CODEN STJSAO ISSN 0562-1887
ZX470/1385 UDK 621.224-233.12:539.55:539.414

An Estimation of Sufficient Impact Toughness for the Material of a Turbine Shaft

Nenad GUBELJAK[1], Jozef PREDAN[1], Dražan KOZAK[2], Jelena TUMA[3], Boštjan KOVAČIČ[4], Pejo KONJATIĆ[2] **and** ***Josip SERTIĆ[1]***

1) Fakulteta za strojništvo, Univerza v Mariboru (Faculty of Mechanical Engineering, University of Maribor), Smetanova ulica 17, 2000 Maribor, **Slovenia**

2) Strojarski fakultet u Slavonskom Brodu Sveučilišta J. J. Strossmayera u Osijeku (Mechanical Engineering Faculty, J. J. Strossmayer University of Osijek), Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod, **Republic of Croatia**

3) Inštitut za kovinske materiale in tehnologije (Institute of Metals and Technology), Lepi pot 11, 1001 Ljubljana, **Slovenia**

4) Fakulteta za gradbeništvo, Univerza v Mariboru (Faculty of Civil Engineering, University of Maribor), Smetanova ulica 17, 2000 Maribor, **Slovenia**

dkozak@sfsb.hr

Keywords

Carrying capacity
Impact toughness
Limit load for torsion
SINTAP
Turbine shaft

Ključne riječi

Granično opterećenje obzirom na uvijanje
Nosivost vratila
SIMTAP
Udarna žilavost
Vratilo turbine

Received (primljeno): 2008-11-15
Accepted (prihvaćeno): 2009-06-15

Original scientific paper

The fracture of a turbine shaft in the case of overloading can exhibit brittle or plastic failure, depending on the material properties, the turbine-shaft geometry and the form of loading. Usually, when the toughness increases, the stiffness of the shaft material is reduced, which can lead to the plastic twist of the shaft. If the fatigue crack appears in the critical region of the shaft then the low impact-toughness value may induce a brittle fracture. During the retrofit of a hydro-power plant a new turbine shaft was produced by quenching-and-tempering technology. Charpy impact-toughness tests showed lower values for the shaft material than those prescribed by the project documentation. Since the turbine shaft for a hydro-power plant is a massive and expensive component, it is necessary to determine a sufficient impact toughness for the material in terms of the geometry and the manner of loading for the turbine shaft. Since only the yield strength and the impact toughness of the material were prescribed, the level 0 of the SINTAP should be applied. The minimum impact toughness values that ensure the ductile fracture of the shaft, cracked circumferentially was also estimated. We also analyzed the variation of the shaft's carrying capacity resulting from a reduction of the non-cracked ligament in the transversal direction.

Procjena dostatne udarne žilavosti materijala vratila turbine

Izvornoznanstveni članak

Lom vratila turbine u slučaju preopterećenja može biti krhak ili plastičan ovisno o svojstvima materijala, geometriji vratila turbine i obliku opterećenja. Uobičajeno se s porastom žilavosti krutost materijala vratila smanjuje, što može dovesti do plastičnog uvijanja vratila. Ako se zamorna pukotina pojavi u kritičnom području vratila, tada niska udarna žilavost može indicirati krhki lom. Za vrijeme remonta hidroelektrane ugrađeno je novo vratilo turbine, koje je proizvedeno s tehnikom kaljenja i popuštanja. Ispitivanje Charpy udarne žilavosti materijala vratila pokazalo je niže vrijednosti u odnosu na one dane projektnom dokumentacijom. Budući da je vratilo turbine hidroelektrane masivna i skupa komponenta, neophodno je odrediti dostatnu udarnu žilavost materijala za danu geometriju i vrstu opterećenja vratila turbine. S obzirom na to da su bili poznati jedino granica tečenja i udarna žilavost materijala, primijenjena je razina 0 SINTAP postupnika. Procijenjena je vrijednost minimalne udarne žilavosti, koja osigurava duktilan lom vratila s obodnom pukotinom. Također je analizirana promjena nosivosti vratila u ovisnosti o smanjenju neslomljenog ligamenta u poprečnom smjeru.

1. Introduction

A stress and strength analysis based on stress-concentration-factor calculations for the critical cross-section of the shaft assumes an isotropic and homogeneous material, thereby excluding the possibility that a crack might be initiated and propagated as a result of material imperfections or from the surface scallops as a consequence of the applied process technology. Such a crack could advance due to dynamic loading to its critical value and, as a result, cause the shaft to undergo catastrophic failure. The fracture is either brittle or

Symbols/Oznake

a	- crack length, mm - duljina pukotine
a_c	- cricital crack length, mm - kritična duljina pukotine
F_A	- axial tensile force, kN - aksijalna vlačna sila
F_Y	- yield load, kN - sila tečenja
K_I	- mode I stress intensity factor, MPa·m$^{1/2}$ - koeficijent intenziteta naprezanja za odcjepni lom
K_{II}	- mode II stress intensity factor, MPa·m$^{1/2}$ - koeficijent intenziteta naprezanja za smični lom
K_{III}	- mode III stress intensity factor, MPa·m$^{1/2}$ - koeficijent intenziteta naprezanja za vijčani lom
K_{IC}	- fracture toughness, MPa·m$^{1/2}$ - lomna žilavost
K_{eq}	- equivalent stress intensity factor, MPa·m$^{1/2}$ - ekvivalentni koeficijent intenziteta naprezanja
K_{mat}	- fracture toughness of material where crack tip is located, MPa·m$^{1/2}$ - lomna žilavost materijala u kojem se nalazi pukotina
K_r	- normalized value of the stress intensity factor, MPa·m$^{1/2}$ - normalizirana vrijednost koeficijenta intenziteta naprezanja
KV	- toughness of material, J - žilavost materijala
L_r	- dimensionless load parameter - bezdimenzijski parametar opterećenja
$M_{ks,tg}$	- maximum short cuircuit moment, kN·m - maksimalni moment kratkog spoja
T_Y	- yield torsion load, kN·m - moment tečenja materijala
T_t	- torsion load, kN·m - moment torzije
$T_{t,max}$	- maximum torque moment, kN·m - maksimalni moment torzije
R_1	- inner radius, mm - unutarnji polumjer
R_2	- outer radius, mm - vanjski polumjer
R_e	- yield strength, MPa - granica tečenja
R_t	- shear yield stress, MPa - smična granica tečenja
SF	- safety factor - faktor sigurnosti
σ	- applied stress, MPa - naprezanje
σ_Y	- yield stress, MPa - naprezanje tečenja
t	- wall thickness, mm - debljina stijenke
τ	- shear stress, MPa - smično naprezanje
τ_Y	- shear yield stress, MPa - smično naprezanje tečenja

ductile, depending on the shaft material's toughness and geometry. A satisfactory toughness value under critical conditions tends to lead to ductile fracture, which is more acceptable when it comes to possible damage to the bearings and other mechanical parts. In contrast to this, a critical crack value in a low toughness material leads to an instantaneous failure across the whole cross-section, which may result in damage to the driving gear and a falling out of the aggregate from the operation. The task of the designer is to estimate regularly sufficient impact toughness for the turbine-shaft material in accordance with the technological demands and to ensure a reliable in-service inspection and exploitation using fracture-mechanics practice. A conventional approach used in the project documentation of the hydro-power plant, Slovenia [1], requires that the supplied turbine shaft must have a minimum toughness at the working temperature (in this case KV = 28 J at 0 °C), which is considered as a quantitative measure of the material's suitability, without any connection between the strength analysis and the material's toughness. The problem appears if the measured impact toughness of the shaft is found to be lower than that required. This is why the strength analysis has to be performed together with the fracture toughness of the material, with the aim being higher safety margins for the turbine shaft before the break. Fracture-toughness calculations based on a strength analysis in the critical cross-section consider:

- the most critical operating conditions,
- the most critical crack position and the type of crack-front propagation.

Such an approach ensures increased safety as a result of an analysis and an interpretation of the results. A complete fracture-toughness analysis includes:

a) the fracture resistance of the material in terms of the fracture due to fatigue,

b) an integrity assessment of the turbine shaft from the initial condition to the critical crack-length formation, in terms of the maximum allowed loading and the maximum operating loading.

The analysis under a) is based on an experimental determination of the material's resistance to crack propagation under fatigue, where the standard fracture-toughness specimens have to be made from the same material as the shaft, according to the standard ASTM 647-99.

The analysis under b) is based on the mechanical properties of the shaft material, obtained by experiment. This means a determination of the tensile mechanical properties according to the standard DIN 50125 and Charpy impact toughness (DIN 50115) as well as a fracture-toughness determination. The fracture toughness has to be determined according to the standards:

[2] for brittle materials, where the parameter K_{IC} represents the fracture behaviour,

[3] or [4] for ductile materials, characterized by the J_{IC} and CTOD parameters.

From the experimental results it is possible to determine the lower bounds of the fracture toughness, the critical crack value and the allowed applied loading with some procedures for the structural integrity assessment (e.g., SINTAP, EPRI, R6, and WES 2805).

An extensive experimental analysis is sometime difficult or even impossible, to perform, and in such a case, therefore, the [5] is the implemented component-integrity assessment, based on the minimum number of entry data: the yield strength R_e and the impact toughness KV at the operating temperature. Hence, the carrying capacity and the fracture behaviour can be estimated from the loading limit, but not the material's resistance to fatigue collapse.

An analysis based on the minimum amount of input data includes a determination of:

- the maximum overloading of the turbine shaft in the initial condition without a crack,
- the variation of the allowable applied load with a reduction of the bearing cross-section caused by a crack extension,
- the critical crack length due to dynamic loading,
- the impact and fracture toughness of the material that ensures the ductile collapse of the turbine shaft.

2. Analysis of the entry data

2.1. Loading data and the material's mechanical properties

The analysis performed in this study was submitted to the Vuhred hydro-power plant, Slovenia. All the turbine-shaft loading conditions used in this research, listed below, were taken from the enclosed project documentation [1]:

- axial tensile force F_A = 3 674 kN,
- maximum torque moment $T_{t,max}$=2 064 kN·m,
- maximum short-circuit moment $M_{ks,tg}$=2 827,7 kN·m.

The lowest values of the shaft material's mechanical properties are guaranteed by the supplier's certificate, i.e.:

- yield strength R_e=276 MPa, shear yield strength R_t=202 MPa and
- impact toughness KV = 12 J for an ISO-V specimen at 0 °C.

2.2. Loading data and the material's mechanical properties

The critical transversal cross-section of the shaft, according to the strength analysis is located under the carrying bell (4905 mm from the bottom), where the outer shaft diameter is 750 mm and the inner diameter is 300 mm (Figure 1). The stress and strength analyses show that the highest stresses were found on the shaft's surface in the critical cross-section. The hypothetical crack has been assumed at stress concentration area. It is assumed that two hypothetical crack orientations are possible, the crack in transversal and longitudinal orientation as shown in Table 1.

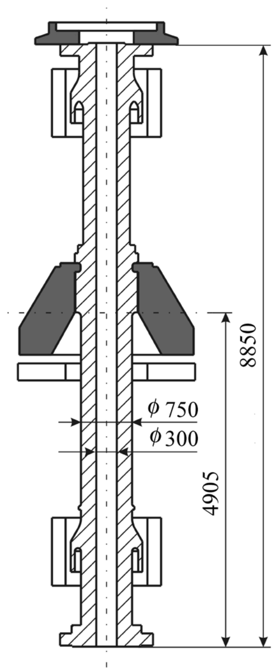


Figure 1. Critical cross section position by turbine shaft [1]

Slika 1. Mjesto kritičnog poprečnog presjeka turbine vratila [1]

Table 1. Typical crack propagations through the thickness of turbine shaft
Tablica 1. Tipična propagacija pukotine kroz debljinu stijenke vratila turbine

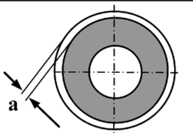
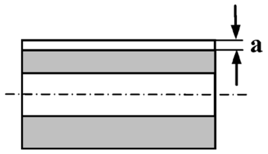
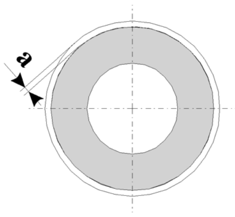
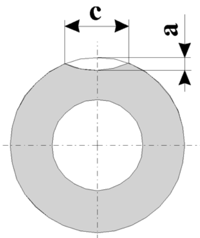
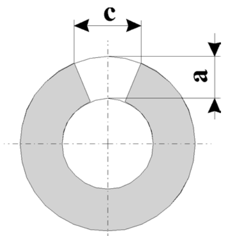
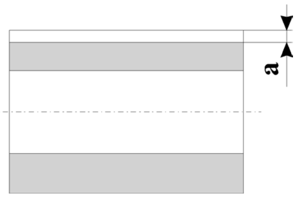
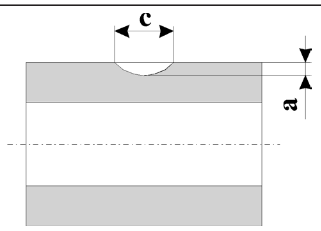
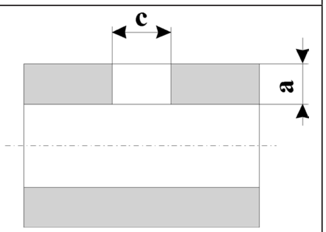
Type / Tip	Crack propagation type / Tip napredovanja pukotine	Schematic overview of shaft cross section / Shematski prikaz poprečnog presjeka vratila
A	Transversal: The circumferential crack propagation from the surface to the centre of shaft / Poprečno: Napredovanje obodne pukotine od površine prema središtu vratila	
B	Longitudinal (parallel with the shaft axial axis): The crack propagates longitudinally from the surface to the centre of shaft. / Uzdužno (paralelno sa aksijalnom osi vratila): Pukotina napreduje uzdužno od površine prema središtu vratila	

Table 2. The selection of more conservative ways of the crack propagation for the analysis
Tablica 2. Izbor najkonzervativnijeg puta napredovanja pukotine za analizu

Type / Tip	Conservative cases considered in this paper / Konzervativni slučajevi razmatrani u ovom članku	Local crack propagation from the surface[1] / Lokalno napredovanje pukotine od površine[1]	Local crack propagation through the wall-thickness[2] / Lokalno napredovanje pukotine kroz debljinu stijenke[2]
A	 A.1	 A.2	 A.3
B	 B.1	 B.2	 B.3

[1] additional crack measure *c* appears by surface crack propagation, which corresponds to the crack length on the shaft surface / dodatna mjera pukotine *c* pojavljuje se zbog napredovanja površinske pukotine koja odgovara duljini pukotine na površini vratila
[2] by crack propagation through the thickness, crack depth *a* is equal to the shaft wall-thickness, while the crack length *c* on the surface is variable dimension / napredovanje pukotine kroz debljinu stjenke, dubina pukotine *a* jednaka je debljini stijenke vratila, dok je duljina pukotine *c* na površini promjenljiva veličina

3. SINTAP on the level 0

The SINTAP (Structural Integrity Assessment Procedure) originates from two very similar procedures:

- R6, which was developed by British Energy [6],
- Engineering Treatment Model-ETM, which was established at the GKSS Research Centre in Geesthacht, near Hamburg [7].

In this analysis the R6 procedure will be used, based on the so-called FAD (Failure Assessment Diagram) for assessing the allowable crack length. The FAD concept for estimating the acceptance of the crack is based on the Failure Assessment Curve (FAC), which is based on the dependence between the dimensionless loading L_r and the function of the crack acceptance $f(L_r)$. This function of the crack acceptance $f(L_r)$ is limited by its cut-off value L_r^{max} in the region of the plastic collapse. The FAC is particularly defined in relation to the level of the SINTAP analysis. Because of the minimum number of input data in our case (yield strength R_e, shear yield stress R_t and Charpy impact toughness KV), the analysis was made at the level 0 of the SINTAP.

It is necessary to calculate the value of the stress-intensity factor K_{eq}, which is a function of the crack length and the loading level, as well as the loading conditions of the structural component.

The loading path in the FAD may be defined by the increasing loading that keeps the crack length as a constant value or increases the crack length by a constant value of the maximum operating load. The first analysis is applied when the maximum carrying capacity of the shaft has to be determined and the second one when the fracture behaviour of the shaft during the exploitation has to be assessed (i.e., a lifecycle estimation).

The loading path for the turbine shaft in both analyses is drawn as a loading curve that employs a normalized value of the stress-intensity factor K_r for the applied loading and a normalized value of the loading L_r with the same loading.

$$K_r = K_r(F,\ T_t) = K_r(L_r)\,. \tag{1}$$

The measure of the proximity to the plastic yielding L_r is defined as the ratio of the applied tensile load F_A to the yield load of the component F_Y and applied torsion load T_t to the yield torsion load T_Y,

$$L_r = \frac{F_A}{F_Y} + \frac{T_t}{T_Y}\,, \tag{2}$$

where the yield load F_Y and yield torsion load T_Y give the yield stress of non-cracked ligament of shaft. The loading limit σ_Y is equal to the strength of the plasticity R_e by the tension loading or the shear strength τ_Y by the torsion type of loading. Yield load solution for tension loading is given by [8]:

$$F_Y = \frac{2}{\sqrt{3}}\pi \cdot \left[R_2^2 - (R_1 + a)^2 \right] \cdot \sigma_Y\,. \tag{3}$$

The measure of the proximity to the elastic fracture K_r is generally defined by:

$$K_r = \frac{K_{eq}(a,\ \sigma)}{K_{mat}}\,, \tag{4}$$

where K_{eq} (a, σ) is the stress-intensity factor (SIF) of the defective component of interest and K_{mat} is the fracture toughness of the material where the crack tip is located. The SIF depends on the magnitude of the applied stress σ, the crack length a, and its position and shape as well as on the type of loading of the component.

Limit load for torsion moment is determined by finite element (FE) analysis by using ABAQUS 6.4 implicit solver [9]. Finite element analyses were performed on the shaft with three different crack depths. The yield moment was determined at the torsion moment where the complete yielding of net section occurred, as shown in Figure 2. The limit load solution for mode III of loading for full circumferential surface crack in the shaft is given according to FEM analysis (Figure 2) and by approximation of curve on Figure 3,

$$T_Y = T_Y(a=0) \cdot \left[0{,}426 \cdot \left(\frac{a}{t} \right)^2 - 1{,}4339 \cdot \frac{a}{t} + 1{,}0079 \right], \tag{5}$$

where T_Y (a=0) corresponding to maximum yield torsion moment of shaft cross section without crack. Note that T_Y=1,64×10[4] kN·m of hollow shaft corresponding to torsion yield stress R_t = 202,3 MPa, according to the Eq. (14).

K_{mat} is the fracture toughness in terms of K (MPa·m½), and it is equal to K_{IC} for brittle fracture behaviour. At the SINTAP level 0 the value of K_{mat} should be determined from the empirical correlation between the Charpy toughness and the fracture toughness:

$$K_{mat} = K_{mat}(KV) = \left[(12\sqrt{KV} - 20) \cdot \left(\frac{25}{t} \right)^{0,25} \right] + 20, \tag{6}$$

where KV is the Charpy impact toughness at the operating temperature and t is the wall thickness of the shaft $t = (R_2 - R_1) / 2$.

The fracture is to be expected at the point where the loading path intersects the failure-assessment curve f (Lr), which can be written in the form:

$$f(L_r) < \frac{K_{eq}(a,\sigma)}{K_{mat}}\,. \tag{7}$$

For materials that do not have a continuous transition form elastic to plastic behaviour, the failure-assessment curve for the crack acceptance should be determined as:

$$f(L_r) = \left[1 + \frac{1}{2} L_r^2 \right]^{-1/2} \cdot \left[0{,}3 + 0{,}7 e^{-0{,}6 L_r^6} \right]; 0 \le L_r \le L_r^{max}. \tag{8}$$

The plastic collapse of a material with Lüders behaviour, such as with our shaft material (CK35 without heat treatment, according to DIN standard) is defined by the maximum cut-off loading L_r^{max} as:

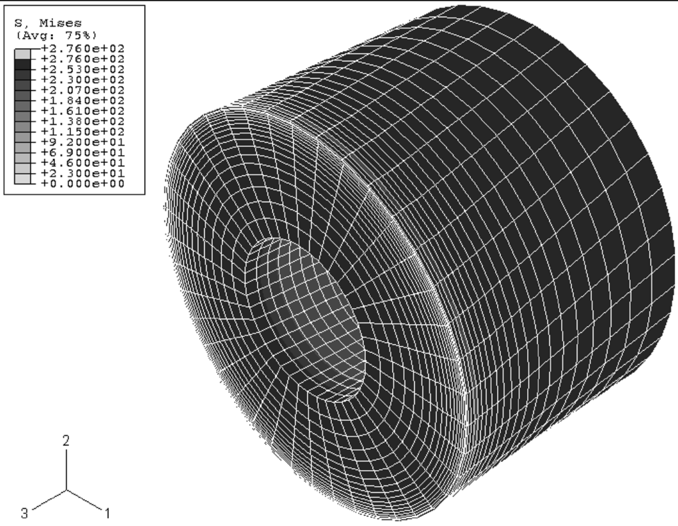
$$L_r^{max} = 1. \tag{9}$$

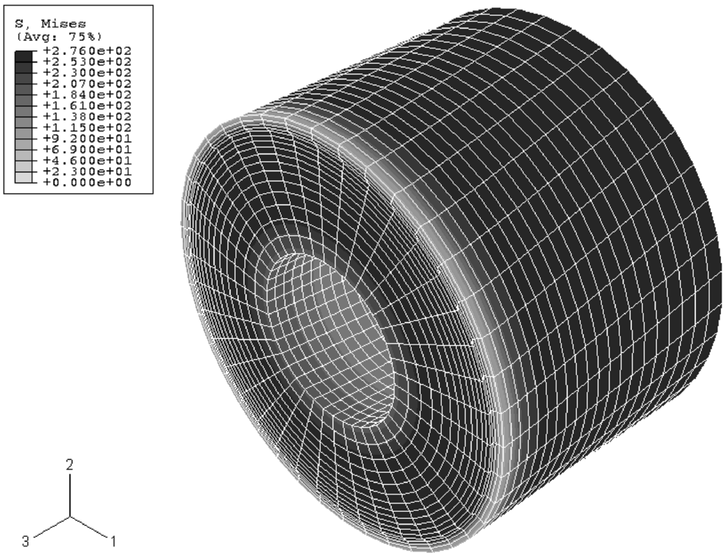
Equations (1) to (9) are generally valid, regardless of the direction of crack propagation and the loading conditions of the structural component, while the K_I (a, σ) and L_r parameters depend on the shaft geometry and the type of loading.

The critical cross-section of the turbine shaft lies 4 905 mm over the gear (Figure 1). It can be realistically supposed that the crack located in the critical section will propagate from the surface to the inner side of the shaft (Figure 4), which is indicated as type A in Table 1.

With regard to the two different types of loading on the turbine shaft, two components of SIF will appear: that due to the axial tensile force (F_A) - K_I and that due to the torsion load (T_t) as a shear component of SIF - K_{III}. If the conditions of linear elastic fracture mechanics are valid (i.e., the impact toughness of the material is lower than

<table>
<tr>
<td>a) Without crack / Bez pukotine

Limit torsion moment / Granični moment torzije
T_Y=1,64×10^4 kN·m</td>
<td>
</td>
</tr>
<tr>
<td>b) Crack length / Duljina pukotine
a=5 mm
Crack depth / Dubina pukotine

a/t=5/225=0,022
T_Y=1,62×10^4 kN·m</td>
<td>
</td>
</tr>
<tr>
<td>c) Crack length / Duljina pukotine
a=75 mm
Crack depth / Dubina pukotine

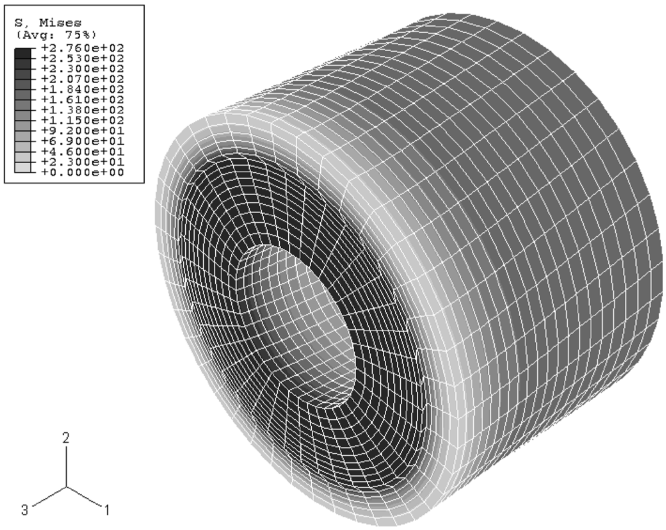
a/t=75/225=0,33
T_Y=9,47×10^3 kN·m</td>
<td>
</td>
</tr>
</table>

Figure 2. Finite element model of shaft with circumferential surface crack in tube for limit load solution

Slika 2. Model konačnih elemenata vratila s obodnom površinskom pukotinom u cijevi za rješenje graničnog opterećenja

28 J), both components of the SIF can be calculated by using Richard criterion [10]:

$$K_{\mathrm{eq}}(a,\sigma)=\frac{K_{\mathrm{I}}(a,F_{\mathrm{A}})}{2}+\frac{1}{2}\sqrt{K_{\mathrm{I}}^{2}+5,34\cdot K_{\mathrm{II}}^{2}+4\cdot K_{\mathrm{III}}^{2}}\ , \quad (10)$$

where K_{II} corresponding to mode II of loading. In our case the K_{II} is equal to zero!

The analytical expressions for the stress-intensity factors K_{I} and K_{III} in the case of a circumferential crack in tube, which is subjected to both an axial force and a torsion moment (the shaft's diameters ratio amounts to R_1 / R_2=300 / 750 = X = 0,4) are given in the literature [11]:

$$K_{\mathrm{I}}=\sigma\sqrt{\pi\cdot a}\cdot\frac{0,84}{\left[1-0,6X\right]^{2}-0,16}\cdot$$

$$\cdot\left\{0,8+\frac{0,6X}{1-0,6X}\left[4+\frac{0,432}{0,6\cdot(1-X)}\right]\right\}^{-0,5}, \quad (11)$$

$$K_{\mathrm{III}}=\tau\cdot\sqrt{\pi\cdot a}\,\frac{0,9744\cdot(1-0,6X)}{(1-0,6X)^{4}-0,0256}\cdot$$

$$\cdot\left\{1+\frac{0,6X}{1-0,6X}\left[7,111+\frac{0,9872}{0,6\cdot(1-X)}\right]\right\}^{-0,5}, \quad (12)$$

where the normal and shear components of stress can be calculated from:

$$\sigma=\frac{4\cdot F_{\mathrm{A}}}{(R_2^2-R_1^2)\cdot\pi}, \quad (13)$$

$$\tau=\frac{16\cdot R_2\cdot T_{\mathrm{t}}}{\pi\cdot(R_2^4-R_1^4)}. \quad (14)$$

The maximum applied axial load F is constant and equal to force F_{A}=3 674 kN, while torsion load T_{t} increasing from zero to maximum so call "short circuit moment of generator" $T_{\mathrm{t,max}}$=2 827,7 kN·m.

The pairs of values [L_{r}, $f(L_{\mathrm{r}})$] and [$L_{\mathrm{r}}^{\max}$, $f(L_{\mathrm{r}}^{\max})$] were calculated from equations (2) and (8), respectively, and transferred to the diagram for the FAD concept (Figure 5). The normalized value of K_{r} depends on the applied loading T_{t}, which gives rise to the stress τ. Tensile stress σ is constant due to constant F_{A} stress. Its value can be calculated as the ratio of $K_{\mathrm{eq}}(a,\sigma)$, from Eq. (10), and $K_{\mathrm{mat}}(KV)$, from Eq. (6):

$$K_{\mathrm{r}}=\frac{K_{\mathrm{eq}}(a,\ \sigma)}{K_{\mathrm{mat}}(KV)}. \quad (15)$$

Using loading calculations the moment of torsion T_{t} increased from the value 0 to the maximum of the operating loading $M_{\mathrm{ks,tg}}$ or to the loading that induces the fracture in the shaft, while the axial force F_{A} was kept at a constant value. The loading path depicted in Figure 5 was plotted, calculating the corresponding value of K_{r} for the characteristic values of L_{r} using Eqs (3) and (2), respectively. According to the criteria given by Eq. (7) the fracture of the structural component at level 0 could be expected at the point where the loading path intersects with the failure-assessment line. Figure 5 shows only one of the loading paths, where the maximum loading of the shaft cracked circumferentially at a depth of 168 mm, which amounts to T_{t}=2 827,7 kN·m and axial load F_{A}= 3 674 kN. By varying the crack length a similar procedure could be performed to find the maximum loading for different limit conditions. These values are presented in Fig. 6, showing how the carrying capacity decreases by reducing the bearable cross-section. The critical circumferential crack length a_{c}=168 mm cross the failure assessment curve at loading point T_{t}=2 827,7 kN·m.

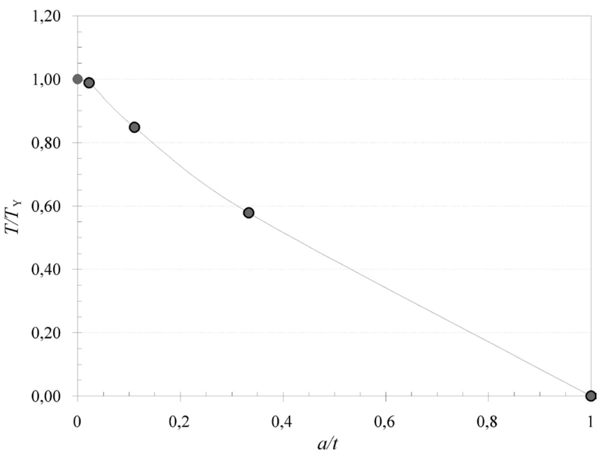


Figure 3. Limit load solution for cross-section of shaft with circumferential surface crack in tube (for torsion loading)

Slika 3. Granično opterećenje za poprečni presjek vratila s obodnom površinskom pukotinom u cijevi (za opterećenje na uvijanje)

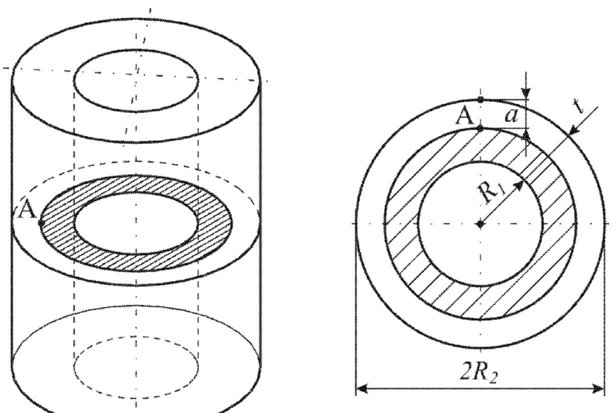


Figure 4. Transversal crack propagation in shaft critical cross section

Slika 4. Propagacija pukotine u poprečnom smjeru u kritičnom presjeku vratila

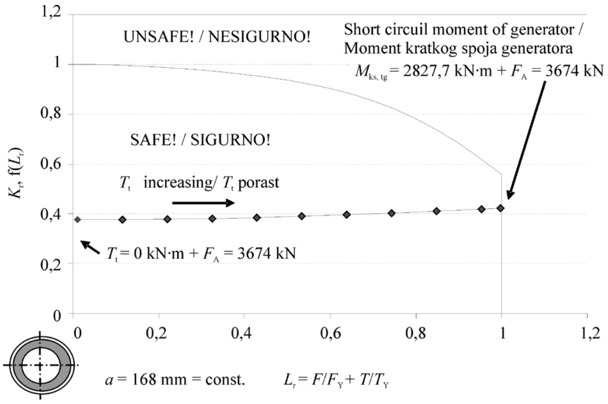


Figure 5. The determination of maximal carrying capacity of the shaft with constant circumferential transversal crack (a = 168 mm)

Slika 5. Određivanje maksimalne nosivosti vratila s konstantnom obodnom pukotinom u poprečnom smjeru (a = 168 mm)

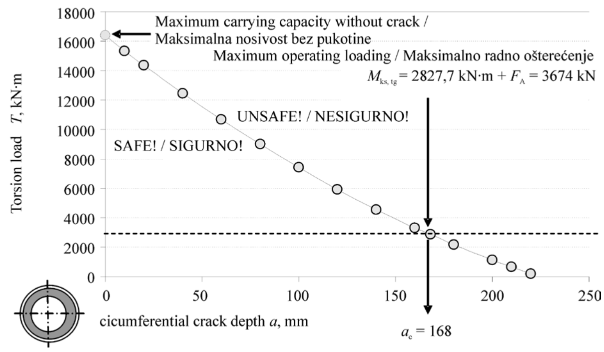


Figure 6. Carrying capacity variation due to the bearable cross section reduction

Slika 6. Promjena nosivosti s obzirom na smanjenje nosivog poprečnog presjeka

The maximum shaft loading in the initial condition (without the crack) is equal $T_t = T_Y$ = 16 400 kN·m, which corresponds to a safety factor of 5,8 ($SF = T_Y/M_{ks,tg}$). The traditional strength analysis has taken into consideration the stress-concentration factor K_t = 3 in the critical section. Figure 6 shows that unsafe fracture appears when the crack reaches a length of 168 mm, while the shaft will break when the crack length reaches 220 mm, due to the shaft's own weight and the weight of the water that pressurizes the turbine (T_t=0). If the maximum operating loading is kept constant by increasing the crack length it is possible to draw an alternative loading path, as shown in Figure 7. The starting point lies on the abscissa L_r and represents the initial operating condition without a crack (a = 0 and K (a, σ) = 0 and L_r > 0). In the FAD each point corresponds to the appropriate crack length with a constant maximum loading ($M_{ks,tg}$ = 2 827,7 kN·m + F_A=3674 kN). Such points, mutually connected, form the loading path, which crosses over the f (L_r) curve for a crack with length a = 168 mm, as presented in Figure 6.

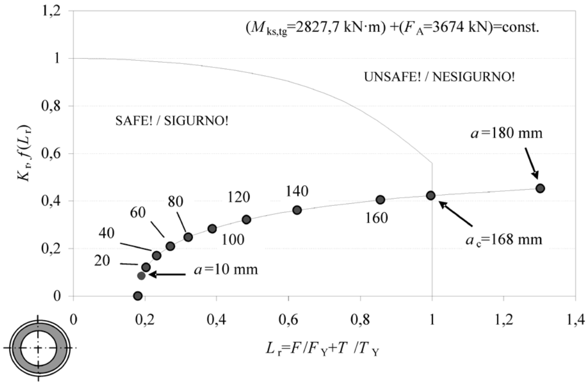


Figure 7. Variation of remained carrying capacity

Slika 7. Promjena preostale nosivosti

4. Discussion of results

If a crack present in a shaft subjected to fatigue propagates to its critical value, the shaft can break in a stable way due to the toughness of the material. The fracture-toughness values in the transversal direction are sufficient to provide the ductile fracture of the shaft, depending on the crack depths given in Figure 7. We calculated using SINTAP the minimum toughness vs. critical crack length as shown in Figure 8.

Figure 9 shows increasing of critical crack length a_c with increasing of impact toughness. The pairs (critical crack length a_c, fracture toughness K_{mat}) lie on the failure assessment curve-FAC up to the critical crack length a_c=168 mm and toughness K_{mat} =20 MPa·m$^{1/2}$. If the crack length increases (e.g. a_c =180 mm) the L_r values is higher than L_r^{max}=1 and the point lies in an unsafe area! In order to ensure the plastic collapse of the shaft in a critical cross section the impact toughness should be higher (e.g. K_{mat}=55 MPa·m$^{1/2}$). The higher toughness causes decreasing of assessment point at the same crack length, (e.g. assessment point a_c =168 mm for goes down because toughness increases from 20 to 40 MPa·m$^{1/2}$). Therefore, if the FAC is cut-off at L_r^{max}, the critical crack length is determined at a_c =168 mm and minimum K_{mat}=20 MPa·m$^{1/2}$. The higher toughness and corresponding impact toughness provides higher plastic failure. The value K_{mat}=20 MPa·m$^{1/2}$ corresponding to the lower bound of toughness for structural steel, according to SINTAP, see Eq. (6). Structural integrity assessment of the shaft confirms that the shaft is over-dimensioned. Because the circumferential crack depth is significant (168 mm, a/t=0,75), it could be detected during routine inspection. In the supplied condition the shaft has a minimum toughness of 12 J at 0 °C and a yield stress of R_e=276 MPa and yield shear stress R_t=202,3 MPa for the maximum operating loading, and it is suitable for being built in. A minimum toughness value of 12 J at 0 °C should be enough for ductile fracture to appear in the shaft with a circumferential critical crack length.

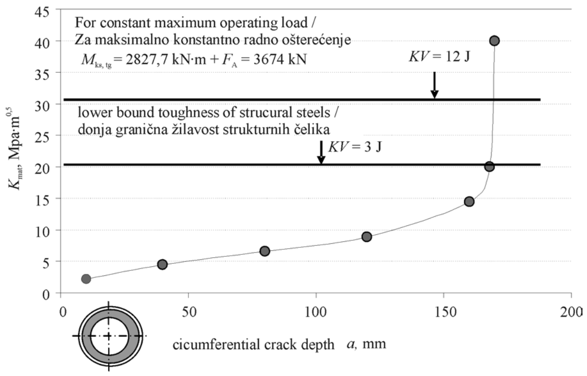


Figure 8. The determination of fracture toughness for the ductile fracture

Slika 8. Određivanje potrebne lomne žilavosti za osiguranje duktilnog loma

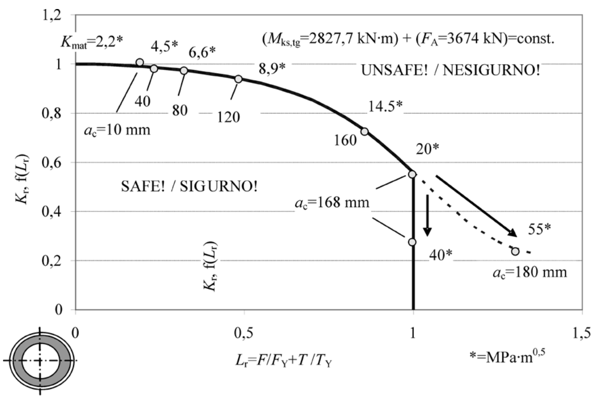


Figure 9. Increasing of critical crack length a_c with increasing of impact toughness KV along the failure assessment curve FAC

Slika 9. Povećanje kritične duljine pukotine a_c s porastom udarne žilavosti KV uzduž krivulje procjene greške FAC

5. Conclusions

The structure integrity assessment of the hydro-power plant's turbine shaft has been performed by taking into account axial tensile load (mode I) and torsion load (mode III). In order to perform an assessment the limit load solution for torsion load has been found by finite element modelling and analysis.

The obtained results show that the turbine shaft is over dimensioned regarding maximum loading conditions. The safe factor for elastic loading is 5,8. The fracture toughness of K_{mat}=30,3 MPa·m^{½} (corresponding to impact toughness KV=12 J) provide ductile fracture at critical circumferential crack depth a_c=168 mm!

Acknowledgments

The authors of the paper would like to thank the support of both the Slovenian and Croatian Ministries of Science and Technology, provided by the bilateral project: "*Application of fracture mechanics by revitalization of energetic components*".

REFERENCES

[1] POROČILO 3131-A: *Trdnostna analiza turbinske gredi-Dodatek 1: Upoštevanje koeficientov koncentracije napetosti v kritičnih prehodih gredi*, *Litostroj E. I.*

[2] ASTM E 399-90: *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials*, Philadelphia: Annual Book of ASTM Standards, Vol. 02.02; 1990.

[3] ASTM E 1290-93: *Standard test method for crack-tip opening displacement (CTOD) fracture toughness measurement*, American Society for Testing and Materials, Philadelphia 1993.

[4] BS 7448: *Fracture mechanics toughness tests: Method for determination of K_{IC}, critical CTOD and critical J values of metallic materials*; British Standard Institution 1997.

[5] SINTAP: *Structural Integrity Assessment Procedure*, Final Revision, EU-Project BE 95-1462, Brite Euram Programme, 1999.

[6] R6-Code User Manual 1994, Nuclear Electric report.

[7] SCHWALBE, K.-H.; ZERBST, U.; KIM, Y.-J.; BROCKS, W.; CORNEC, A.; HEERENS, J.; AMSTUTZ, H.: EFAM ETM-97: *The ETM method for assessing the significance of crack-like defects in Engineering structures*, comprising the version ETM 97/1 and ETM 97/2, GKSS Research Centre, GKSS/98/E/6, Geesthacht 1998.

[8] KUMAR, V.; GERMAN, M.D.; SHIH, C.F.: *An Engineering Approach for Elastic-Plastic Fracture Analysis*, EPRI, NP-1931; 1981.

[9] ABAQUS 6.4 Standard Manual, 2005. *Dravske Elektrane Maribor*, Maribor, 2001.

[10] RICHARD, H. A. and BENITZ, K.: *A loading device for the creation of mixed mode in fracture mechanics,* International Journal of Fracture, 22, (1983) 2, R55–R58.

[11] ROOKE, D.P.: *Stress Intensity Factors for Cracks at a Row of Holes*, International Journal of Fracture, 18, (1982) 2, R31-36.