REPEATED FATIGUE FAILURE OF SHAFT OF CABLEWAY

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The shaft of the drive of a cable car failed after three years' service and was replaced by a newly designed one. This shaft again failed after three years. This second failure of the shaft was thoroughly analyzed and attributed to fretting fatigue. A numerical analysis of the fretting contact problem was performed by the finite element method in order to improve the design to prevent future failure with the limiting condition that no changes were allowed to buildings and to the general design of the cableway.

INTRODUCTION

A cable way was built in 1987. In the summit station a specially designed arrangement of shafts, wheels and counterweight allows pretensioning of the rope. (Fig. 1) Here the wire rope is wound around 2 large wheels which are mounted on the same shaft, one fixed and the other one sitting on a roller bearing.

After 3 years of service this shaft broke. It was found that the failure had been caused by fatigue and the design was changed. (Fig. 2) Another 3 years later in 1993 the shaft with the supposedly improved design showed considerable eccentricity and had to be replaced. Now a detailed failure analysis, including a finite element analysis of the local load situation around the contact area, was performed which showed that the failure had been caused by fatigue and that the crack had been initiated by numerous preexisting cracks due to fretting corrosion between shaft and inner ring of roller bearing. (Hereafter this second design is referred to as the "old design".)

A new shaft (3rd design) was installed in 1993 which is shown in Figure 3. The new design features a pretension rod through the center of the shaft applying an axial compression force of 3 MN. The contact area between the inner ring and the shaft was removed from the main bending stresses in the shaft by increasing the inner diameter of the roller bearing under which the fretting fatigue crack initiated to 360 mm. The shrink fit was changed to always ensure an interference.

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FAILURE INVESTIGATION

The failure analysis on the old shaft design included a visual inspection, fractography, metallography, and a tensile test. A standard stress analysis was performed to ensure that common engineering rules had not been violated in the design phase.

The visual inspection revealed clear traces of fretting on the surface of the shaft under the inner ring of the bearing. A crack on the surface could be seen which reached approximately around half the circumference of the shaft in a slight angle with respect to the circumferential direction. When the shaft was cut and separated at the crack, clear marks of a fatigue crack due to bending were revealed.

The position and appearance of the surface cracks indicated that they had been shaped due to fretting corrosion.

The mechanical parameters most important for fretting fatigue are (e.g. Kreitner et. al. (1)) the amount of the local alternating slip between the inner ring and the shaft, alternating shear stresses acting on the contact area (if local slip occurs the shear stresses depend on the local radial pressure in the shrink fit) and local von Mises stresses in the shaft at the contact area (a stress concentration occurs due to a change in stiffness). For an improvement of the design these parameters must be improved.

Fractography by scanning electron microscope and metallography both revealed that the fracture had started from a surface crack, that a multitude of similar surface cracks were present at the surface of the shaft and that the fatigue crack had grown slowly, the area of the fatigue crack amounting to nearly 60% of the whole cross section.

All the values of a tensile test exceeded the requirements stated in DIN 17200 (34CrNiMo6 DIN material number 1.6582) for this steel.

The loads acting on the old shaft design shown in Figure 1 result in a nominal bending stress of 108 MPa at the critical cross section. A stress analysis following standard engineering rules (e.g. Decker (2)) gives an allowable stress of 159 MPa and does not reveal a potential for failure.

Crack growth was approximately 200 mm in 3 years corresponding to a mean crack growth rate of $7 \cdot 10^{-6}$ mm/cycle, which seems quite normal for this material and does not indicate additional detrimental influences.

NUMERICAL ANALYSIS OF THE CONTACT PROBLEM

The loads carried by the old and new shaft design are shown in Figure 1. The pretension of the cable results in a radial force acting on the wheel. Some of this load is transmitted to the shaft through the critical roller bearing.

The numerical analysis was performed to ensure that the new shaft design indeed improves the fretting fatigue behavior. For this purpose the regions around the critical contact areas of the old and new shaft design were modeled with three-dimensional finite element models. The modeled regions include the inner ring of the roller bearing and part of the shaft. Here only the analysis of the new design is presented.

Figure 3 indicates the modeled region of the new shaft design. In the model gap-friction elements provide frictional and gapping connections between any two nodes of the structure.

In the commercial finite element program (3) used for the analysis, the modeling of gap-friction is based on the imposition of kinematic constraints. Conditional logic determines when to enforce a constraint or when to ignore it. During the evaluation of the stiffness matrix the gap status (open, frictional stick, or frictional slip) is based on the estimated strain increment. By iteration the final position of the parts was found. In this calculation also the friction between shaft and inner ring of the bearing was considered (4).

Coefficients of friction between 0.4 and 0.8 are given in the literature for shrink fits between two steel components, e.g. Kreitner et. al. (1) and Häusler (5). The largest local slip can be expected for a small coefficient of friction. For the analysis a value of 0.4 was assumed. The material behavior was modeled as linear elastic. Young's modulus E = 210'000 MPa and Poisson's ratio ν = 0.3 were assumed.

RESULTS AND DISCUSSION

The material properties of the failed shaft were within standard limits. The operating stresses calculated by following standard engineering practice were on the safe side. The main crack leading to the failure was clearly a fatigue crack. The position and appearance of the surface cracks indicated that they had been initiated due to fretting fatigue. Traces of fretting on the shaft surface confirm the fractographic and metallographic findings.

The numerical analysis of the contact problem indicates that in the case of the old shaft design the contact between shaft and inner ring is lost during operation opposite of the radial force. The complete loss of contact over part of the circumference for an oversized inner ring resulted in numerical problems because the system of equations becomes instable. This reflects the true physical behavior. Chattering may occur during operation that is only limited by the distance sleeves on both sides of the roller bearing (see Figure 3).

The increased interference fit in the new shaft design improved the contact situation. The inner ring remains in contact with the shaft over the whole width and around the full circumference during operation.

The local alternating slip between the inner ring and the shaft is an important parameter influencing the fretting fatigue behavior. Figure 4 shows the range of slip that occurs during one revolution of the shaft for the old shaft design with a radial interference of -17.5 μm and for the new shaft design. The slip is practically identical for the whole possible interference range of the new shaft design. The maximum alternating slip reaches 61 μm in the old shaft design and occurs at the side of the roller bearing, which corresponds to the location where the cracks initiated. The maximum alternating slip in the new shaft design is approximately 2 μm.

The inner ring causes a stress concentration of the bending stresses at the ends of the inner ring where the material is most susceptible to fretting fatigue due to the combined effect of alternating slip and shear stresses. The stress concentration will accelerate the crack growth of small surface cracks initiated by fretting fatigue.

The situation is completely different for the new shaft design. The contact area is removed from the effect of the bending moment. In fact, no axial stress component can act at the ends of the inner ring because of the shaft shoulder. However, the shoulder introduces an additional stress concentration in the shaft. Proper attention has to be paid to this.

CONCLUSIONS

The failure of the old shaft was attributed to fretting fatigue where the combined effect of local alternating slip and shear stresses had initiated several small surface cracks in the shaft close to the edge of the contact area. One of these cracks grew due to the stress concentration at the edge of the inner ring and later due to the global bending stresses. The global bending stresses were small and only caused slow crack growth.

The numerical analysis of the old shaft design predicts large local slip at the location where the surface cracks initiated and a stress concentration that enabled the continued growth of the cracks. These results are consistent with the findings of the failure analysis.

The numerical analysis of the new shaft design predicts a considerably smaller slip, smaller shear stresses and the absence of an axial stress component at the critical locations. Accordingly it can be concluded that the new shaft design will be safe with respect to fretting fatigue in the contact area.

The numerical study shows that contact problems can be analyzed with a commercial finite element program using gap-friction elements, which unfortunately requires many iterations to obtain the state of equilibrium even for linear elastic material behavior.

The following general rules for the improvement of a shrink fit design can be derived from the results of the investigation:

- The radial interference should be large enough to ensure complete contact of the two components during operation which decreases the local alternating slip. On the other hand, if complete contact during operation can be guaranteed, an additional increase of the radial interference will just increase the local stresses and will be detrimental to the fretting fatigue behavior.

- The edges of the contact zone should be isolated from the effects of global external loads. Otherwise additional stresses will accelerate the propagation of surface cracks initiated by fretting fatigue. An additional positive effect arises from the fact that in this case the deformations of the two contact partners are more likely to be equal or at least similar and, therefore, reduce local slip.

According to this analysis the improved design will be safe with respect to fretting fatigue in the contact area of the wheels on the shaft.

REFERENCES

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(4) *'MARC User Information, Volume A';* MARC Analysis Research Corporation; Palo Alto, USA

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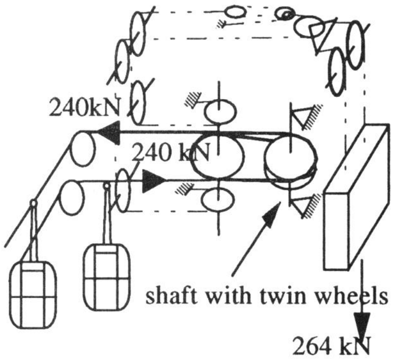

Figure 1: Layout of summit station

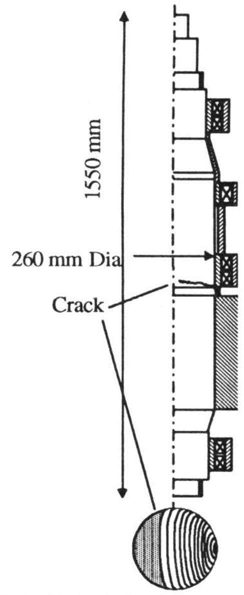

Figure 2: Failed shaft of cable car

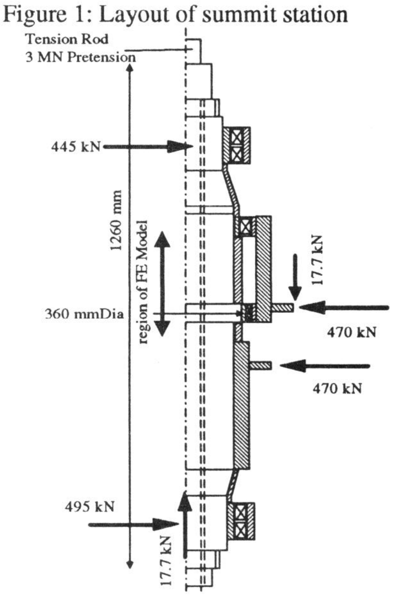

Fig. 3 New shaft design, schematically

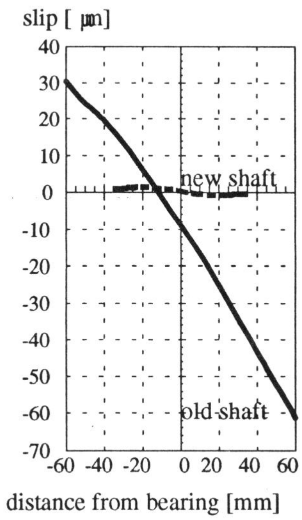

Fig. 4 Results of numerical analysis