Application of a Subsurface Stress/Strain Fatigue Life Approach to Contact Components under Cyclic Bending Loads

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ABSTRACT. *A subsurface stress/strain fatigue life approach was previously developed in order to overcome discrepancy in the life prediction of components due to geometrical differences. In the following, the subsurface approach is used to estimate the life of common wind turbine gear box low speed shaft collar fit subject to cyclic bending. The subsurface stress gradient is obtained from a detailed 3D finite element analysis. For this casting application the life is in the high cycle fatigue region and hence maximum principal stress life prediction criteria is used. The stress damage is summed up along a critical subsurface path and the estimated fatigue life using the subsurface stress approach is compared with predictions using hot spot surface approach and a recently developed fatigue limit critical distance to crack propagation method. It is shown that the subsurface approach fatigue lives are in good agreement with empirical based methods and can be used when the fatigue limit has been exceeded.*

INTRODUCTION

The subsurface stress/strain fatigue life approach was developed in the early 90's to overcome discrepancy in the life prediction of components due to geometrical differences [1]. The approach is based on the estimation of the critical subsurface strains or stresses path under the surface and consists of a fatigue damage summation procedure in the affected area utilising finite element simulation and critical plane fatigue failure theories. Further development of the method appears to improve estimates of fatigue lives by evaluating strains from the fatigue-critical subsurface planes.

Often for service components in contact, the critical areas include a combination of cyclic loads and mean loads. Usually the perpendicular contact pressure contribution is constant and results in higher cyclic axial stress. Common examples are in aerospace structures near interference fit fasteners and in gearboxes' collar fits of low speed shaft. It was shown in the past that interference fit in general is beneficial to fatigue strength. However, in cases where a geometrical edge contact exist the surface stress is relatively high and could also include fretting fatigue. In this case there is usually a stress/strain gradient through the material thickness and the fatigue life is shorter in comparison to non-contact data [2].

In this work the subsurface approach is used to estimate the life of common commercial 2MW wind turbine gear box low speed shaft collar fit subject to cyclic bending. The subsurface stress gradient is obtained from a detailed 3D finite element analysis. For this casting application the life is in the high cycle fatigue region and hence maximum principal stress life prediction criteria is used. The stress damage is summed up along a critical subsurface path and the estimated fatigue life using the subsurface stress approach is compared with predictions using hot spot surface approach; with empirical stress gradient approach, and with limited experimental data.

Summary of the subsurface strain path approach

The subsurface model was used in the past in assessment of several components and experimental data mainly in low cycle fatigue region where elastic-plastic cyclic strain analysis was used [1]. In the following investigation the life of the component under the contact is in the elastic, high cycle fatigue region. Hence the subsurface model has been modified by using stresses instead of strains with similar subsurface path considerations.

A critical high stress path up to a critical depth is numerically calculated. A subsurface multiaxial strain parameter along a critical path is divided into equal increments. Using the material stress-life (SN) relation the life corresponding to the average stress from each increment is obtained. Contribution to the fatigue damage process from each increment of stress under the surface is weighed and assumed to decrease with the distance from the surface.

A linear accumulation of the subsurface damage is carried out along a critical path. The average stress from each increment is calculated as:

$$\sigma_n = \frac{\sigma_i - \sigma_{i-1}}{2} \tag{1}$$

where σ_n is the average incremental stress, n is the increment number with i = n-1. The incremental damage parameter is calculated using the simulated stress gradient divided by the total stress gradient;

$$D_n = \frac{\sigma_i - \sigma_{i-1}}{\Delta\sigma_{total}} \tag{2}$$

where $\Delta\sigma_{total}$ is the total stress gradient at a typical critical distance.

The relative distance from the surface of each stress increment is introduced through a weight function that modifies the damage values with regard to surface distance, for example;

$$D_n^* = D_n(1-(\sum_1^{n-1} D_n^*)) \tag{3}$$

where D_n^* is the modified damage parameter. After calculating the modified incremental damage, the total life to failure is summed as:

$$N_{fD^*} = \sum_1^{n-1}(N_{fn} D_n^*) \tag{4}$$

where N_{fD^*} are the modified cycles to failure for a particular surface stress range and N_{fn} is the number of cycles to failure at a certain depth along the critical path, corresponding to the average incremental stress σ_n at that depth.

Stress analysis of contact in solids

A detailed analysis of the basic stress theory of contact mechanics elasticity is given by Johnson [3]. Most of the fatigue/fracture analytical theories were developed to establish solutions of a generalised or specific stress intensity factor. Fig. 1 is a general description of edge contact in solids. More recently elastic-plastic analysis was used and several theories were developed to establish the non-linear relation between the material subjected to the contact loads and cyclic loads and include analysis of fretting fatigue.

A detailed description of the contact including fretting fatigue process is given in ESDU 90031 [4]. The material damage is shown to be influenced by several factors such as type of loading surface roughness and mean stress. The stresses in the contact surface layer, Fig. 1 are the resultants of the applied alternating loads, applied normal to the contact surface, and the contact pressure. The combined action of those forces is to initiate a crack that is not normal to the surface, but most commonly start at the contact edge. Below the surface the radial stress is usually compressive. This compressive stress slows down (retards) further growth of the initial crack. Further fracture depends on the magnitude of alternating loads and mean load. If the applied alternating stresses are sufficiently high the crack could propagate to fracture. The applied tensile mean stress may also overcome contact compressive stress and will promote contact related crack growth.

Fatigue limit analysis of solids in contact

In a recent publication [5] a simplified design procedure for fatigue limit integrity assessment of solids subjected to contact, under complex fatigue load was proposed. The procedure was to estimate the fatigue limit to fracture using short cracks subsurface distance [6]. Using a fairly detailed elastic FEA model of the contact region and several critical load cases the local stresses along a path normal to the contact edge are obtained.

Stress intensity factors (SIFs) are calculated along a crack path in 2 directions, K_I and K_{II}, taking into account the existing subsurface stress gradients up to an arbitrary distance under the surface that extend well beyond the material initial stage cracking [5]. At first estimation 10mm subsurface distance seems reasonable.

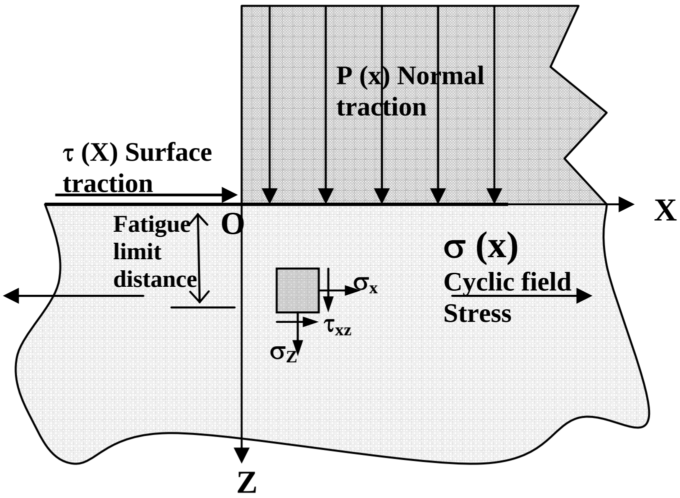

Figure 1. Stresses at the edge of solids in contact

It was shown in [5] that if the calculated critical crack due to the stress is longer than that of material fatigue limit it means that the stress is not high enough to propagate a crack at the critical distance and vice versa.

Finite element simulation of wind turbine low speed shaft in cyclic bending

A typical wind turbine tubular shaft section with an interference pressure collar was loaded in bending. An FEA axisymmetric model geometry and mesh are shown in Fig. 2. A bending moment of 3700 kNm was applied perpendicular to the X axes. In the region of the contact edge a refined FEA mesh was used having a mesh size of about 0.25mm. Data accumulation geometry boundaries for the analysis were +5mm and -10mm along the Z (longitudinal) axes from the contact edge and 15mm along the y (radial or normal) axes for the same Z coordinates from the shaft surface inward.

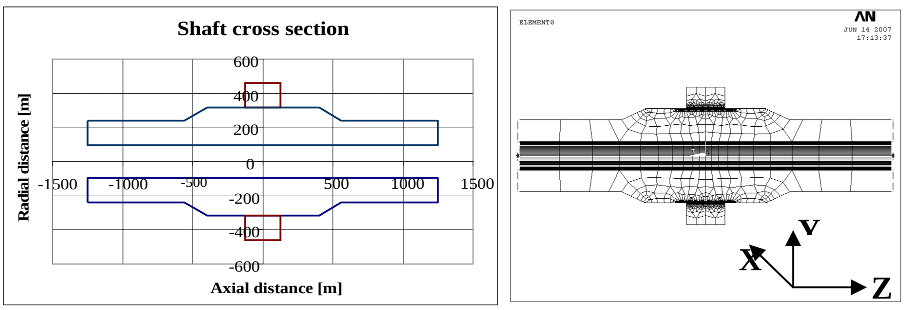

Figure 2. Geometry and FEA model of the low speed shaft

MATERIALS AND SIMULATION RESULTS

The material properties of commercial wind turbine low speed shaft materials were initially not available. Instead, three typical commercial nodular cast iron (SG) materials were considered, grades 370/17, 420/12 and 500/7 for the fatigue limit assessment. For the life prediction a more recent grade GGG material has been used. The relevant material properties are shown below.

Table 1. Mechanical properties of four typical wind turbines nodular cast irons

Grade	Minimum Tensile strength (MPa)	Alternating fatigue strength (MPa)	Fracture Toughness ΔK_{1c} (MPa√m)	Threshold ΔK_{th} (MPa√m)	Calculated fatigue limit (mm)
370/17	370	63	91	5.5	2.426
420/12	420	67	91	5.5	2.145
500/7	500	75	85	5.1	1.4718
GGG	700	205*	N/A	N/A	N/A

*estimated

Finite Element Analysis Results

Initial FEA simulations of the shaft have shown axial stress at the edge of the collar of about 1200 MPa which appears unrealistically high. Further FEA simulation applied half of that initial interference pressure for which the maximum axial stress was approximately 500 MPa and subsequent verification analysis applied a very low IF pressure to assess the effect of the IF stress on the shaft behaviour. A refined FEA model was subsequently used near the contact edge area and the data was analysed in terms of the shaft stress field.

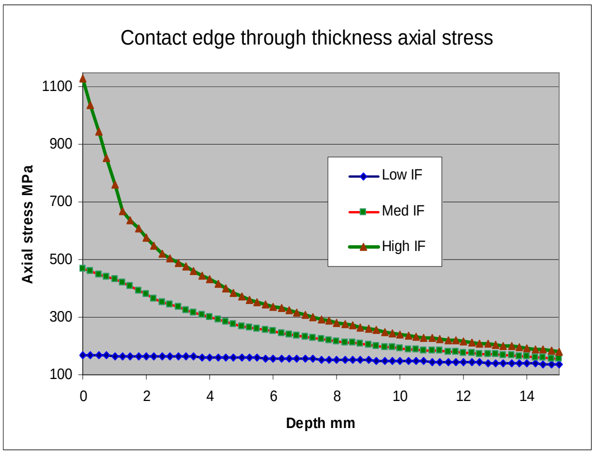

Figure 3. Maximum axial stress vs. thickness distance at the contact edge.

High stresses and gradient with high IF and much lower stress and gradient for the lowest IF are shown in Fig. 3. The highest surface stresses are at the contact for the highest IF. Under the contact, stress increases linearly with IF level. At the subsurface the maximum stress is under the contact, but at a much lower level and at the free subsurface the stress is changing very little, as to be expected.

STRUCTURAL ASSESSMENT

Fatigue limit analysis

Using the short cracks subsurface limit approach summarized above, fatigue limit length through the thickness of 2mm for the three types of SG cast irons was approximated from Table 1. The FEA result of the maximum stress value at the contact edge location with 2mm depth was used to calculate a critical stress intensity factor for each IF level simulation [5]. By using the critical SIFs, fatigue limit crack lengths as a percentage of the applied load were calculated; assuming a linear relationship between the applied load, the maximum stress and the maximum SIF.

Fig. 4 shows application of the critical crack length method to the FEA simulations. It should be noted that this analysis is limited to a linear elastic fracture. The analysis shows that the analysis is highly dependent on the IF level in the collar and critical conditions. The fatigue crack propagation limits are reached at about 35%, 17% and 7% of the applied load for the low, medium and high IF pressure respectively. This could mean that fatigue limit was exceeded and preceded by fatigue crack growth. Further FCG analysis has shown that if a 2mm crack exists in the structure it is likely to propagate through the shaft thickness subject to the load in 20 years of the component expected life.

Fatigue life analysis

Fatigue life prediction of the collared shaft under cyclic bending having three levels of interference fit was carried out by using three different methods. These were the subsurface critical path approach described above, an empirical design procedure according to the Forschungskuratorium Machinenbau (FKM) analytical strength assessment [7], and life prediction using the critical maximum surface stresses (hot spot). All those methods used the same results from the FEA model. The theoretical analysis was compared with experimental data obtained from ESDU 68005 – Shafts with interference fit collars part IV: fatigue strength of plain shafts [2].

HCF SN equation employing an industry standard slope of 5 for the life of up to the fatigue limit was used similar to non-contact data. However, since it is shown in [2] and elsewhere that near the contact the fatigue cracks initiate and propagate early in life under a very low stress level, fatigue limit was not considered to exist for the life prediction and the GGG material SN curve was used as follow:

$$\sigma_a = 3249 N_f^{-\frac{1}{5}} \tag{5}$$

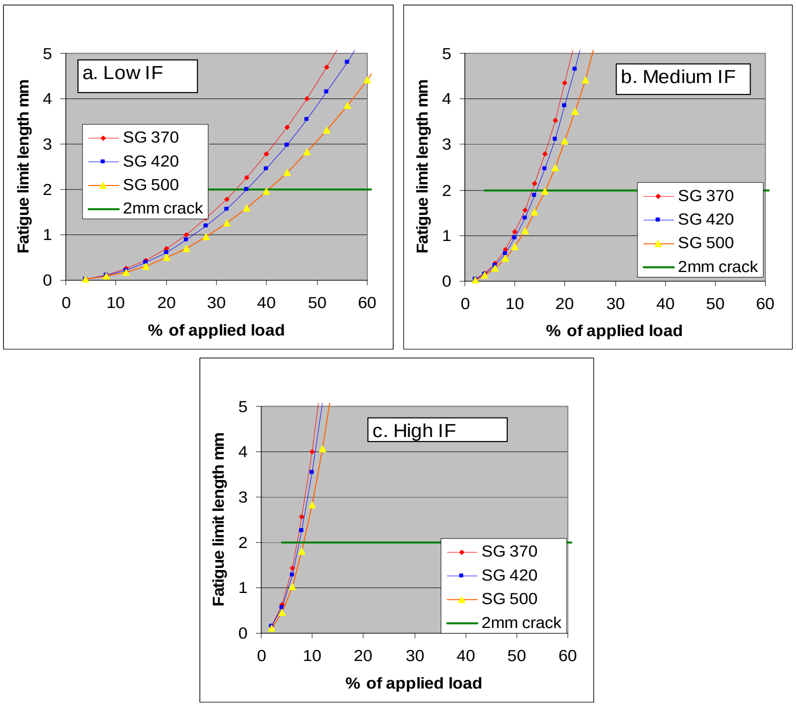

Figure 4. Fatigue critical crack length vs. % of applied load for 3 collar pressures.

The shaft applied cyclic bending level was approximately the level of the extreme events occurs 1000 times in 20 years of operation. At this load an elastic nominal maximum bending stress amplitude in the shaft surface is about 125 MPa. Using this value the life to total failure based on the experimental data in [2] is approximately 2×10^7 cycles, Fig. 5. A subsurface life assessment was carried out using the stress path equations, 1-4 above and the FEA results for 3 interference levels. The subsurface critical distance for the contact analysis was assumed to be 2mm which is approximately the critical limit for short cracks cyclic crack growth in the cast iron. Fatigue damage and lives were evaluated and summed from stresses at the thru thickness increments of 0.25mm along a subsurface path that is in a radial direction to the surface contact starting from the hot spot location. In this analysis a mean stress correction was applied by substituting the nominal axial cyclic stress from the total axial FEA stress at any point. The equivalent stress was then calculated by using Goodman mean correction. This equivalent stress was used to obtain the incremental subsurface life using equation 5. The results are shown in Fig. 5.

For comparison with the subsurface model, the FKM stress gradient correction [7] was applied to the nominal stress amplitude obtained from Goodman analysis of the FEA results. In this approach the total subsurface normal stress gradient is computed at a reference point and a set of empirical equations are used to obtain a general factor that is applied to the material SN fatigue life at a particular hot spot point. The results of the computed lives for the same hot spot locations as the subsurface and surface predictions are shown in Fig. 5.

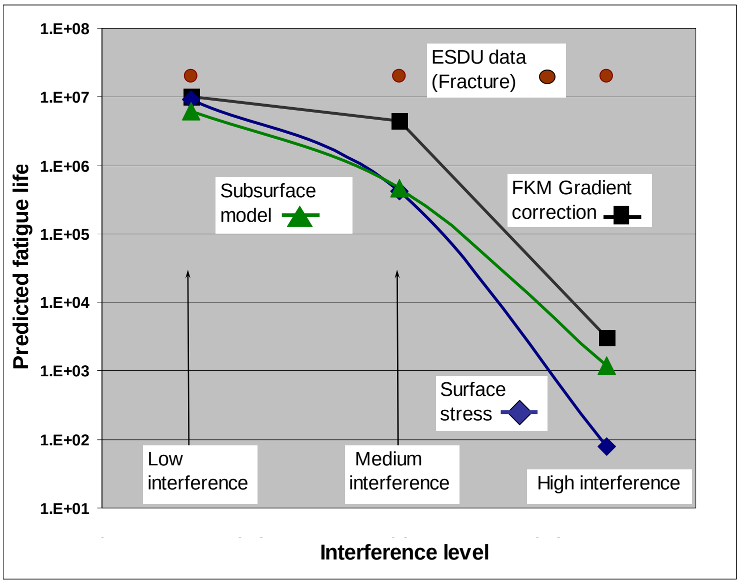

Figure 5. Life prediction of a typical wind turbine low speed shaft under cyclic bending.

CONCLUDING COMMENTS

1. A subsurface path approach, previously used for low cycle fatigue strain analysis, appears to be adequate to account for subsurface stress gradient at the high cycle fatigue region.
2. Fatigue damage in components in contact appears early in life and hence assessment of fatigue life prediction is required in addition to the fatigue limit analysis even for relatively low cyclic nominal stresses.
3. If high geometrical stress gradient exist the FKM predictions appear similar to the subsurface path approach predictions while at lower stress gradient the FKM results are less conservative. Hotspot analysis is the most conservative due to the contact surface stress concentration.

REFERENCES

1. Shatil, G., Smith D.J., (1996) ASME J. Engng. Mater. Technol., 118, pp. 529-534.
2. ESDU 68005, Shafts with interference fit collars : fatigue strength of shafts, (1968).
3. Johnson K.L., Contact mechanics (1985), Cambridge University Press.
4. ESDU 90031, Fretting Fatigue, (1990).
5. Shatil, G., (2009), Proceedings 2nd Int. Conf. on material and component under variable amplitude loading, pp 559-568, Darmstadt.
6. El Haddad, S., Smith, K.N. and Topper T.H. (1979), Engng. Fract. Mech., 11, 573–584.
7. FKM-Guideline, (2003), Analytical Strength Assessment of Components in Mechanical Engineering, 5th Edition, Frankfurt am Main.