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Appears since 1960

Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Probabilistic approach to lifetime assessment of steam turbines

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Abstract

The paper presents a probabilistic method of computational estimation of steam turbine life. The need for the use of probabilistic analysis results from the inherent uncertainty in estimating lifetime expenditure due to creep and thermal fatigue. As a starting point for analysis, a deterministic method of lifetime consumption calculation of steam turbines critical components was presented, and main sources of uncertainty present in this approach were discussed. Then, a mathematical model proposed for probabilistic calculations was described in detail. As an example of probabilistic approach, an analysis of failure probability of a 200 MW steam turbine HP stop valve resulting from the scatter of material data was given. Numerical simulations were performed using a computer code developed by ALSTOM Power.

Keywords: Steam turbines; Steam turbines lifetime; Probabilistic analysis

Nomenclature

F – cumulative distribution function,
n – number of cycles, -,
N – permissible number of cycles, -,
P – probability, %,
R – strength, MPa,
T – temperature, °C
t – time, h,
x – random variable,
z – lifetime expenditure, -,
ε – strain, -,
σ – standard deviation, -,

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Subscripts

B – creep,
N – low-cycle fatigue,

1 Introduction

Steam turbine components operating at high and highly variable temperatures are exposed to degradation due to creep and thermal fatigue processes [1]. Their lifetime is limited already at the design stage and results from creep and fatigue characteristics of the material used. The operational wear brings about the loss of lifetime and decrease of reliability of turbine components, which manifests itself by their increased failure frequency and lower availability.

The problems of lifetime and reliability are essential not only from the viewpoint of avoiding premature failure of a component before its design life expiration, but also from the point of view of extending the service life of power plant equipment beyond its design life [2]. The lifetime extension is driven by economics, but nevertheless must always be technically sound to ensure safe operation of turbosets.

The basis for any efforts aiming at extending the service life of power turbosets is the assessment of the current degree of damage of their components, including the main components of steam turbines. Such assessments are done with the use of metallographic tests and theoretical analyses, which are the necessary elements of complex assessment of material state. Theoretical analyses resolve themselves into determining the so-called lifetime fractions and are based on deterministic models, in spite of large scatter and uncertainty of operating and material data used for the calculations. It means that the lifetime assessment done with this method is not definitive and therefore requires complementing by a probabilistic analysis.

The purpose of this paper is to present a method of introducing the probabilistic analysis to theoretical analyses of steam turbines lifetime. As an illustration, lifetime calculations of main stop valves, performed both with deterministic and probabilistic methods, are presented.

2 Deterministic method of lifetime assessment

Once the design lifetime of a turbine has expired, the question arises whether it can be safely operated, and if so, for how long and with which conditions? These questions can be answered after analysing the history of the turbine operation and assessing the lifetime expenditure, since the state of material of individual components after 100,000 operating hours depends, first of all, on the manner of operation. For this sake it is necessary to perform strength analyses for the turbine main components, resulting in theoretical (computational) damage of material. Estimation of the degree of damage on the basis of operating time only is insufficient since it does not account for fatigue damage depending on the number of start-ups from various initial thermal conditions.

Three types of information are required for remaining lifetime assessment of a turbine component [3]:

- current degree of damage,
- damage accumulation rate,
- degree of damage causing failure.

The current degree of damage (lifetime consumption) of steam turbines components is determined on the basis of operating data and mathematical model assumed, describing the process of creep and fatigue damage accumulation. Theoretical damage due to creep and thermal fatigue is determined with the help of the lifetime fractions summation method. In steam turbine practice, a linear model of damage in the form of linear rule of damage summation is generally used. This rule states that total damage is the sum of creep and LCF damage, and can be written as follows [4]:

$$Z = Z_B + Z_N, \tag{1}$$

where Z_B denotes creep damage, and Z_N – fatigue damage.

The magnitude of total creep damage Z_B depends on the duration time t of load at a given temperature, and on the magnitude of damage $1/t_B$ in unit time, where t_B is time to rupture. Its value is derived from the minimum creep curve. According to the linear rule of creep damage accumulation (Robinson's hypothesis), a summation is performed proportionally to the load duration time. For a set of stresses and temperatures at steady-state operation, the creep damage can be calculated from the following formula [4]:

$$Z_B = \sum_{i=1}^{r} \frac{t_i}{t_{Bi}}, \tag{2}$$

where r stands for the number of stress and temperature levels.

The magnitude of total LCF damage Z_N depends on the number of load cycles n and the magnitude of damage $1/N$ in each load cycle, where N is the number of cycles to crack initiation. Its value is derived from the minimum LCF curve. According to the linear rule of fatigue damage accumulation (Palmgren's-Miners' hypothesis), a summation is performed proportionally to the number of

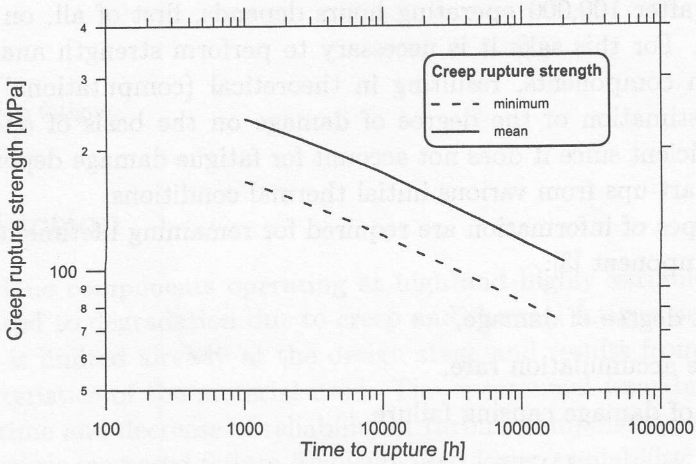


Figure 1. Creep rupture strength of Cr-Mo-V cast steel.

cycles. For a stress spectrum, which in real turbine operation conditions consists of start-ups from cold, warm and hot states, as well as load changes, the fatigue damage is calculated from the following formula [4]:

$$Z_N = \sum_{i=1}^{q} \frac{n_i}{N_i}, \tag{3}$$

where q denotes the number of stress levels.

Theoretically, the computational lifetime is exhausted when the total damage Z reaches 1. Such a critical value, i.e. the value of exhaustion causing failure, is assumed for fatigue cycles and it denotes crack appearance. Further operation from the instant of crack initiation to the instant of total rupture is not permitted. In case of creep damage, the moment that microcracks appear coincides with the onset of tertiary creep, which is reached after 75% of the time to rupture t_B. Due to this, for steam turbine components where creep and fatigue processes occur in parallel, the critical value of 0.75 is assumed [1, 4]. Once this critical value D is reached, one may expect a failure possibility since there is no further safety margin (turbine is operated with gradually increasing risk of failure). The end of theoretical service life is a warning signal indicating the necessity of initiating a systematic test programme and applying extended supervision of the operated component.

3 Sources of uncertainty in deterministic approach

Many years' experience of numerous laboratories shows that the scatter of properties for most high-temperature creep resisting steels is in the range of $\pm 20\%$ of mean values of creep rupture strength and creep limit. The corresponding scatter in time reaches several hundred percent [5]. This approximate character of experimental data and resulting limitations in full use of extrapolated values result from:

- heterogeneity of the material and differentiation in chemical composition, structure and heat treatment of the same materials at different melts,
- errors in creep tests (control and measurement of temperature and stress),
- differentiation in operating conditions and the influence of environment as compared to laboratory parameters,
- existence of physical variation of phenomena occurring in short-term tests and during service,
- impact of technological and design factors on the material lifetime.

For example, creep tests are done in air at elevated temperature where oxidation effects adversely affect the strength of steels. In actual conditions, the oxidation effect with reference to a large section of rotor, for example, may be negligible [2]. Typical examples of scatterband of creep rupture strength for cast steel used for casings is shown in Fig. 1.

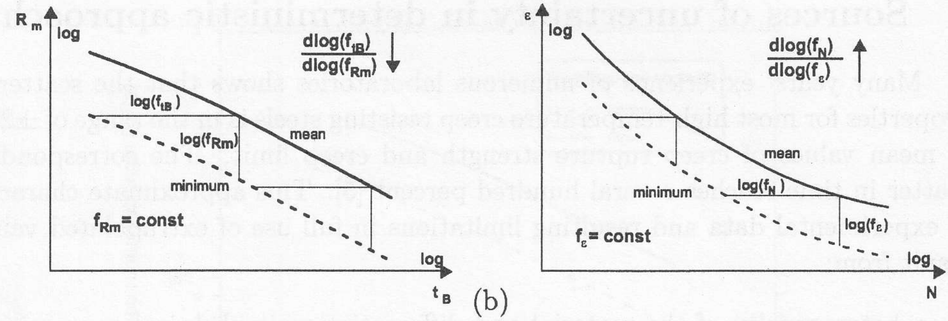
A similar trend is observed in fatigue characteristics of turbine steels. Typical scatterband of total strain amplitude in low-cycle fatigue is on the level of $\pm 10\%$ of strain mean value.

The above factors make the lifetime assessment, based on deterministic model and minimum strength properties, very conservative.

An additional factor introducing uncertainty into the deterministic model is the averaging of operating conditions. The lifetime studies are performed for typical start-ups from a cold, warm and hot state, prepared from an extensive operating data provided by the turbine user. An example of the analysis taking into account the scatter of operating parameters in determining stresses in 200 MW turbine stop valves is presented in reference [6].

4 Probabilistic method of lifetime assessment [7]

The probabilistic methodology of lifetime assessment is based on laboratory testing where the scatter of creep and fatigue properties of turbine steels can be described by log-normal distribution. Based on the data contained in the



(a) (b)

Figure 2. Determination of standard deviation for time to rupture (a) and number of cycles to crack initiation (b).

material database developed by ALSTOM Power Baden, it can be assumed that minimum and mean values of creep rupture strength R_m and strain amplitude ε_a are related by a constant factor f_{Rm} and f_ε. (see Fig. 2a and 2b).

The adequate relationships are as follows:

$$R_m\left(P=50\%\right)=f_{Rm}R_m\left(P=p_{\min}\right), \tag{4}$$

$$\varepsilon\left(P=50\%\right)=f_\varepsilon\varepsilon\left(P=p_{\min}\right). \tag{5}$$

In order to determine the unknown factors f_{tB}, f_N one can write on the basis of geometrical relations from creep and fatigue curves:

$$\frac{d\log\left(R_m\right)}{d\log\left(t_B\right)}=-\frac{\log\left(f_{Rm}\right)}{\log\left(f_{tB}\right)}, \tag{6}$$

$$\frac{d\log\left(\varepsilon\right)}{d\log\left(N\right)}=-\frac{\log\left(f_\varepsilon\right)}{\log\left(f_N\right)}, \tag{7}$$

and after transformations, one obtains a formula for time to rupture factor f_{tB}

$$f_{tB}=10^{-\frac{d\log t_B}{d\log R_m}\log f_{Rm}}, \tag{8}$$

and factor f_N for the number of cycles to crack initiation

$$f_N=10^{-\frac{d\log N}{d\log\varepsilon}\log f_\varepsilon}. \tag{9}$$

In the above relationships, the factors describing creep rupture strength and strain amplitude, as well as the slopes of creep and fatigue curves, are known from creep and fatigue characteristics and their scatter.

Since

$$\log t_B\left(P=50\%\right)=\log t_B\left(P=p_{\min}\right)+\log f_{tB}, \tag{10}$$

$$\log N\left(P=50\%\right)=\log N\left(P=p_{\min}\right)+\log f_{N}, \tag{11}$$

then

$$t_{B}\left(P=50\%\right)=f_{tB}t_{B}\left(P=p_{\min}\right), \tag{12}$$

$$N\left(P=50\%\right)=f_{N}N\left(P=p_{\min}\right). \tag{13}$$

On this basis one can calculate standard deviation for the time to rupture

$$\sigma_{tB}=\frac{\log\left(\dfrac{t_{B}\left(P=50\%\right)}{t_{B}\left(P=p_{\min}\right)}\right)}{x\left(F\left(x\right)=p_{\min}\right)}, \tag{14}$$

and standard deviation for the number of cycles to crack initiation

$$\sigma_{N}=\frac{\log\left(\dfrac{N\left(P=50\%\right)}{N\left(P=p_{\min}\right)}\right)}{x\left(F(x)=p_{\min}\right)}. \tag{15}$$

In formulae (14) and (15) x is a value of the random variable X, for which the cumulative distribution function F of standardised normal distribution [8] is equal to minimum value of probability $p_{\min}$.

Having the standard deviation one can easily calculate values of time to rupture and number of cycles to crack initiation for any value of probability p, using the following formulae:

$$\log\left(\frac{t_{B}\left(P=p\right)}{t_{B}\left(P=50\%\right)}\right)=-x\left(F\left(x\right)=p\right)\sigma_{tB}, \tag{16}$$

$$\log\left(\frac{N\left(P=p\right)}{N\left(P=50\%\right)}\right)=-x\left(F\left(x\right)=p\right)\sigma_{N}. \tag{17}$$

According to the linear rule of damage accumulation used in deterministic approach, it can be written:

$$Z=\frac{t}{t_{B}\left(P=p_{\min}\right)}+\frac{n}{N\left(P=p_{\min}\right)}. \tag{18}$$

For a failure probability P the degree of damage $Z=1$, which can be written as:

$$Z\left(P\right)=\frac{t}{t_{B}\left(P=p\right)}+\frac{n}{N\left(P=p\right)}=1. \tag{19}$$

Taking into account the fact that for fatigue damage the permissible limit D_N is different than the limit D_B for creep damage, equation (19) can be rewritten as follows:

$$Z\left(P\right)=\frac{1}{D_{B}}\cdot\frac{t}{t_{B}\left(P=p\right)}+\frac{1}{D_{N}}\cdot\frac{n}{N\left(P=p\right)}=1. \tag{20}$$

For a given operation time t_{op} the number of start-ups n_{op} is known, which allows to express the time to failure as:

$$t\left(\frac{1}{D_B t_B\left(P=p\right)}+\left(\frac{n_{op}}{t_{op}}\right)\cdot\frac{1}{D_N N\left(P=p\right)}\right)=1. \tag{21}$$

Taking into consideration that

$$Z_B=\frac{t_{op}}{t_B\left(P=p_{\min}\right)}, \tag{22}$$

$$Z_N=\frac{n_{op}}{N\left(P=p_{\min}\right)}, \tag{23}$$

and distinguishing cold, warm and hot cycles, the following formula is obtained

$$t=\frac{t_B\left(P=p_{\min}\right)}{\left[\dfrac{t_B\left(P=p_{\min}\right)}{t_B\left(P=p\right)}\cdot\dfrac{1}{D_B}+\sum\limits_{i=Z,C,G}\left(\dfrac{Z_{N,i}}{Z_t}\cdot\dfrac{N\left(P=p_{\min}\right)}{N\left(P=p\right)}\cdot\dfrac{1}{D_N}\right)\right]}. \tag{24}$$

The above formula describes the operation time t required to reach the failure probability p. Failure denotes here initiation of fatigue cracks or beginning of tertiary creep.

5 Computational example

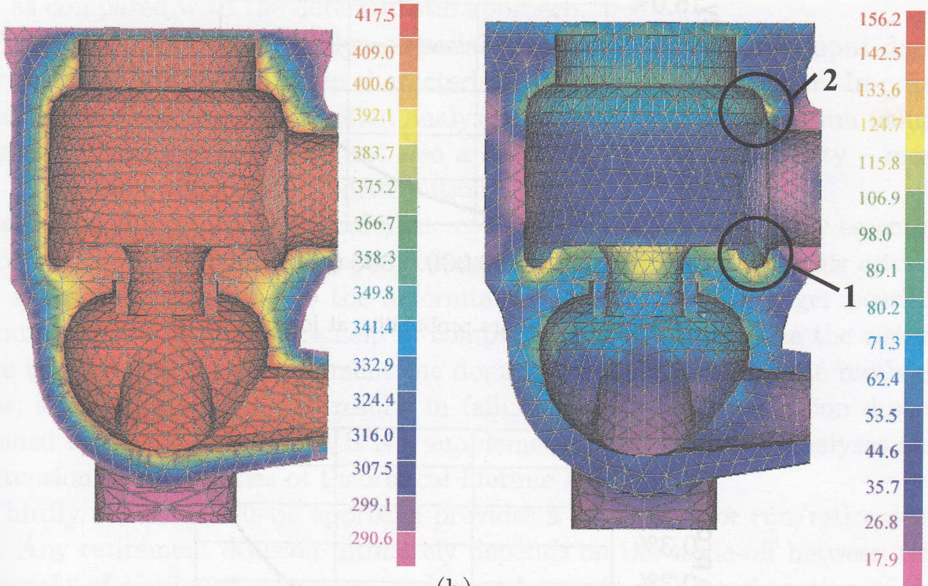
The methodology described above of applying the theory of probability in lifetime studies was applied to an 200 MW turbine HP stop valve manufactured by ALSTOM Power Elblag. The valve is highly loaded with thermal and mechanical stresses, since it is operated at 535°C and 13 MPa, and is therefore considered a critical turbine component.

For deterministic estimation of the degree of valve material damage, thermal and strength computations using finite element methods were carried out. As a result of these calculations, 3D temperature and stress distributions for various start-ups and in steady-state were obtained. On this basis, the most highly loaded locations were identified. Moreover, stresses and temperatures required for lifetime calculations were evaluated.

An example of temperature and stress distribution in the valve casing during start-up is shown in Fig.3, where also critical locations are marked.

For the lifetime calculations the following operating data were assumed:

- total operation time – 133 381 h,
- number of cold starts – 205,



(a) (b)

Figure 3. Temperature (a) and stress (b) distribution during stop valve heating.

- number of warm starts – 159,
- number of hot starts – 289.

The lifetime expenditure was calculated with the help of the method described in section 2, and for the operating data given above. The results of simulations are summarised in Tab. 1. On this basis, calculations of the probability of crack

Table 1. Lifetime expenditure of HP stop valve.

Location	Fatigue life expenditure Z_N [–]			Creep life expenditure Z_B [–]	Total life expenditure Z [–]
	Cold	Warm	Hot		
1	0.021	0.027	0.029	0.702	0.778
2	0.021	0.018	0.029	0.278	0.345

initiation in the valve casing were performed, using the methodology described in section 3. The results of calculations are presented in Figs. 4 and 5.

At location 1, the current degree of damage is equal to 0.778, which is greater than the critical value, and the failure probability is 0.1%, while at location 2 the failure probability corresponding to damage 0.345 is 0.0005%. In the former case

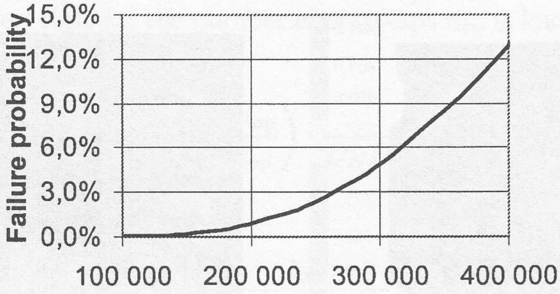


Figure 4. Failure probability at location 1.

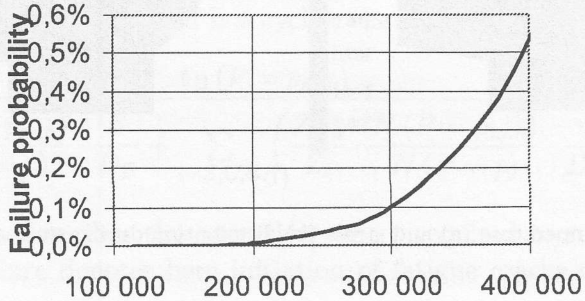


Figure 5. Failure probability at location 2.

it means that 1 out of 1000 valves in operation will fail, whereas in the latter case – 5 out of 1000000.

The examples given illustrate more and more intensive increase of failure probability of the valve. Assuming a certain critical level of failure risk, it is possible to determine a further allowable operation time with increasing probability of valve failure. It must always be remembered that failure is defined as fatigue crack initiation or the onset of tertiary creep, and not as total rupture. Growth of these cracks can be monitored with the help of both deterministic and probabilistic methods, as well.

6 Summary

The methodology of probabilistic assessment of steam turbine lifetime presented here has large practical importance since it is a complementary method to deterministic analyses, and can be employed for developing a practical tool for engineering simulations. The probabilistic approach possesses numerous advantages as compared with the deterministic approach.

Firstly, in probabilistic analyses special emphasis is laid on the input data, as for instance fatigue and creep characteristics discussed in the paper. In order to perform the lifetime consumption analysis not only mean or minimum values of a given quantity is required, but also a description of its uncertainty – most often in the form of probability distribution.

Secondly, the results of probabilistic computations are particularly essential for operation times with damage exceeding the critical value. Once this critical value is reached, according to the deterministic model, it is no longer possible to monitor operation with the help of computational methods since the risk of failure is unknown. At this moment the dominant role of probabilistic methods begins, since such an analysis results in failure probability distribution during continued operation. Therefore, it is a supplement to deterministic analyses and an extension of capabilities of theoretical lifetime studies.

Thirdly, the probabilistic approach provides a solid basis for run/retire decisions. Any retirement decision ultimately depends on the trade-off between risk and benefit of continued operation, and must be made with participation of the turbine manufacturer and operator.

The presented methodology possesses all the advantages listed above. It was used in a practical engineering tool and its usefulness illustrated with an example of practical application to a steam turbine component.

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