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MECHANICAL DESIGN OF HIGHLY LOADED LARGE STEAM TURBINES

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ABSTRACT

There are no internationally recognized standards, such as the ASME Boiler and Pressure Vessel Code or European boiler and pipe codes, for the mechanical design of large steam turbine components in combined cycle power plants, steam power plants and nuclear power plants. One reason for this is that the mechanical design of steam turbines is very complex as the steam pressure is only one of many aspects which need to be taken into account.

In more than one hundred years of steam turbine history the manufacturers have developed internal mechanical design philosophies based on both experience and research. As the design of steam turbines is pushed to its limits with greater lifetimes, efficiency improvements and higher operating flexibility requested by customers, the validity and accuracy of these design philosophies become more and more important.

This paper describes an integral approach for the structural analysis of large steam turbines which combines external design codes, material tests, research on the material behavior in co-operation with universities and experience gained from the existing fleet to derive a substantiated design philosophy. The paper covers the main parameters that need to be taken into account such as pressure, rotational forces and thermal loads and displacements, and identifies the relevant failure mechanisms such as creep fatigue, ductile failure and creep fatigue crack growth. It describes the efforts taken to improve the accuracy for materials already used in power plants today and materials with possible future use such as advanced steels or nickel based alloys.

INTRODUCTION

Since the beginning of the 20th century steam turbines have played an important role in the generation of electricity. Today more than 70% of electricity worldwide is generated in power plants using steam turbines. One reason for this is the compatibility with many different primary energy sources such as hard coal, lignite, nuclear fission, natural gas, bio mass or solar radiation. Another reason is that the generation of electrical power via steam is an approved and safe technology with high availability.

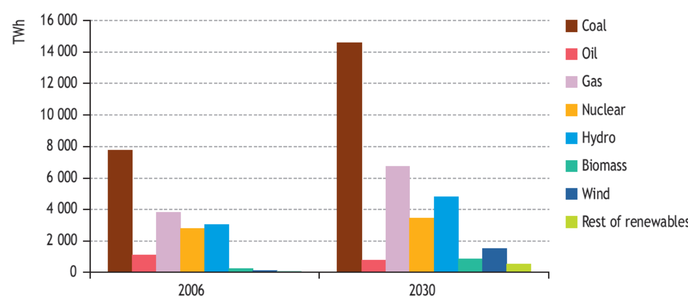

Figure 1: World Electricity Generation by Fuel in the Reference Scenario of [1]

Figure 1 looks ahead to world electricity generation in 2030. This scenario can be characterized by two parallel developments: on one hand the efforts of the industrialized countries to adopt green technologies and shift from fossil electricity generation towards renewable energy sources, on the other hand the emerging countries with their permanently increasing demand for electricity which will mostly be generated from locally available coal.

From the shares of the primary energy sources it can be deducted that the demand for steam turbines will remain. But at the same time the technical requirements will change significantly. Fighting global warming requires the forceful reduction of carbon dioxide emissions. A very economical way to do this is to increase power plant net efficiencies. Different measures can be taken and many of the most important ones,

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such as increased steam temperatures and pressures, result in higher design requirements.

Figure 2 shows the progress in power plant and steam turbine technology for combined cycle power plants (CCPP), steam power plants (SPP) and nuclear power plants (NPP). Design challenges arise from

- increased temperatures such as the 600°C live steam temperature implemented in the Irsching 4 CCPP,
- increased power output such as the 1715MW implemented in the Olkiluoto NPP,
- a combination of increased parameters such as those implemented in the Yuhuan SPP (600°C, 26.2MPa, 1000MW).

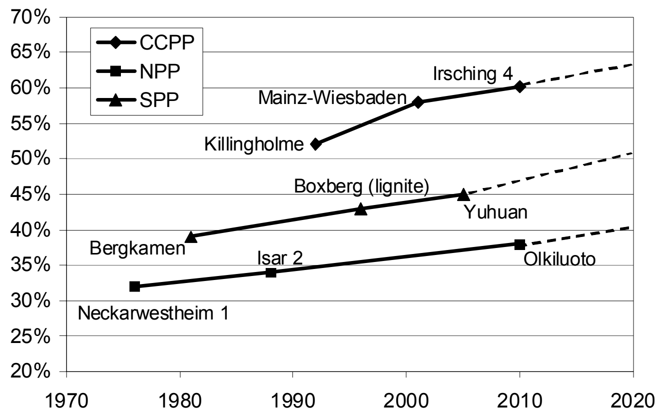

Figure 2: state of the art power plant efficiencies

The rising amount of installed wind turbine and solar power capacity also poses a big challenge for steam turbines as wind and solar radiation cannot be controlled. Consequently there is the necessity for quicker load changes and faster starts of steam turbines to stabilize the grid which results in higher temperature gradients and thermal stresses.

The demand for higher flexibility as well as increased efficiencies illustrates the need for high-end design philosophies which allow safe long term operation with the most economical use of material possible.

There are no internationally recognized standards for large steam turbine components. Instead each manufacturer uses their own set of design philosophies. This paper describes an integral approach which guarantees an economical design with high availability combined with maximum efficiency and operating flexibility.

NOMENCLATURE

a_0	initial defect size
a_{crit}	critical defect size
C^*	energy integral
CCPP	combined cycle power plant
D	total damage
D_c	creep damage
D_f	fatigue damage
E_{allow}	allowable limit for creep fatigue utilization
HP	high pressure
IP	intermediate pressure
K_{1C}	critical mode 1 stress intensity factor
K_{1id}	idealized mode 1 stress intensity factor
LP	low pressure
N	number of cycles
N_f	number of cycles to failure
N_f^{**}	predicted number of cycles to failure
NPP	nuclear power plant
$R_{p\varepsilon/t/T}$	creep elongation limit
$R_{u/t/T}$	creep rupture strength
S	safety factor
SPP	steam power plant
t	time
T	metal temperature
t_a	time to crack initiation
t_u	time to failure
UTS	ultimate tensile strength
YS	yield strength
ε	strain
ε_{cr}	creep strain
$\varepsilon_{cr,u}$	creep strain at failure
σ	stress

MECHANICAL DESIGN OF HIGHLY LOADED LARGE STEAM TURBINES

Most components used in the water steam cycle of large power plants cannot be designed freely but are governed by regulations. This is the case for boiler components, pressure vessels and pipes. Different codes and standards apply depending on the location of the power plant, customer and equipment manufacturer. This is for historic reasons, as many nations have developed their own set of standards. The most important ones today are the American ASME Codes and the European standards. An incomplete list for component standards used in the water steam cycle of large power plants is given in Table 1.

Table 1: selected codes and standards for power plant components

<table>
<tr><th>Application Range</th><th>Code / Standard</th></tr>
<tr><td rowspan="3">Boiler</td><td>DIN EN 12952: Water-Tube Boilers and Auxiliary Installations [2]</td></tr>
<tr><td>Technical Rules for Steam Boilers (TRD) [3]</td></tr>
<tr><td rowspan="2">ASME Boiler and Pressure Vessel Code [4]</td></tr>
<tr><td rowspan="3">Pressure Vessels</td></tr>
<tr><td>DIN EN 13445: Unfired Pressure Vessels [5]</td></tr>
<tr><td>AD2000 Merkblätter [1]</td></tr>
<tr><td rowspan="2">Piping</td><td>ASME B31.1 - 2004 Power Piping [6]</td></tr>
<tr><td>DIN EN 13480: Metallic Industrial Piping [8]</td></tr>
</table>

These codes and standards have in common that they do not only contain calculation procedures, but are comprehensive. The main components of the standards are:

- list of materials
- material design data
- quality assurance
- manufacturing procedures
- design rules
- monitoring during operation.

For steam turbine components such standards do not exist, one of the reasons being that pressure is not the primary design criterion for steam turbines. Instead the design of steam turbines is influenced by multiple, complex load cases, multiple failure mechanisms and the interaction of different components such as rotors and casings. These topics will be dealt with in the following chapters.

In contrast to the component-specific codes and standards mentioned above there are also general design procedures. Examples are the British Energy Procedures R5 [9] and R6 [10] or the German FKM Guidelines "Analytical Strength Assessment" [11] and "Fracture Mechanics Proof of Strength for Engineering Components" [12]. Steam turbines cannot be designed using these procedures alone as they do not contain all the necessary information and rules to safely design a turbine. The R5 and R6 procedures for example do not contain any material data, only lists of the necessary properties are given. As safety factors depend on the processing of material test results such as scatter band analysis, safety factors are not included in these procedures either. The FKM Guidelines, as another example, do not contain any procedures for high temperatures dealing with creep failure.

By being general and widely applicable the design procedures mentioned in the previous clause have the immanent characteristic of being more conservative than a component- specific design philosophy which focuses on the specific load cases.

The integral design philosophy which is currently used at Siemens and described in this paper is such a component based concept which allows less conservative - yet still safe - life time predictions in comparison to general procedures and thus allows the efficient and economic use of material. Whereas none of the above-mentioned codes, standards or procedures can be used to design steam turbines, certain structures and concepts are adopted from them.

The integral design philosophy as shown in Figure 3 is comprehensive and contains the components listed above. Besides considering internationally recognized standards it is based on material tests, research into failure mechanisms and component behavior, as well as the fleet experience, which is constantly growing. This is the reason for another important aspect of the design philosophy: it is constantly evolving, adopting new research results and operating experience.

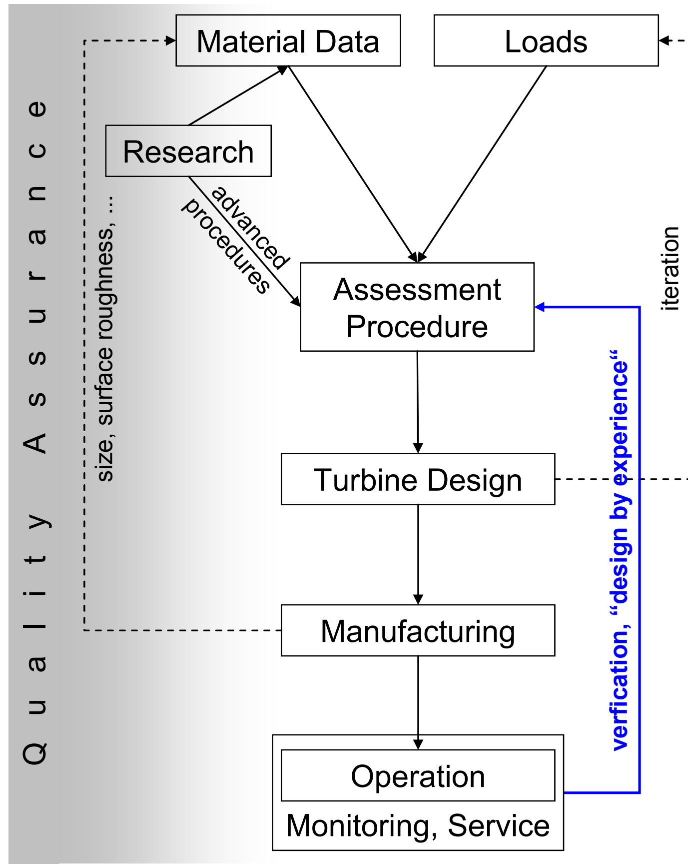

Figure 3: integral design philosophy for steam turbines

LOADS

The loads imposed on a turbine generator set result from operational effects such as steam pressure and temperature, as well as from effects of manufacturing and installation such as residual stresses and the conditions imposed by bolted or shrink-fitted connections. Some of these effects are of steady-state nature, some are of a low-cycle nature e.g. restrained thermal expansion during startup and some are also of high-cycle type, e.g. alternating bending stresses induced in rotating shafts due to their deadweight. In addition, effects related to the operating environment of the machine, such as oxidation, corrosion and erosion must be taken into account. All of these effects must be carefully considered in the course of design, analysis and material selection.

A summary of the main loading conditions are:

<u>Metal Temperature T_i:</u>

- High at HP / IP admission (today up to 620°C)
- Low during cold starts and at LP sections (resulting in surface wetness)

<u>Static loads causing stresses σ_i:</u>

- Primary type:
  Internal and external steam pressure (vacuum),

centrifugal forces, deadweight, torque due to load, flow-induced forces

- Secondary type:
  Joints (bolted and shrink fitted), restrained thermal expansion

Dynamic loads causing stress ranges $\Delta\sigma_I$ and strain ranges $\Delta\varepsilon_i$ for a number of cycles N_i:

- Low-cycle:
  Restrained thermal expansion during startup, load changes and shutdown
- High-cycle:
  Alternating bending stress induced in rotating shafts due to their deadweight or unbalance, dynamic flow forces, self-excited vibrations
- Impact loads:
  Rapid changes in steam conditions (e.g. water ingress), short circuits, seismic events

Environmental effects:

- Oxidation, corrosion, erosion

At temperatures T_i > 400°C steels are subject to the phenomenon of creep, causing a time-dependent behavior. For this reason the design time t_i must be considered as a loading parameter for such high temperatures as well.

Multiple of the above mentioned loading conditions act on each steam turbine component. Depending on the component and the region of the component, different sets of loading effects must be considered resulting in different damage mechanisms. The synthesis of such load sets is very important as the interaction of different load cases such as creep and fatigue influences the development of damage.

Using a 300MW steam turbine as an example, Figure 4 shows an overview of the distribution of potential damage mechanisms.

MATERIALS

Depending on the component and its loads as described in the previous chapter, different material behaviors and different property profiles are required by designers. Table 3 shows the necessary property profiles for major steam turbine components.

Instead of using material data from standards, Siemens uses design data which is consistent with the other parts of the steam turbine design philosophy. This material design data is gathered from tests on extra material from real components or on near-component material volumes using standardized tests with specific specimens. The test material retains the typical manufacturing features representative for a component in application, such as forging cycle, heat treatment history and property differences surface to center. In part, larger specimens are used for testing the relevant material behavior to improve the transformation of standardized test results to large components under service conditions. In addition, component-like tests are performed including effects such as creep-fatigue, multiaxiality influence and creep crack growth.

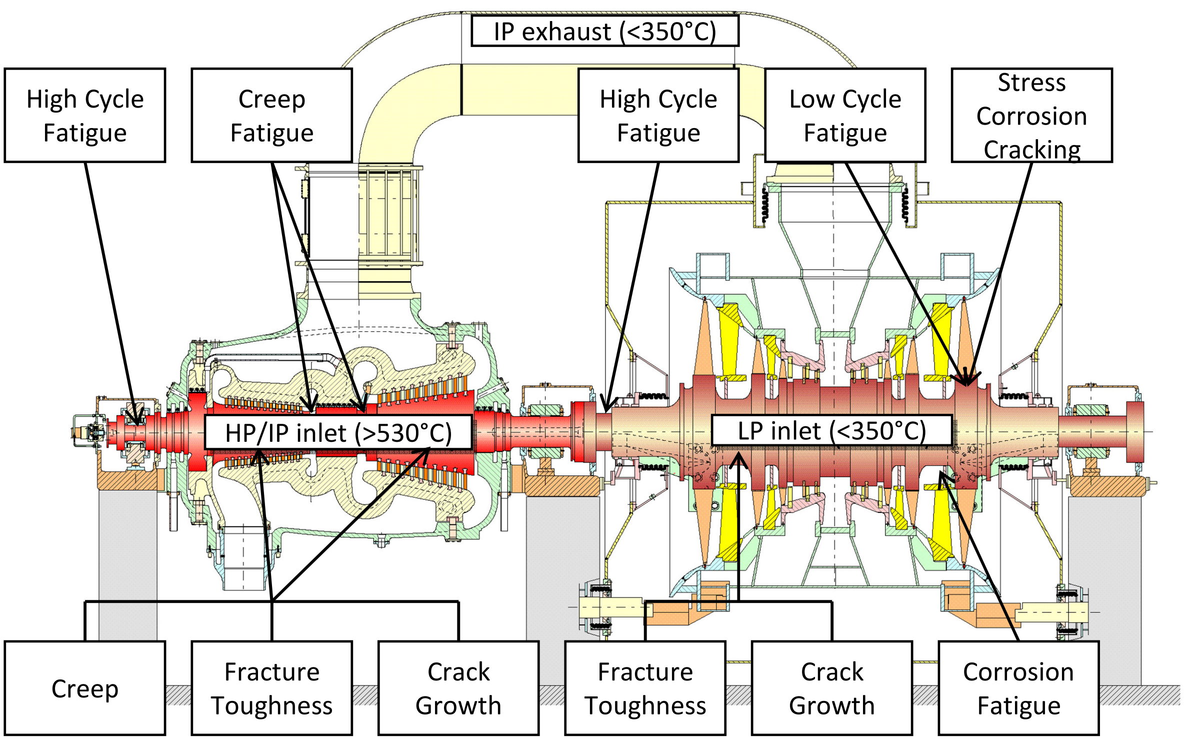

Figure 4: **Potential** damage mechanism**s** and steam temperatures for a 300MW steam turbine

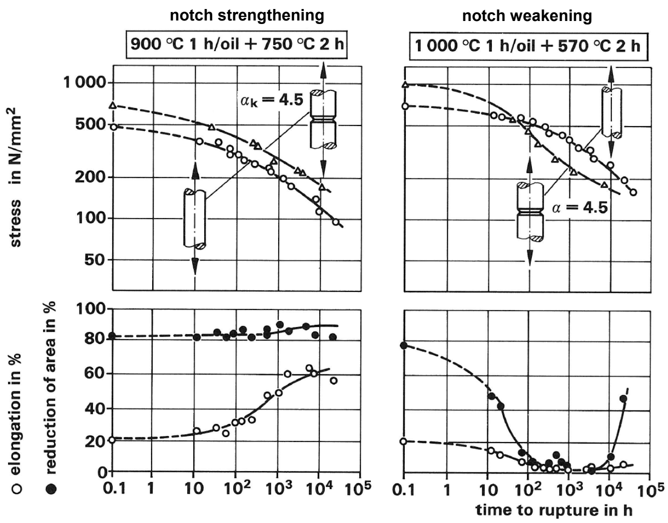

Figure 5: Creep rupture behavior of 1%CrMoV Steel at 550°C for two different heat treatments [13]

Figure 5 shows test results from notched specimens, which serve as an example for such component-like tests. Since the very beginning of long-term testing in Germany, notched tensile and creep specimen have always been included in material test programs to simulate threaded connections, other geometrical notches or manufacturing defects at elevated temperatures. In addition to providing adequate creep rupture strength, the prevention of notch weakening is one of the most important measures for assuring operational safety. Only then is stress redistribution possible without leading to early crack formation at locally highly-stressed locations.

As shown in Figure 5, creep testing of notched specimen can be used to indentify notch weakening effects and thus allows the prevention of early crack formation at locally highly-stressed locations by ensuring the ductility necessary to redistribute stresses.

For a safe design, different strength and toughness criteria have to be applied to ensure the safe operation of the turbo-set during its designed life time. Transfer of the test results to the actual components is made by models and rules based on standards such as those mentioned in Table 1, whereas special aspects are investigated in R&D projects and are brought into industrial practice.

The summary in Table 2 shows the different criteria which depend on the relevant damage mechanisms and on the loads as described in the previous chapter and which play a key role for the engineers.

Different kinds of analysis have to be made to ensure the reliable and safe operation of the components. Starting with the stress analysis, the fracture mechanic evaluation and the fatigue evaluation have to be performed. The respective material properties used are determined in the following material tests:

- Tensile: 0.2 yield strength YS, ultimate tensile strength UTS, elongation (considering notch weakening effects)
- Creep rupture: creep rupture strength Ru for a time t at temperature T, Ru/t/T (considering notch weakening effects)
- Creep elongation: creep elongation limit Rpε for a time t at temperature T, Rpε/t/T
- Fracture toughness: linear-elastic static fracture toughness KIC

Table 2: Summary of design criteria for steam turbines

Imposed load data	Material data	Limit values	Allowable values	Required Material Properties
	Stress evaluation			
σ_i	0.2YS, UTS, Elongation	0.2YS	$\sigma_i \leq$ 0.2YS /S	0.2YS / UTS /Elong. = f (T)
	Creep rupture strength	0.8*Ru/t/T	$\sigma_i \leq$ Ru/t/T /S	Ru/t/T = f (T, t)
	Creep elongation limit	0.8*Rpε/t/T	$\sigma_i \leq$ Rpε/t/T /S	Rpε/t/T = f(T, t)
	Fracture mechanic evaluation (a_0 = start defect size)			
$\Delta\sigma_i$	- short term safety a_0, K_{IC}	a_{crit}	$a_0 \leq a_{crit,1}/S$	K_{IC} after long term exposure
$\Delta\varepsilon$	- long term safety			
	cyclic : a_0, da/dN	Δa_i	$a_0 + \Sigma\,\Delta a_i \leq a_{crit,2}/S$	da/dN = f (ΔK, T)
T_i	static : a_0, da/dt	Δa_i		at low stress rate
	Fatigue evaluation			Creep Crack initiation
N_i	- with defect (a_0)			t_A = f (K_{Iid})
	cyclic : da/dN = f (ΔK)	Nf_i	$\Sigma\, N_i/Nf_i + \Sigma\, t_i/tu_i \leq E_{allow}$	= f (C^*)
t_i	static : da/dt = f (K_{Iid})	(tu_i)		$\Delta\varepsilon$ = f (N, T)
	- without defect (with notch)			$R_{u/t/T}$, $R_{p\varepsilon/t/T}$ = f (t, T)
	cyclic : Nf_i = f ($\Delta\varepsilon$)	Nf_i		
	static : tu_i = f ($R_{u/t/T}$)	tu_i		

i: index for different service loading conditions

Table 3: Material data requirements for application in steam turbine design

Requirements	HP- & IP-Rotors	LP-Rotors, LP-Discs	HP- & IP-Casings	HP- & IP-Blades	LP-Blades	HP- & IP-Bolts
Static strength:						
tensile strength	●	●	●	●	●	●
Creep Rupture Strength:						
creep behaviour	●		●	●		●
Toughness:						
fracture toughness	●	●	●	●	●	●
Fatigue properties:						
Low cycle fatigue (LCF)	●	●	●	●	●	●
High cycle fatigue (HCF)	●	●		●	●	
Crack growth:						
static - Creep CG	●		●			●
alternating - Fatigue CG	●	●	●			●
Corrosion						
local corrosion		●		●	●	●
stress corrosion cracking		●			●	●
corrosion fatigue		●			●	
Erosion behaviour	●	●	●	●	●	
Oxidation behaviour	●		●	●		●

HP = High Pressure turbine IP = Intermedium Pressure turbine LP = Low Pressure turbine

- Fatigue crack growth: amplitude of stress intensity ΔK, crack growth rate da/dN
- Creep crack growth: stress intensity factor K, crack growth rate da/dt
- Creep crack initiation: stress intensity for static crack initiation KIid and energy integral C*
- Low cycle fatigue: amplitude of strain $\Delta\varepsilon$, cycles to failure N_{fi} (considering hold time effects)

The initial crack sizes a_0 have to be determined by appropriate non-destructive testing during quality assurance in the material procurement process.

Today creep behavior is one of the most critical properties in application because design life is increasing from 100,000 h to 200,000 h operation time due to customer requests. Long-term testing has to be performed, and accurate extrapolation methods have to be developed and validated.

During the last few decades, new high temperature creep resistant steels have been developed and successfully introduced to the market. The criterion of success in all of these developments for new 9-12CrMoV steels was set as an improved creep rupture strength tested by conventional creep specimens. The other properties determined in standard tests are accepted if they are not worse than for1CrMoV steels.

Compared to the conventional 1Cr steel, a 50-70 Kelvin increase in application temperature is possible without any significant design changes. This is because 9-10Cr steels reach the same 100,000h creep rupture strength as 1Cr steels, but at 50-70K higher temperatures. For extrapolation to a relevant design life of at least 100,000h it is necessary to perform long-term tests in the laboratory. So far in Europe these have reached up to 100,000h for different melts from real components [14]. This is of high importance for the reliability of the extrapolation.

The advantageous creep behavior of the new steels enables the design of high temperature turbo-sets with the same design rules as for conventional machines.

Material Application

Material properties and turbine design are closely connected. In order to design economical steam turbine components thorough material knowledge is essential.

A good example for this close connection is the combined IP/LP turbine, which consists of a welded design. Two single monoblock forgings with different material properties are welded to meet the special design requirements. The 3.5NiCrMoV Low Pressure rotor material used combines high strength at the last stage blade roots with exceptionally good ductility in the rotor axis. The 1Cr Intermediate Pressure part is a material with well-known characteristics and a lot of service experience. The advantages of this concept are the use of fully optimized materials, a cost effective design solution and an increased supplier base. The wide experience of Siemens-Westinghouse was integrated in the manufacturing route and is a well established process today.

The design features are summarized in Table 4, showing the current activities in transferring the welded rotor concept to further turbine components on the basis of excellent experiences from the IP-LP welded design.

The high quality of components is ensured via the qualification of appropriate suppliers in close cooperation with the turbine manufacturer. Intensive partnerships are encouraged and discussions held about the given requirements to explain the technical background. Continuous monitoring processes are

Table 4: Main turbine rotor design characteristics and material properties

	HP	IP	LP	Combined HP-IP	Combined IP-LP
max. steam inlet temperature / C	565/600	565/620	350	565/565	565/350
rotor type - monoblock - welded construction	 • 	 • (•)	 • (•)	 • (•)	 • •
number of flows - single flow - double flow	 • 	 • •	 •	 • - • 	 • - •
creep properties	+	+	---	+	+
fracture toughness	+	+	+	+	+
materials	**1Cr, 10Cr**	**1Cr, 10Cr 2Cr-10Cr**	**3.5Ni CrMoV**	**2Cr 2Cr-10Cr**	**2Cr 1Cr/2Cr-3.5NiCr**

installed at the supplier, and the supplied raw parts are inspected by the supplier and / or the turbine manufacturer. Only if a closed loop of quality assurance actions is secured, enabling direct feed-back through lessons learned, can the required high quality be ensured. For that, a quality system has been introduced to the global Siemens network and the supplier base.

ASSESSMENT METHODS

Assessment methods are the central part of each design philosophy as they interlink material data, component geometry and operational loads. Separate methodologies are used for the different failure mechanisms which could occur if a steam turbine is not safely designed. The major ones are

- ductile failure
- creep failure
- fatigue (both low cycle and high cycle fatigue)
- interaction of creep and fatigue
- brittle failure of defective structures

In addition, further failure mechanisms such as oxidation, stress crack corrosion and thermal ratcheting must not be neglected in steam turbine design. In order not to go beyond the scope of this paper, these mechanisms will not be dealt with in detail.

Ductile failure is probably the best known and most comprehensively investigated failure mechanism in the history of mechanical engineering. Assessment methods are widely available in codes and standards which usually distinguish between design by formula (DbF) and design by analysis (DbA) approaches. The latter are used in the steam turbine design philosophy as they are superior for complex geometries. Depending on the component there are two options:

- Calculation of a characteristic stress for a cross section and comparison with the yield strength
- A limit load calculation assessing the ratio of applied load to plastic collapse load.

With the increases of steam temperature over the past decades creep assessment procedures have become an important part of steam turbine design. They fulfill two purposes: the first being to rule out creep fracture and the second to rule out inadmissible deformations. Three dimensional inelastic finite element calculations are done which use temperature dependent creep models. Depending on the material, different creep models can be used which model either primary and secondary creep or primary, secondary and tertiary creep.

Different methods are available to interpret the results. These are either stress based or strain based. Strain based concepts have the advantage that strain is an accumulating quantity which automatically accounts for stress relaxation effects.

As steam turbines are subject to thermal cycles which locally cause yielding a fatigue assessment is necessary. The steps of assessment are:

- Classification of load cases
- Determination of a stress and/or strain range for each cycle
- Calculate the number of cycles to crack initiation N_i using fatigue strength curves
- Calculation of fatigue damage D_f:

$$D_f = \sum_i \frac{n_i}{N_i} \tag{1}$$

  where n_i is the number of cycles for each cycle type
- Check that D_f is below an admissible limit.

A lot of publications are available on low cycle fatigue. Effects such as cyclic hardening or softening and a mean stress influence can be implemented in the procedure described above.

For areas which are subject to both significant creep and fatigue, the creep-fatigue interaction needs to be considered. Different rules for damage accumulation are available, but in order to not go beyond the scope of this paper, only the easiest one is described, which is linear:

$$D = D_f + D_c \qquad (2)$$

where D is the total damage and D_c the creep damage. The creep damage can be calculated using either a time fraction rule

$$D_c = \sum_i \frac{t_i}{t_u} \qquad (3)$$

or a strain fraction rule

$$D_c = \sum_i \frac{\varepsilon_{cr,i}}{\varepsilon_{cr,u}} \qquad (4)$$

where t_i is the total time of load case i within the creep range, t_u is the time to fracture for this load case, $\varepsilon_{cr,i}$ is the creep strain accumulated in load case i and $\varepsilon_{cr,i}$ is the creep strain which causes failure. After calculating the damage it is necessary to check that it is below an admissible limit.

Because the large components necessary for steam turbines cannot be manufactured flawlessly, fracture mechanics are used. In steam turbines flaws can cause failure by growing either due to cyclic loads or due to creep effects. Thus both cyclic fracture mechanic approaches and creep fracture mechanic approaches are used. The basic procedure is to:

- Identify Load cases
- Identify an initial flaw size
- Calculate the time or number of cycles to crack initiation
- Calculate the crack growth after the crack has initiated
- Check if the grown crack is smaller than the maximum allowable crack.

RESEARCH

Research projects are done to investigate new materials, failure mechanisms and to derive new, advanced assessment procedures. As the design philosophy is exclusively for steam turbines, the projects can focus on the requirements of steam turbines, such as component size and typical load cases. This allows the concepts to have smaller scatter bands than general design procedures and thus enables the manufacturer to create a better design with an optimized material usage.

For sustainable results this research needs to be a continuous process. This is especially important when failure mechanisms related to creep are investigated, as a single creep test can take more than 20 years.

Good examples for continuous research such as this are the 9-12%Cr steels introduced over the last decades. In Germany, the application of these new steels to real turbine components is accompanied by extensive research, with industry partnering up with academic institutions to compare the service relevant behavior with that of the low alloyed steels currently used. An overview of the main activities is given in Figure 7. It shows that programs have been run or are still ongoing to check:

- the influence of component size and technical ranges for the chemical analysis on long term creep strength [14]
- the influence of the homogeneity of power plant

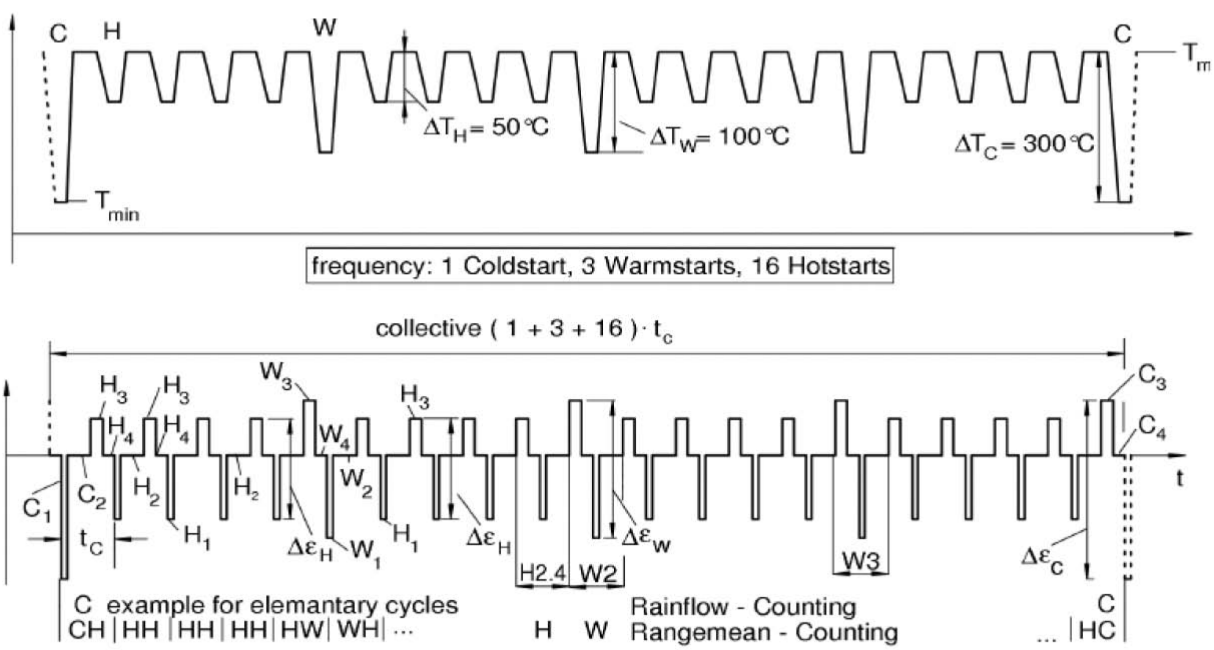

Figure 6: characteristic cyclic profile for steam turbines used in research projects

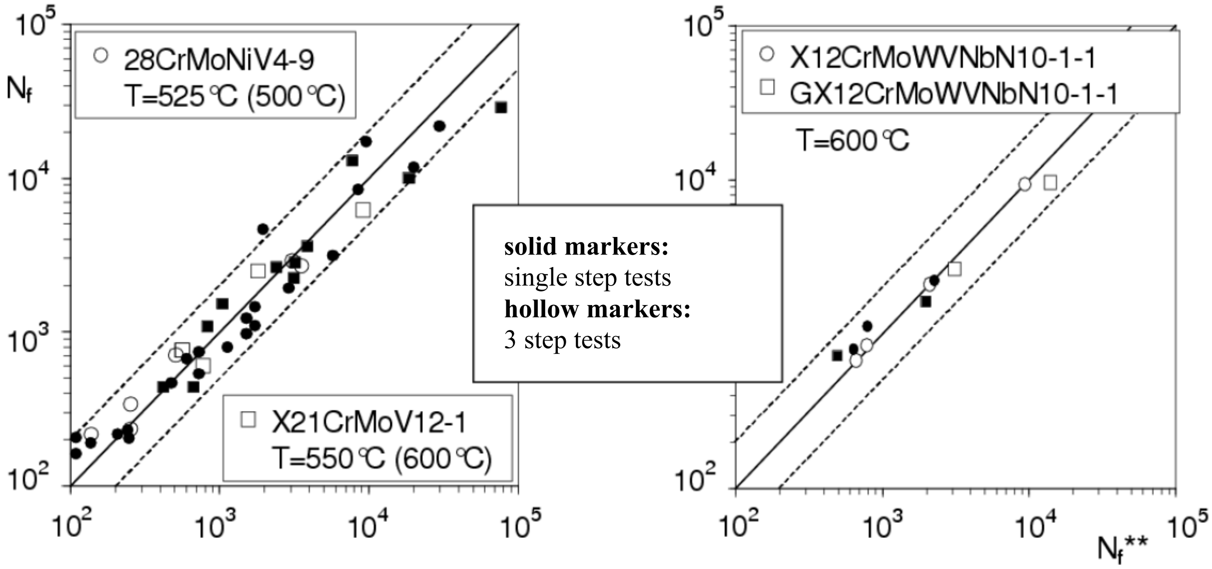

Figure 8: comparison of predicted cycles to crack initiation with tests for different materials. N_f is the number of cycles to crack initiation measured in long term creep-fatigue tests, N_f is the number of cycles predicted for these tests using the developed procedure [21]-[25]**

components on 100,000h creep strength to ensure a safe life time prediction [14]

- creep rupture strength and low cycle fatigue behavior under service-relevant load changing conditions [15], [16]
- high-temperature crack growth behavior to enable performance of fracture mechanics [17]
- the influence of multiaxiality on material behavior [18]

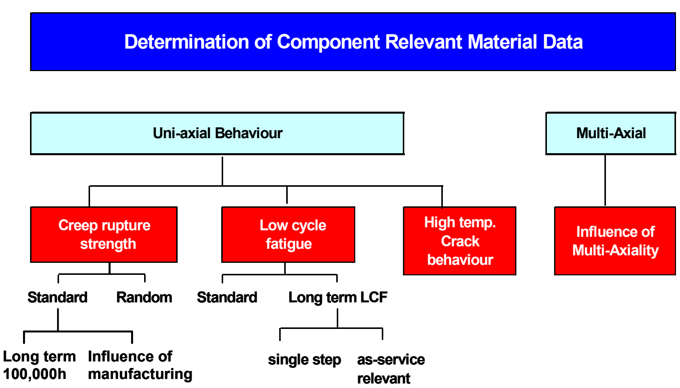

Figure 7: R&D activities for qualification of steels in Europe

The main outcomes are material data, quality improvements, design concepts, and life fraction rules for the further optimization of the design and operation of turbo sets.

In addition, life time evaluation during service, with continuously changed loading conditions, is significantly improved [19], [20].

Figure 6 shows a service relevant load profile used in research projects on creep fatigue. Based on these component-like tests and standard tests a creep-fatigue assessment procedure is under development at the University of Darmstadt in cooperation with industry partners [21]-[25].

By now the assessment procedure is based on a large number of tests for different materials and allows an accurate prediction of component life. Continuous research allows extension of the procedure to different materials, cycle types, non-isothermal cycles, different hold times and different strain rates. The software is able to calculate the stress strain hysteresis for cycles containing up to four hold times at different temperatures within the creep regime.

Figure 8 uses a scatterband to show the quality of the developed procedure for different materials comparing predicted and measured values.

FLEET EXPERIENCE

As mentioned above great efforts are made to make a product safe and reliable. However, all these tests need to be simplified with respect to operating time or component size, i.e. full scale tests are typically not possible. Thus fleet experiences are included by Siemens for continuous improvement of design processes, material data evaluation, quality processes and monitoring of non-steady-state conditions.

An HP inlet section serves as an example for the continuous improvement process which is utilized to verify the whole design process.

The stress relief groove shown in Figure 9 is a typical location for material damage caused by low-cycle fatigue and creep-fatigue interaction. The initial rotor contour was designed about 30 years ago and experienced rotor cracking in service. Since then numerical methods, material data availability and evaluation methodologies have developed dramatically. In this case the life expectancy was drastically increased by improved component contouring.

Even more important for the design concepts which are developed nowadays is the opportunity to benchmark and continuously improve these concepts and the whole design process.

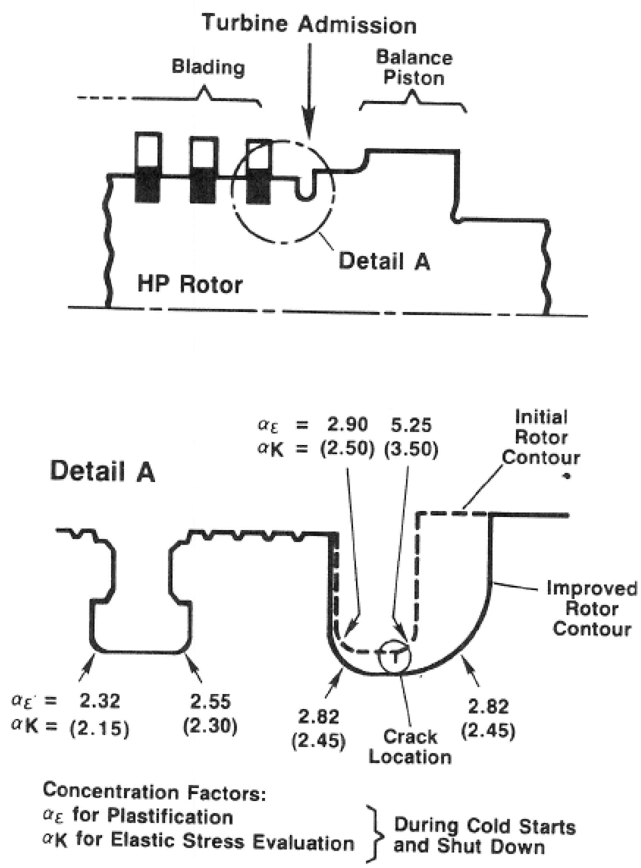

Figure 9: Example of an improved detail design

In this case material data for aged components was gathered and the evaluation of creep and creep-fatigue interaction, and the monitoring concept of the component were checked and compared with the current design process.

So in the end fleet experience is utilized to close the gap between theoretical evaluations, component sizes and the shortcomings of material testing due to unavoidable limitations of testing times.

SUMMARY

The paper gives an overview of a currently used comprehensive design philosophy for steam turbines. It follows the structures of internationally recognized standards, but is tailor-made for steam turbine components. Load cases and assessment procedures are described. An important characteristic of the concept is that it is constantly evolving. Material tests are used to increase the design data database, research projects are used to investigate failure mechanism and to derive new, advanced assessment procedures. Service experience and monitoring during operation allow the methodologies used to be verified and improved. As an example for such an improvement the HP inlet section design is described, which was changed due to service experiences and the availability of improved numerical methods. The result of all these activities is a design concept which allows designing for high thermal efficiencies, high operating flexibility and safe operation.

REFERENCES

[1] "World Energy Outlook 2008", International Energy Agency, Paris, 2008

[2] Deutsches Institut für Normung, 2010. "DIN EN 12952: Water-Tube Boilers and Auxiliary Installations", Beuth Verlag, Berlin

[3] Deutscher Dampfkessel Ausschuss, 1997. "Technical Rules for Steam Boilers" Carl Heymanns Verlag, Cologne

[4] "ASME Boiler and Pressure Vessel Code", The American Society of Mechanical Engineers, New York, 2007

[5] Deutsches Institut für Normung, 2010. "DIN EN 13445: Unfired Pressure Vessels", Beuth Verlag, Berlin

[6] Arbeitsgemeinschaft Druckbehälter, 2008. "AD2000 Merkblätter" Verband der TÜV e.V., Berlin

[7] "ASME B31.1 - 2004 Power Piping", The American Society of Mechanical Engineers, New York, 2004

[8] Deutsches Institut für Normung, 2008. "DIN EN 13480: Metallic Industrial Piping", Beuth Verlag, Berlin

[9] "An Assessment Procedure for the High Temperature Response of Structures", Assessment procedure R5, Issue 3, British Energy Generation Ltd, 2003

[10] "Assessment of the Integrity of Structures Containing Defects", R6 Revision 4, British Energy Generation Ltd, January 2009

[11] "Analytical Strength Assessment", Forschungskuratorium Maschinenbau (FKM), 5th edition, 2003

[12] "Fracture Mechanics Proof of Strength for Engineering Components", Forschungskuratorium Maschinenbau (FKM), 2nd edition, 2009

[13] Muhle, E-E and Ewald, J, 'High-Reliability Steam Turbine Components - Materials and Strength Calculation Aspects', High Temperature Materials for Powder Engineering 1990. I; Liege; Belgium; 24-27 Sept. 1990. pp. 251-280. 1990

[14] Mayer K H and Blum R, Hillenbrand P, Kern T-U, Staubli M, 'Development steps of new steels for advanced steam power plants', 7th int conf Materials for Advanced Power Engineering, Liege, Belgium, 2002

[15] Schwienheer M and Haase H, Scholz A, Berger C, 'Long term creep and creep-fatigue properties of the martensitic steels of type (G)X12CrMoWVNbN10-1-1', 7th int conf Materials for Advanced Power Engineering, Liege, Belgium, 2002.

[16] Berger C and Schwienheer M, Scholz A, 'Creep and fatigue properties of turbine steels for application temperatures up to 625°C', 8th int conf Materials for Advanced Power Engineering, Liege, Belgium, 2006.

[17] Mueller F and Scholz A, Berger C, 'Crack behavior of 10Cr steels under creep and creep-fatigue conditions', int conf ECCC Creep and Fracture in High Temperature Components- Design and Life Assessment, London, UK, 2005.

[18] Ringel M and Roos E, Maile K, Klenk A, 'Constitutive equations of adapted complexity for high temperature loading', int conf ECCC Creep and Fracture in High Temperature Components- Design and Life Assessment, London, UK, 2005.

[19] Bagaviev A, 'Steam turbine component integrity analysis based on high temperature fracture mechanics', int conf ECCC Creep and Fracture in High Temperature Components- Design and Life Assessment, London, UK, 2005.

[20] Bagaviev A and Sheng S, 'Industrial application of creep/fatigue crack initiation and growth procedures for remaining life analysis of steam turbine components', int conf ECCC Creep and Fracture in High Temperature Components- Design and Life Assessment, London, UK, 2005.

[21] Granacher, J., Scholz, A. and C. Berger: Creep Fatigue Behaviour of Heat Resistant Turbine Rotor Steels Under Service-Type Strain Cycling, Proc., Ed. by the Institute of Materials, London, 1997, pp. 592–602.

[22] Haase, H., A. Scholz and C. Berger: Simulation of multi-stage creep-fatigue behaviour, Proc. of the Eighth Int. Fatigue Congress, A. F. Blom (ed.), Vol. 5/5, Stockholm, 2002, pp. 3133/40

[23] Kloos, K.H., Granacher, J. und A. Scholz: Mehrstufige betriebsähnliche Dehnwechselbeanspruchung warmfester Stähle, Mat-wiss. u. Werkstofftech., Vol. 27, 1996, pp.331–337

[24] Kloos, K.H., J. Granacher und A. Scholz: Langzeitverhalten einiger warmfester Stähle unter betriebsähnlicher Kriechermüdungsbeanspruchung, Mat.-wiss. u. Werkstofftechn. 24 (1993) S. 409/17

[25] Schwienheer, M., A. Scholz, H. Haase und C. Berger: Influence of hold times and notches on life time under service-type creep-fatigue loading, Int. Conf. on Low Cycle Fatigue, Eds. Portella, Sehitoglu, Hatanaka, Berlin (2003) S. 245-250