Residual life prediction of power steam turbine disk with fixed operating time

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KEYWORDS

Turbine disk, elastic-plastic stress analysis, mechanical properties, low-cycle fatigue, simulation models, residual life

ABSTRACT

This study is concerned with power steam turbine disk residual life assessment. Elastic-plastic stress analysis of turbine disk to determine stress distribution in the structure is performed under operation conditions. Both smooth and notched specimens cut out from the critical zones of turbine disk, with different operating time in service are tested under static, harmonic and program types of loading. The main mechanical properties changes and low-cycle fatigue and fracture resistance material properties of disk with fixed operation time were found.
Determined by fitting both numerical and experimental data equations for turbine disk residual life estimation were obtained. Residual fatigue life of turbine disk with fixed operating time based on stress-strain state date, static and low-cycle fatigue material properties in critical zones was calculated.
In accordance with imitation modeling principles fatigue tests of simulation models of disk with saving operation damages under fixed operation time were performed. As a result, residual fatigue life estimations of turbine disk simulation models were performed.

INTRODUCTION

At present time the power steam turbine elements at heat-power engineering enterprises have exhausted their life span or come nearer to their limiting values. Fatigue failures of rotating turbine disks were detected. The subject of our consideration is a disk of 20th stage of 185 MW power steam turbine with operation time t=103000 hours. Initiation of cracks in turbine disks has occurred in a blade and disk rivet attachment (Fig.1). Damage accumulation and growth for turbine disk took place on the inner surface of the disk mounting hole.

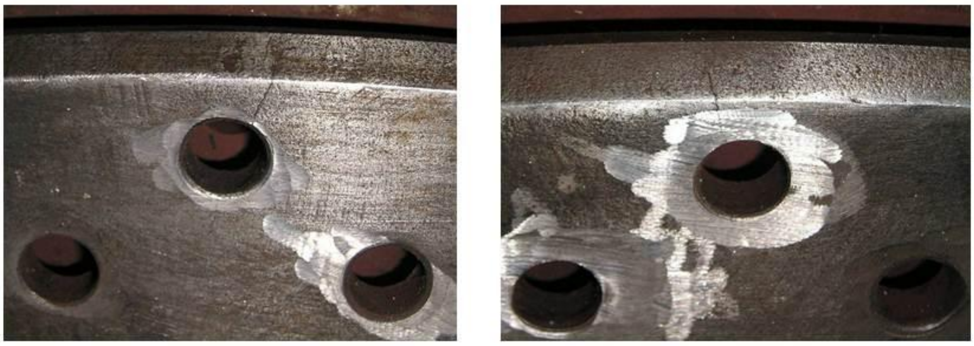


Fig. 1: Operation damage of the turbine disk

This study is concerned with residual fatigue life prediction for turbine disk with fixed operation time. Residual life prediction for turbine disk involves numerical stress analysis in real structures in order to determine stress distribution at critical zones, determination of fracture resistance properties of the disk material and testing simulation models under loading equivalent to operation conditions.
In this study fatigue life estimation approach based on the FEA results and experimental data is applied to predict residual durability of power steam turbine disk taking into account both operating time and accumulated damages.

ELASTIC-PLASTIC STRESS FIELDS IN TURBINE DISK

The finite-element method was used to carry out stress analysis in order to determine the total stress-strain state of the turbine disk and the stress distribution at critical zones. In operation turbine disk is subjected to inertia loading from own weight of the disk and blades. The inertia loading from blades is transferred to the disk hole through rivets.
The numerical analysis of stress state of full-size 3D finite element model of the turbine disk is performed under operation conditions. Finite element model represented in Fig.2 is a segment of the turbine rotor, including disk, blades and rivets. At the side surface of the rotor segment cyclic symmetry conditions were applied.

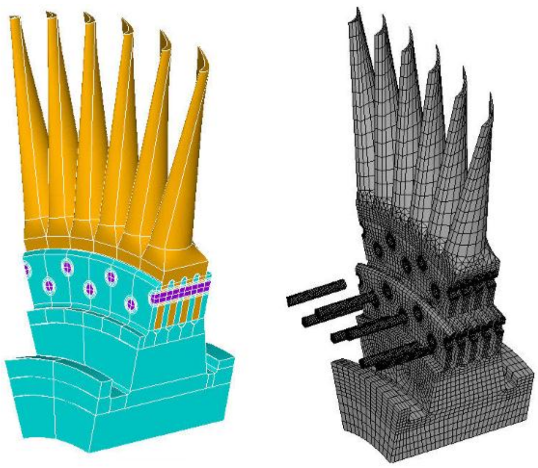


Fig. 2: Finite element model of turbine disk

Finite element mesh of full size 3D-model of turbine disk is shown in Fig.2. The FE analyses are made by using 20-node isoparametric three-dimensional solid and contact elements. Material deformation behavior is described by bilinear kinematic hardening model. The main mechanical properties of the disk and blade rivet attachment elements with zero operation time are listed in Table 1.

	Steel	Yield stress	Engineering tensile strength	Ultimate tensile strength	Strain hardening exponent	Reduction of area	Ultimate strain	Young's modulus
		σ_y, MPa	σ_t, MPa	σ_f, MPa	m	ψ, %	δ, %	E, GPa
Disk	34XH3MA	785	930	1410	7.58	35	11	206
Blade	2X13Ш	635	755	2900	4.42	50	14	200
Rivet	25X1MФ	750	900	1520	5.5	50	10	199

Table 1. The main mechanical properties for the disk and blade rivet attachment elements.

As a result, the critical zones of the disk and operating stresses for those zones are determined. Fig. 3 gives equivalent stress distribution in the turbine disk.

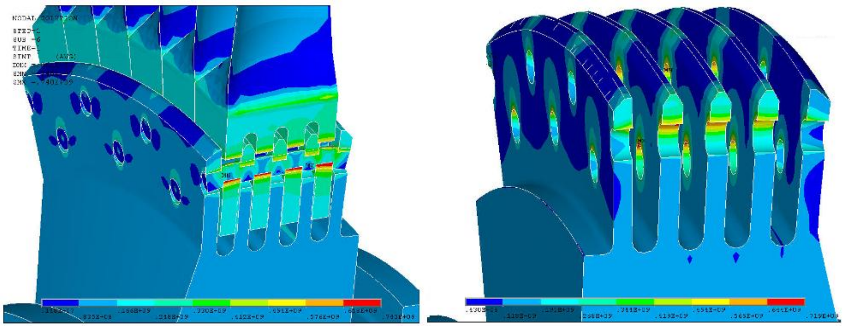


Fig. 3: Equivalent stress distribution in the turbine disk

LOW-CYCLE FATIGUE AND FRACTURE RESISTANCE DISK MATERIAL PROPERTIES

The tensile tests were performed in order to determine the main mechanical properties of the disk's material after loading history. Both smooth and notched specimens were cut out from the critical zones of turbine disk. In Fig.4 the area of specimens cut from the turbine disk is presented.

Experimental study of the material mechanical properties of the turbine disc with fixed operation time was performed on uniaxial 25 kN servo hydraulic testing machine (BiSS corp.). The material mechanical properties changes as a function of both the critical zone position and the operating time are established.

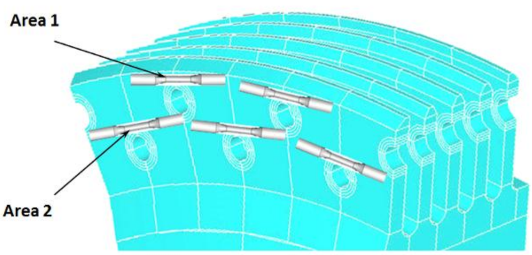


Fig.4. Areas of specimens cut for turbine disk

Fig.5 shows stress-strain curves of smooth specimens with different operation time. The main mechanical properties for critical zones of the disk with different operation time are listed in Table 2.

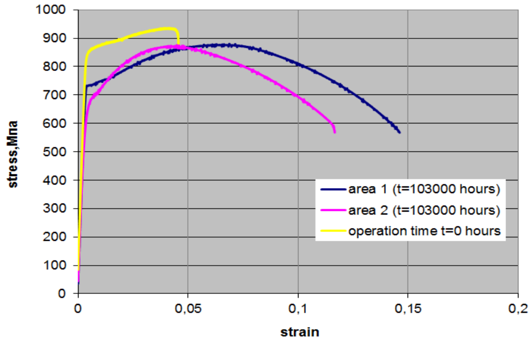


Fig.5. Stress-strain curves of smooth specimens with different operation time.

	Steel	Yield stress	Engineering tensile strength	Ultimate tensile strength	Strain hardening exponent	Reduction of area	Ultimate strain	Young's modulus
		σ_y, MPa	σ_t, MPa	σ_f, MPa	m	ψ, %	δ, %	E, GPa
Operation time 103000 hours								
Area 1	34XH3MA	735	881	1255	9,59	61	14	206
Area 2	34XH3MA	684	877	1152	9,93	61	11	206
Operation time 0 hours								
	34XH3MA	850	930	2100	5.44	56	5	222

Table 2. The main mechanical properties for critical zones of the disk with different operation time

The low-cycle fatigue tests were performed with the harmonic test-cycle and especially designed program test-cycle which is equivalent to start-stop cycle of turbine. As a result, the low-cycle fatigue resistance material properties of smooth and notched specimens were obtained. S-N curves presented in Fig. 6 shows the influence of the load history on the cyclic behavior of smooth and notched specimens. Fig. 7 shows that there are contrary trends of low cycle behavior for stress-strain hysteresis loops of smooth and notched specimens.

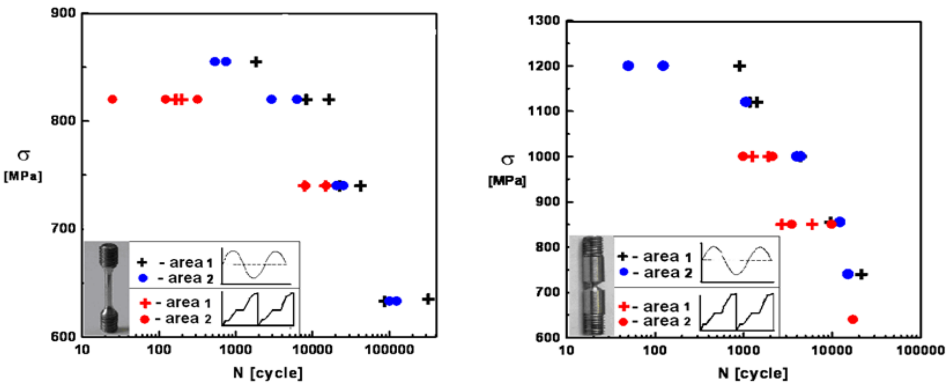


Fig.6. S-N curves of smooth and notched specimens with different loading types.

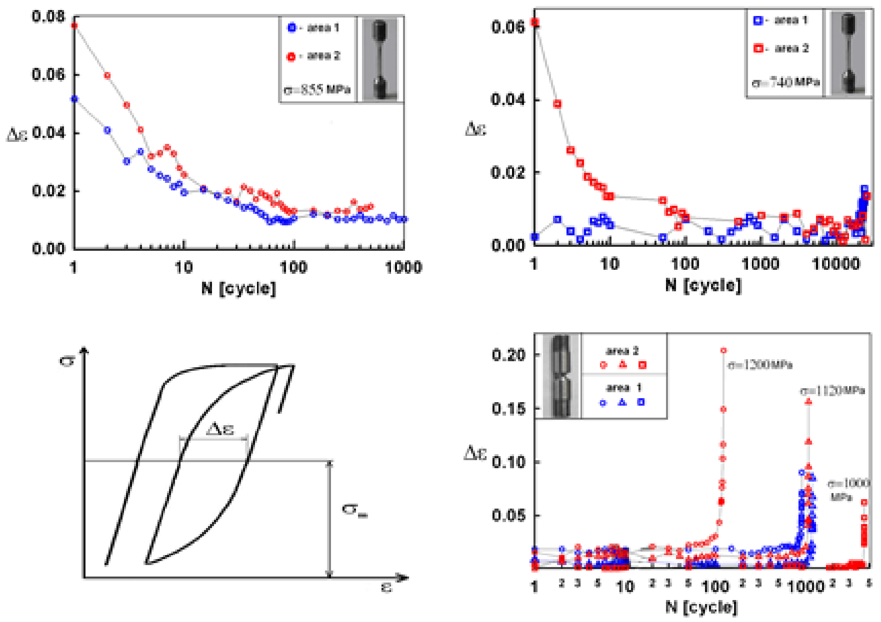


Fig.7. Kinetics of stress-strain hysteresis loops for smooth and notched specimens.

RESIDUAL LIFE PREDICTION OF TURBINE DISK

Residual fatigue life of turbine disk can be obtained based on mentioned above results of both numerical and experimental studies. Special FEA-calculations were performed to determine true elastic-plastic strains in smooth and notched specimens for each applied engineering stresses level in fatigue tests. As a result, the relation between engineering stresses, applied elastic-plastic strain and cyclic fracture strain for critical zones were established (Fig.8).

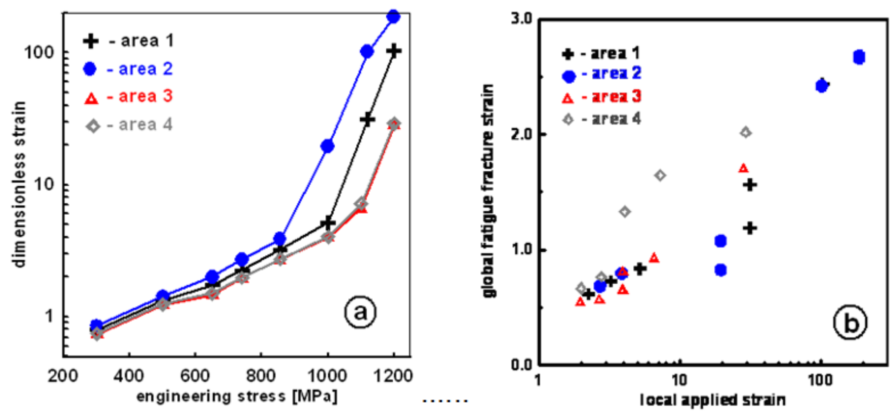


Fig.8. – (a) Local strains versus engineering stresses and (b) relations between critical fatigue fracture and applied strains.

The equation describing the relation between applied elastic-plastic strain and cyclic fracture is as follows:

$$\bar{\varepsilon}_c = C\left(\bar{\varepsilon}^{FEM}\right)^k \qquad (1)$$

where, $\bar{\varepsilon}_c$ - cyclic fracture strain, $\bar{\varepsilon}^{FEM}$ - elastic-plastic strain in critical zone.

Residual life as a function of cyclic fracture strain $\bar{\varepsilon}_c$ obtained from Eq.1 can be estimated as follows:

$$N_f = \left(D/\bar{\varepsilon}_c\right)^p \quad (2)$$

where N_f - residual life of critical zone

The residual fatigue life values N_f for each critical zone are obtained by substitution of applied plastic strains $\bar{\varepsilon}^{FEM}$ into Eq.1 and then $\bar{\varepsilon}_c$ into Eq.2. The results of such calculation are presented in Table 3.

Area	$\bar{\varepsilon}^{FEM}$	$\bar{\varepsilon}_c = C\left(\bar{\varepsilon}^{FEM}\right)^k$		$N_f = \left(D/\bar{\varepsilon}_c\right)^p$		N_f [cycle]
		C	k	D	p	
1. Upper row of disk and blade rivet attachment	1.3131	0.4771	0.3295	22.581	2.6802	24279
2. Lower row of disk and blade rivet attachment	1.3673	0.4441	0.335	8.891	3.9124	81997

Table 3. The main mechanical properties for critical zones of the disk

Residual fatigue life of the turbine disk with fixed operation time based on knowledge of 3D elastic-plastic stress-strain analysis, true fracture plastic strains and static and low-cycle fatigue material properties in critical zones are calculated.

ASSESMENT OF RESIDUAL LIFE OF TURBINE DISK BY MEANS OF SIMULATION MODELING

This part of the study is concerned with the residual life assessment of turbine disk by means of simulation modeling taking into account accumulated damages in structure. In accordance with simulation modeling principles, geometric parameters of simulation models and their loading types were selected to achieve acceptable stress distribution in a critical zone for the full-scale turbine disk and control zone of the simulation model [2]. In accordance with these principle two types of the geometry of imitation models were presented. All simulation models were cut out from disk and blade rivet attachment with saving operation damages under fixed operating time of the turbine rotor. Areas of cutting from the turbine disk and configurations of the simulation models are presented on Fig. 9.

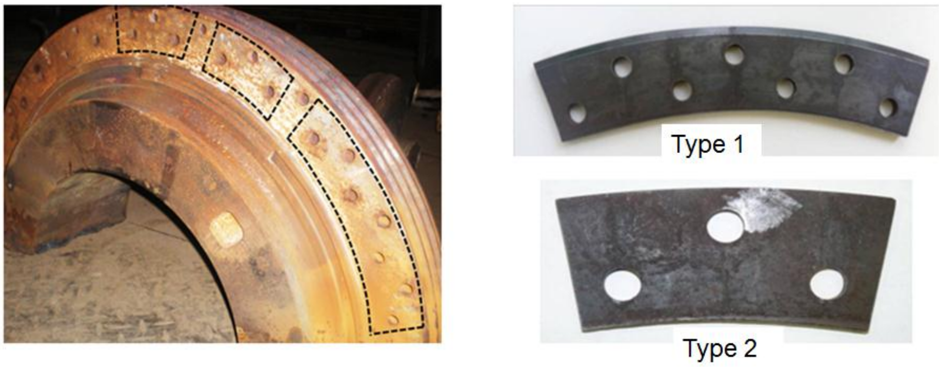
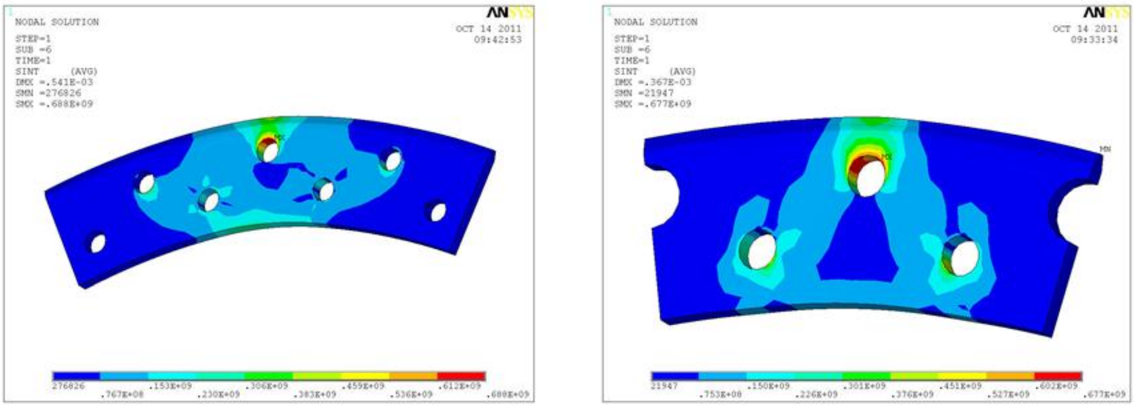


Fig. 9. Areas of cutting and configurations of simulation models

The finite element analysis is used to model stress distribution of the turbine disk in the simulation model with sufficient accuracy. Stress-strain state of the simulation models are shown in Fig. 10. As a result, profile and magnitude of the applied loading for the simulation models on test rig are determined.

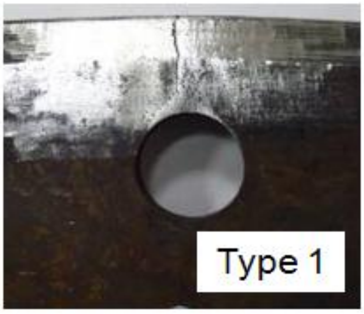


<u>Fig. 10.</u> Equivalent stress distribution in simulation models

Experimental investigations were performed on servohydraulic test system MTS870 100kNLandmark. Simulation models were tested under loading, which is equivalent to operating conditions. Special equipment for operation loading simulation in fatigue tests was designed. The simulation models and equipment mounted on servohydraulic test rig are shown in Fig. 9.

<u>Fig. 11.</u> Simulation models and equipment for operation loading simulation

Results of simulation models fatigue tests are presented in Fig. 8. As it follows from these results the crack initiation directions detected in the turbine disk are realized in simulation model type 2 (Fig. 1). Fatigue test results of simulation models type 2 are listed in Table 4.



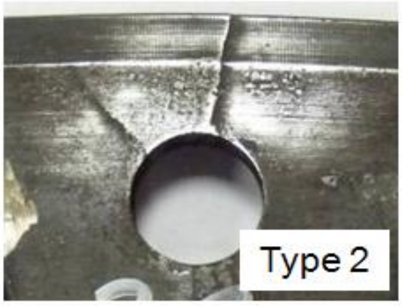


Fig.12. Crack propagation in simulation models

№	σe, MPa	P, kN	N
1	608	52,1	238506
2	608	52,1	222557
3	608	52.1	226522

Table 4. Results of fatigue tests of simulation models.

By means of such approach based on simulation modeling principles, residual fatigue life of real structure fragments with accumulated operation damages was obtained.

CONCLUSIONS

Full-size three-dimensional FE stress-strain analysis of turbine disk is represented under operation loading conditions. As a result, the critical zones of the disk and stress distribution for those zones are determined.
Both smooth and notched specimens cut out from critical zones of the turbine disk, with different operation time in service are tested under static, harmonic and program types of loading. The mechanical properties changes of the disk material as a function of operation time are established. Low-cycle fatigue and fracture resistance disk material properties with fixed operating time are established. Contrary trends of low cycle behavior for stress-strain hysteresis loops of smooth and notched specimens depended on loading history are presented.
Residual fatigue life of turbine disks with fixed operation time based on both numerical and experimental data is calculated.
The residual fatigue life estimation of turbine disks by means of simulation modeling taking into account accumulated damages in the structure is performed.

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