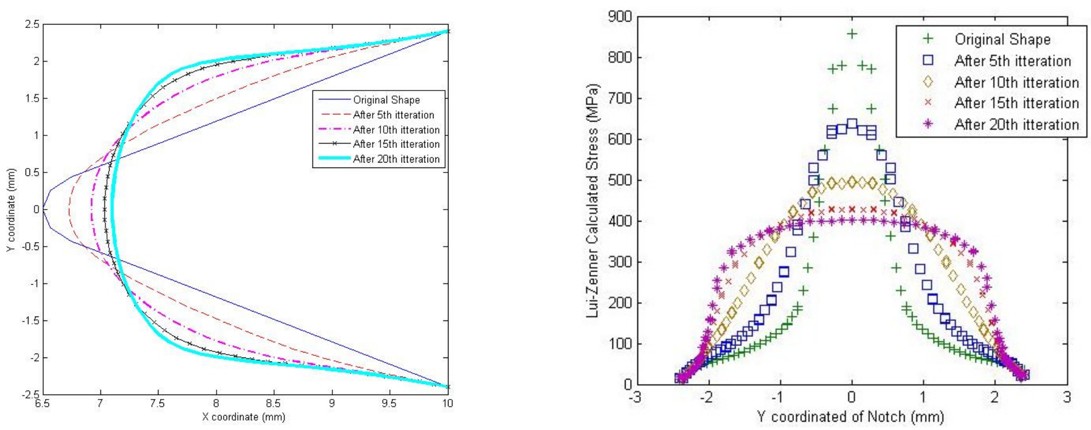
The following notch has been chosen as an example to implement the method. In Fig. 2a the original geometry of the notch is presented. The applied forces are presented in Esq. 10. The loading is 90 degree out of phase.

In Fig. 2b the FEM model developed in Abaqus is presented. Quadratic 20 nodes elements are used for notch and tetrahedral 10 node elements are used for the rest. Material properties are limited to elastic modulus and Poisson ratio for Steel.



a) b)

Figure 2: a) The original geometry of the selected notch, b) The FEM model with the generated mesh.



a) b)

Figure 3: The results of optimized profile a) Optimization evolution of notch geometry
b) Liu-Zenner stress changing by increasing the iteration numbers.

In Fig. 3a the optimization evolution in the notch profile after 5, 10, 15, and 20 iterations is presented. In Fig. 3b alterations of the calculated stress based on Liu-Zenner method through the notch profile for each node is demonstrated. Based on the results for this example, it can be concluded that by implementing this approach the equivalent stress after 20 iterations is reduced from 900MPa to 400MPa, whereas the profile based on the Fig. 3a does not represent a dramatic change.

The iteration loop stops as soon as the difference of the obtained results of two successive iterations is less than the defined tolerance. In the presented example, based on the results, the differences between iteration number 19 and 20 is less than the defined tolerance; thus the optimization can be stopped.

CONCLUSION

A novel optimizing method has been presented for modifying the notched geometry under multiaxial fatigue loading. Based on the obtained results it can be inferred that this method can be effective also for different geometries with unlike kinds of loading. The method has been applied to many different geometries and loading conditions just one of which has been presented in this article. According to the obtained results the method was found to be applicable to a wide range of loading and geometry combinations. Furthermore it was very quick with respect to number of iterations.

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