Prevention of Aerial Tramway Failure by Safety Factors ?

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Abstract

In december 1996 an accident occured on a cableway which caused the death of one passenger and injuries to several others. The cause of the tragic accident was the unexpected failure of the axle that carries the deflecting wheels for the wire rope. During the course of the official investigation it was demonstrated that the failure was due to a fatigue crack that had already propagated through a large portion of the cross-section. This fatigue crack had been initiated by fretting.

Furthermore it was found that safety factors prescribed by the regulations for cableways had not sufficiently been considered in the design calculations.

It also became clear that if different calculating philosophies are to be combined in a project great care is necessary in order to assure that all the important design parameters and failure modes are considered during the analyses, e.g. finite element calculations are employed together with design standards that contain overall factors, to account for stress concentrations and manufacturing inaccuracies

In general it may be concluded that a simple compliance with the factors of safety will not always provide the necessary margin of safety against failure. Safety can only be guaranteed if all the important mechanisms of possible damage have been fully accounted for in the design.

1 Case History

In december 1996 an accident which occurred on a cableway caused one death, injuries to several others and a considerable interruption of the service. Up to the moment of the accident the cableway had been in operation for only one year.
The design was identical to that of other cableways which had been reliable and were approved by the competent authority.

Fig. 1 Cableway after the accident

At the moment of the accident, the axle in the downhill station, that carries two deflecting wheels required to furnish the necessary pretension in the wire rope had broken. As a consequence one wheel had been hurled away and the wire rope had relaxed until it was held back by a concrete pillar. This slackening led to the fatal events.
As turned out in the course of the failure analysis, similar cases had occurred in the past and have since been discussed in the literature (E. Corazza, 1997)

2 Failure Analysis

The failure analysis was performed by EMPA and covered the four main possible sources of such failures: material, design, manufacture and service.
All the available documentation concerning the design calculations, fabrication, terms of the official approval and service conditions of the broken axle was procured. Afterwhich, the axle was subjected to a careful visual examination, to non-destructive testing and to metallographic tests. In addition the strength and the crack growth rate were measured and the critical stress determined.
The thorough investigations showed that the axle had been broken because of a fatigue crack which had already covered approximately 50 % of the cross-section in only one year of service.

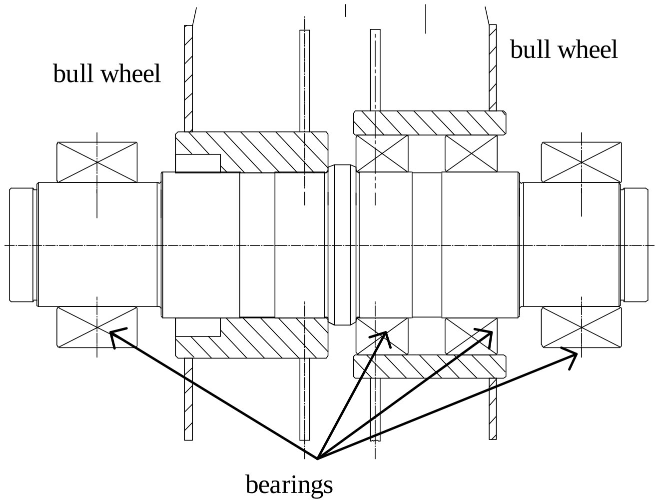

Fig. 2 Axle for bull wheels of ropeway, (axle rotates, one wheel fixed)

Fig. 3 Fracture surface of broken axle

It was observed that the crack did not originate in the vicinity of the calculated high stress location but had been initiated by fretting corrosion under the seat of the hub of the bull wheel.

The damage to the axle outer surface resulted from the simultaneous action of the pressure from the bull wheel hub and the very smalll but repeated relative slipping movement between the hub and the axle. This continual fretting action was responsible for the initiation of the crack as shown in Fig. 4

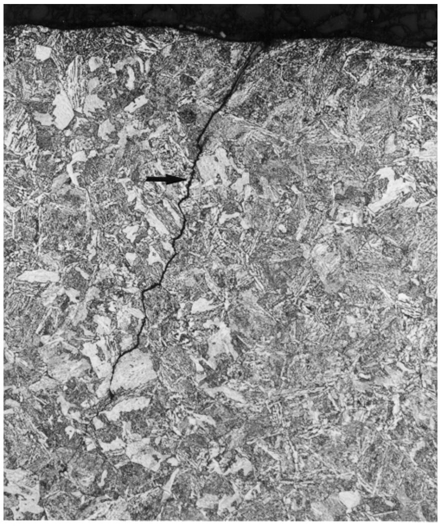

Fig. 4 Crack initiated by fretting fatigue

3 Comment on Design Procedure

A check of the design integrity, which the manufacturer performed at the same time as the failure analysis was conducted, revealed that the design calculations did not comply with the updated mandatory regulations of the ordinance for circulating aerial tramways. Nevertheless the structures built to the old regulations had generally been in service problems. Therefore it was necessary to have a closer look at the calculation methods for such axles.

As a machine element the axle in question is quite straightforward to dimension. One starts from simple bending stresses induced by the external loads, in this case the forces in the hauling rope, and calculates the maximum stress. This stress is then compared to the strength of the material and the corresponding safety factor is determined.

In this simplified description of the procedure to determine the safety factor there was no mention of any regulatory specifications. Components designed for use in public transportation systems must comply with guidelines specified in the federal ordinance for aerial tramways. The specifications in the ordinance furnish rules for the loads and minimum safety factors to be respected. On the other hand, the code does not contain detailed guidelines concerning the design method. In mechanical engineering, it is general practice to employ modifying factors to account for separate effects of design parameters such as stress concentration, manufacturing inaccuracy and surface treatment.

4 Safety Factors

4.1 Verification of Numerical Value - Influences

If a structure has to be calculated, safety factors would not at all be needed if all the pertinent parameters were known, especially the service loads, the resistance of the material, the influence of stress concentrations and of inaccuracies in the manufacturing process.

Unfortunately, this is not the case and times modifying factors are needed to take into account the effect arising from an increase in the external loads and a reduction in structural resistance.

Generally a safety factor is expressed as follows:

S=M/L, where

S - safety factor; **L** - loads, **M** - material resistance,

Safety is guaranteed as long as **M>L,** i.e. if **M≥L•S.**

Here different philosophies are encountered: either **M** and **L** are determined as close to reality as possible and any uncertainties are included in **S** or to account for the uncertainties in **M** and **L** and then to need only a small safety margin in S.

A further question is how to calculate a certain value of **S**. Normally, the structural resistance M is proportional to the product of the loaded cross section **C** and of a characteristic strength **R**, i.e.

M ~ C•R.

This simple expression reveals that a high value of M can be obtained by increasing C (the axle diameter), by using material with a higher strength or by varying both. Note, that a higher safety factor achieved through a shaft with larger diameters leads to a different state of stress and a stress gradient in bending as well as a completely different risk of damage.

Mechanics show that it makes a large difference whether the cross-section, i.e. the diameter of an axle is made larger or a material with higher strength is used.

In the calculation of stresses the diameter appears with an exponent of 3 and for deformations with an exponent of 4. Thus an increase of the diameter is much more effective for the calculation of the safety factoras compared to using a higher strength material. The main disadvantage in attaining a prescribed safety factor by an increase in the axle diameter is that this leads to larger bearings and housing and perhaps a bigger building. As a consequence, the overall cost could also increase.

Even if the factor of safety were to comply with the design specifications, this alone is not sufficien t to guarantee that a failure will not occur. It is also essential to identify and analyze the most critical mechanisms of damage that could otherwise result in catastrophic consequences. In fact, fretting fatigue was responsible for this aerial tramway accident. Fretting fatigue has been discussed in quite a number of conferences and is still a challenge for design engineers (Kieselbach, 1994).

A very important parameter in the phenomenon of fretting fatigue is the amplitude of slip. For this particular accident, the slip resulted from the relative motion of the hub and the axle as it deformed during bending. From fig.5 can be seen that 3 different regimes of slip can be identified. For large amplitudes fatigue life is not reduced significantly and damage is mainly by abrasion; for very low amplitudes there is no wear and no reduction of fatigue life. The problem evidently lies in the region in between where fretting takes place. If the slip amplitude can be reduced by increasing the stiffness then fretting fatigue would no longer be a problem.

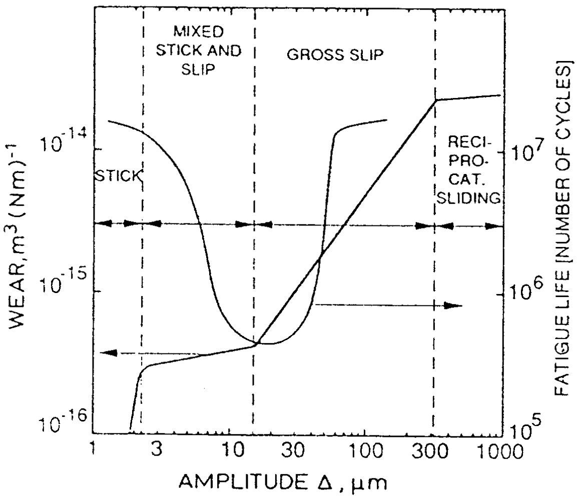

Fig. 5 Damage and slip (Vingsbo and Soederberg , 1988)

The following simple calculation shows that increasing the diameter instead of the material strength is advantageous in bending. A bending moment of 255 kNm applied at the critical point of a (notched solid round) shaft having a stress factor of 2.22 and a safety factor of 2, one obtains the following relation for the fatigue strength σ_a as a function of the diameter D:.

$\sigma_a = \frac{255 \cdot 10^6 \cdot 4.44 \cdot 32}{\pi \cdot D^3}$ as shown in Fig. 6.

Obviously this figure is theoretical in nature, since a fatigue strength of more than 500 MPa cannot be achieved for quenched and tempered steels. Therefore the alternative of increasing the diameter will in most cases be the option to choose.

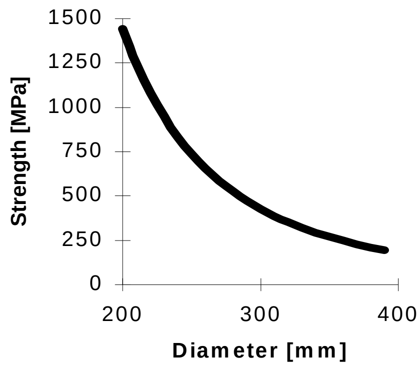

Fig. 6 Relation between strength and diameter of a shaft

4.2 Problems with the Combination of Different Calculation Methods

Numerical calculations using the method of finite elements are more frequent nowadays. On the other hand, it is necessary to demonstrate for structures or components that the stresses and perhaps safety factors comply with the specifications in mandatory codes.

This now leads to a special problem: Is it possible to determine a state of stress in a structure, even if it is of complex shape and loaded in a complex way with an arbitrary accuracy which is limited only by the capacity of the computer? Most standards and ordinances used for calculations nowadays are still based on the assumption that it is not possible to exactly determine stress concentrations and therefore provide categories for groups of loading conditions, load spectra etc. The stress concentrations are then accounted for by an appropriate reduction of the permissible stress for the material in question.

A standard which is often used in different european countries for the calculation of steel structures is the standard for cranes DIN 15018.

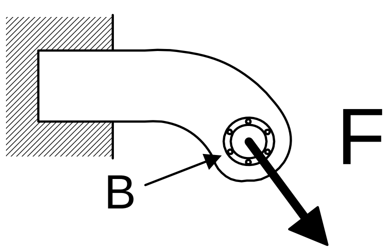

Fig. 7 Example of a structure loaded in tension with a force F, having a stress concentration at the hole B where the load is introduced

To determine the permissible stress in a structure like that of Fig. 7 using a standard like DIN 15018 one has to calculate first the nominal stress for a certain part by a method which is not specified in the standard and then to assign the groups for the appropriate load spectra, design details etc. This yields the permissible stress according to the standard. In general the result contains a superimposition of several safety factors.

The problem arises when regulations of the administration contain mandatory safety factors which also have to account for these uncertainties. In order to avoid that certain phenomena are accounted for more than once which would lead to an overdimensioned structure, it is important to know which factors , specified in the codes, have been already included in the calculation. Unfortunately, clarifications concerning the method of combining or interfacing different calculation techniques are seldom found in the codes.

4.3 Cleverness in Design

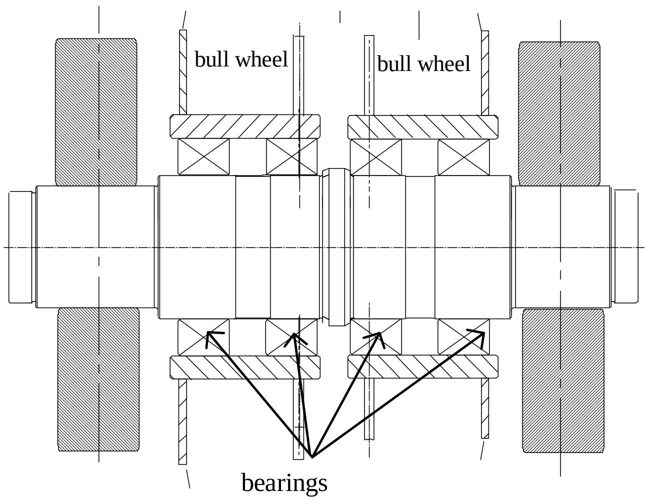

Fig. 8 Design with fixed axle and rotating bull wheels

If the design of the axle is changed as shown in Fig. 8 one gains two advantages. In the first place, one bearing less is needed and also the span-set for fixing one of the wheels is not necessary. The second, most important, advantage is that the mode of stressing changes from rotating bending to simple bending. From the Smith-diagram for fatigue strength shown in Fig. 9 one sees that for alternating bending the maximum permissible stress corresponds to point A (with a safety factor of 2) whereas for simple bending at point B the permissible stress would be twice that value, i.e. the overall safety would be doubled.

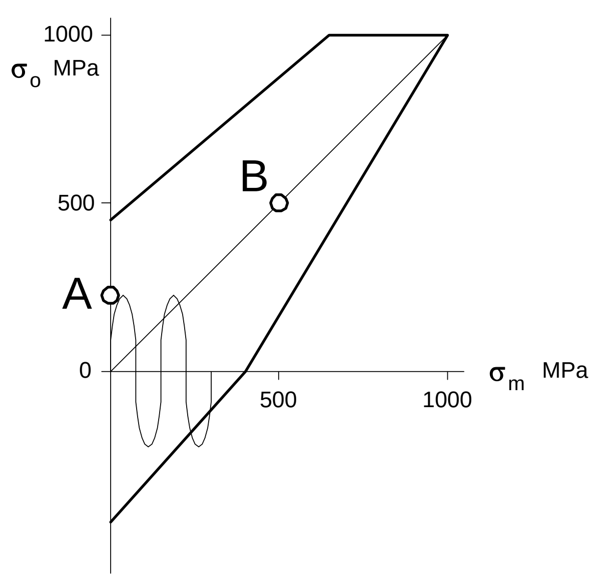

Fig. 9 Smith-diagram for fatigue strength of steel 42CrMo4

5 Summary

The accident of the aerial tramway can be attributed to a combination of a weak design and an oversight in the calculations (safety factor too small). A further consideration shows that a prescribed value of a safety factor can prevent failure only if all the possible mechanisms of damage have been accounted for in the design.

The ability to identify and analyze such mechanisms is a quality that comes with experience or knowhow. Thus, it is strongly recommended that engineers or designers involved with the dimensioning of critical structures or components be trained to identify and analyze such subtle but critical phenomena.

In combining different calculation methods it is important to perform this with caution so as not to consider the safety requirements more than once. Otherwise, this could lead to an overdimensioned structure or component, i.e., unnecessaryly heavy and expensive.

At times, a design can be made more efficient by optimizing the kind, number and location of the support and fixation points. This would lead to a substantiall increase in safety and at the same time avoid certain critical damaging mechanisms.

An additional problem is that designers do not adequately take into account and incorporate experience and existing know-how but do rely too much sometimes on calculations by finite. Special care has to be taken also in simplification of design problems to facilitate calculations and in assumptions of boundary conditions.

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