CHAPTER 14

Causes to damages

Introduction

Damages concerning water turbines are caused mainly by cavitation problems, sand erosion, material defects and fatigue. Damage problems occur primarily in turbines for higher heads than about 250 m. These problems are consequences essentially of high pressures, pressure variations and high water velocities which to some extent depend on the ever prevailing search for a minimising of the costs of the investments.

To cope with these problems, studies and research of the phenomena as well as the properties of materials have been carried out and are going on. Precautions to be taken to avoid or minimise damages have been recommended, criteria for choice of materials and methods for estimation of durability of stressed components have been developed.

In the following section a survey of aspects of the main damage problems and how to reduce or avoid these, are considered.

14.1 Cavitation

The turbine parts exposed to cavitation are the runners and draft tube cones for the Francis, Kaplan and bulb turbines and the needles, nozzles and the runner buckets of the Pelton turbines.

Measures for combating erosion and damage under cavitational conditions are improvements in hydraulic design and production of components, search for erosion resistant materials and arrangement of the turbines for operations within the good range of acceptable cavitation conditions. The further considerations are focused merely on the search for materials with high resistance against erosion from cavitation.

Through the three last decenniums extended research is done on developing new alloy steel qualities. Successively those materials which have performed the best properties, have been tested in relevant applications. As a conclusion it has been an extensive and successful advance in the development of materials with properties as high strength, wear resistance, corrosion resistance, weldability and reduction of defects and brittleness in heat affected zones. This development of material properties is in further progress.

In harmony with these attainments certain types and qualities of materials are chosen according to the prevailing conditions for the different components exposed to cavitation. At present guide vanes and runners exposed to high flow velocities with danger of cavitation or turbulence corrosion are made of stainless steel 13% Cr 4% Ni and 16% Cr 5% Ni respectively. The 16% Cr 5% Ni is used in the runner due to good weldability without preheating.

The upper part of the draft tube cone is also made of stainless steel 16% Cr 5% Ni. The surface of the covers against the guide vane end faces are normally clad welded with stainless steel 16% Cr 5% Ni with hardness of about 300 Brinell. This hardness is about 70 Brinell different from the hardness of the guide vanes and that is chosen to prevent tearing of the surface when the guide vanes are moved.

The parts exposed to high flow velocities such as needle tips and nozzles are made of hardened stainless steel of 13% Cr 4% Ni or 16% Cr 5% Ni.

14.2 Sand erosion

Sand erosion problems in Norwegian water power plants are generally limited to plants at net heads above 200 - 300 m. That implies experiences limited to Francis and Pelton turbines.

Sand erosion is designated as abrasive wear. This type of wear will brake down the oxide layer on the flow guiding surfaces and partly make the surfaces uneven which may be origin also for cavitation erosion. Sand erosion therefore may be both a releasing and contributing cause for damages which are observed in power plants with a large transport of wearing contaminants in the water flow.

The *erosion damages* are to some extent different for Pelton and Francis turbines.

On *Pelton turbines* it is the needle tip, the seal rings in the nozzles and the runner buckets which are most exposed to sand erosion. The wear on needle tips occurs as streaks and indentations forward to the tip. On the buckets the sand contaminants in the water flow is wearing the bucket gap backwards. That causes a delayed contact with the jet and makes an erroneous splitter. The bucket edge is usually exposed to an even wear and tear and becomes wider, and extended indentations may occur just behind the edge.

It should be emphasised that sand erosion even from silt with grain size less than 60 μm have made severe damage on needles and nozzles of a Pelton turbine at 800 m head in Norway while the runner buckets have had negligible damage. This phenomena may be caused by the strong turbulence in the high jet velocity bringing the grain particles to oscillate and rotate in circles causing collisions with the steel surface.

If coarse sand is present, the Pelton buckets are also severely eroded while the damage of the nozzles may be less serious. The reason may be explained by the extreme acceleration of a particle passing the Pelton bucket. A flow analysis shows that an acceleration of 100 000 m/sec^2 may occur for small buckets in a high head turbine.

In *Francis turbines* the guide vane cascade and the labyrinth rings are the major parts which are exposed to wear. In some serious cases also the surfaces of the covers against the guide vane end faces and the runner blades have been damaged. Usually the wear of the guide vane cascade and the labyrinth rings have the most significant influence on the efficiency of the turbine.

Materials resistant to sand erosion

The real mean to minimise sand erosion in the turbines is to apply the most suitable material with properties that match the highest possible resistance against erosion, and contemporary satisfy manufacturing and operating conditions. Against sand erosion stainless steel does not really show acceptable resistance. The materials stellite and titanium show better resistance, but only by a factor of two to three. However, promising work in developing coating processes of ceramic material as wolfram carbides is going on.

At present however, the materials with the best properties against cavitation erosion are also used even if sand erosion is expected. That means guide vanes and runners are made of stainless steel types as 13% Cr 4% Ni or 16% Cr 5% Ni. These same materials are used also in the rotating seal rings on Francis runners, while the static labyrinth seals in the covers are made of Ni-Al bronze which has a hardness different from that of the rotating ring.

For needle tips and nozzles in Pelton turbines which are exposed to high flow velocities, *hardened* stainless steel of 13% Cr 4% Ni or 16% Cr 5% Ni is recommended. If however, severe sand erosion is expected, a ceramic coating on the needle tip and the nozzle ring has been used successfully.

So far ceramic coating of Pelton runners is not commercialised with sufficient success, but improvements are made in recent years. Coating of facing plates of Francis turbines is under development as well, while the guide vanes may be treated in the same way as the needles and nozzles of a Pelton turbine.

A general problem with the surface coating is however, that it will be more rough than a polished steel surface. This means a decreased efficiency of the turbine. Grinding of the coating is also regarded as a problem because the coating may be too thin or even penetrated.

14.3 Material defects

For high head turbines the stress carrying parts are made of fine grain high tensile strength carbon steel. The base for the dimensioning criterias of these parts is the maximum stress and the number of pressure pulsations cycles. To allow for acceptable material and weld defects within realistic values for production, materials with a yield point value above 460 MPa are not recommended.

For large vertical Pelton turbines the development of high tensile steel has allowed for increasing size of turbines for high heads in the range of 800 to 2000 m. With basis in fracture mechanics it is essential to design a turbine to fulfil the requirement that unstable fracture from a crack shall not occur until the crack has penetrated the whole plate thickness. This condition is designated *Leakage Before Rupture* (LBR). The reason is that a crack through the thickness will be easy to detect by the leakage. As long as a crack has not penetrated the whole plate thickness an unstable rupture will be prevented. This requirement limits the maximum size of the turbine depending on the toughness of thick materials.

On the basis of the above mentioned requirements the maximum main stress must be limited to about 200 MPa for any material quality developed untill now.

The most important requirement for the manufacture is the weldability to avoid defects and brittleness in the heat affected zones of the material. To fulfil this requirement limitations in the chemical composition is made. These limits are:

Carbon C < 0,13%, Sulphur S < 0.01% and Vanadium V < 0.09%

Welding defects

Defects will always occur in a weld. Cracks and lack of fusion are the most serious defects because they are two dimensional. Three dimensional defects such as slag and gas cavities are not so dangerous except if sharp edges of slag is connected to a lack of fusion or a crack.. Gas cavities may also indicate hydrogen which is very dangerous due to micro cracks.

The most dangerous defect is a propagating crack with a very sharp edge, e.g., a two dimensional defect or a flaw.

Crack propagation based on fracture mechanics

As defects always occur in a weld or in the heat affected zones in the base material, it is therefore essential to have acceptance criterias for defects which will not grow to rupture under the operational conditions for the regarded structure.

An acceptance criterion for material defects may be based on the theory of fracture mechanics. An applied criterion is briefly described as follows.

The stress in front of a crack tip in a *complete elastic* material is expressed by

$$\sigma = \frac{K}{\sqrt{2\pi r}} \tag{14.1}$$

where σ is the mean stress which cause the crack to propagate
K is the stress intensity factor
r is the distance to crack tip

By means of this theory one will find that the stress at the crack tip will reach an infinite value. This indicates that the crack should propagate even for low average stress values σ in the surrounding of any small crack with depth a in a complete elastic material with no ductility.

However, all materials suitable for structural design will undergo a *plastic* deformation at a certain stress level which limits the stress peak value. If the load or stress level and crack depth are within certain limits the crack will stop in the plastic zone. The material will have a certain crack arresting ability depending on the ratio between the elastic energy and the elastic energy stored in front of the crack tip.

As a conclusion:

A crack will propagate only if the loss of elastic energy is equal or greater than the energy needed to form new fracture surface.

The critical elastic energy at the crack tip is expressed by the stress intensity factor K found in the following way.

If the average stress in the uncracked material is σ, the stress intensity factor becomes

$$K = \sigma\sqrt{\pi a}\,f(\phi) \tag{14.2}$$

where a is the crack depth
$f(\phi)$ is a factor which is a function of crack length and geometry of the material surrounding the crack

An unstable crack propagation will occur if $K \geq K_C$. The constant K_C is a material constant determined by testing of the respective material quality or welding joint. Unstable crack propagation may occur as a brittle fracture with sound speed.

However, if the material cross section is thick another value K_{IC} instead of K_C is valid. But for ductile materials K_{IC} values are not valid.

Materials for turbines are of the ductile type. Depending on the strength of the material and the level of the working stress the material includes both elastic and plastic deformation in front of the crack tip before propagation.

Therefore, another method than to find a critical stress intensity factor must be used to find the crack arresting ability and the critical size of a ductile material. This method is called Crack Tip Opening Displacement (CTOD).

For any material there will be a critical crack size which leads to unstable fractures. This crack size may be based on the CTOD determined experimentally for the base materials and welds.

It is proven however, by small scale CTOD-tests that high tensile strength steel with high working stress level allows for a smaller crack size than a low tensile strength steel with a lower stress level. A critical crack size may be calculated, but this is not further considered here.

14.4 Fatigue

Defects of critical size rarely occur in a new turbine. Such defects will in any case be detected by a leakage or rupture during the pressure test which is a very important type of tests at the end of the manufacture. Smaller defects in a new turbine may however, grow to critical size during life time due to fatigue propagation caused by a certain number of load cycles.

Basically the stress carrying parts in a Francis turbine are statically loaded. A turbine in typical peaking operation however, may be stopped and started, i.e., loaded and unloaded three times or more a day. For a life time of 50 years that leads totally to about 50 000 cycles. In modern fracture mechanics theory this is in the low cycle fatigue domain. In addition minor stress amplitudes caused by pressure oscillations from the turbine regulation will be superimposed.

On the base of this conditions the stresses must be limited to avoid small fabricated cracks and other material defects to grow to critical size. Safety margin to yield stress or ultimate stress is not sufficient as safety criterion if high tensile strength steel is used.

Unfortunately the fatigue crack propagation speed has not decreased by the development of high tensile strength steel even if the toughness and strength have increased. On the contrary some research works have indicated a slight improvement of fatigue lifetime of high cycle fatigue in materials with low yield stress. On the other hand the crack propagation speeds in brittle materials and tougher materials show only negligible differences.

From these experiences the following conclusions are drawn:

- For turbine parts exposed to a number of loading cycles above 20 000 in the lifetime it is not reasonable to increase the maximum working stresses above 200 MPa because acceptable defects then will be too small to be detected.
- In heat affected high tensile strength steels hardening effect and residual stresses may occur. For all thick plates therefore, welds should be heat treated after the welding. Otherwise after a number of years in operation, crack growth may lead to unstable fracture starting from cracks which do not penetrate the whole plate thickness.

Critical area in scroll casings is the joint between the shell and the stay ring where both the stress and wall thickness have the maximum value. For Pelton turbine distributors the bend joint on the inside is the critical point.

Parts exposed to high cycle fatigue and erosion

Runners and guide vanes especially in reversible pump turbines, will be exposed to high cycle fatigue up to the range of 10^{10} - 10^{11} cycles with relatively low stress amplitudes. Pelton runners are normally casted of 13% Cr 4% Ni alloy steel. The same material is used also in Francis runners. However, for Francis runners also the 16% Cr 5% Ni has been used. This steel shows a somewhat better cavitation resistance. Moreover, it may be welded with no preheating except for a moderate temperature of 50 ^{o}C to keep the material well above the dew point during welding. The fatigue threshold limit for a number of cycles higher than 10^{11} indicates infinite lifetime for stress amplitudes $\Delta\sigma \leq 45$ MPa and a surface crack less than one mm in depth and two mm in length.

References

Brekke, H.: Choice of materials for water turbines and the influences this has on the design manufacture, testing and operation. General Doctoral Lecture NTH, Trondheim 1984.

Kværner Brug: COURSE III, Lecture compendium, Oslo 1986