



Risk based analysis of RHPP penstock structural integrity

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ABSTRACT. Risk based analysis of reverse hydro power plant penstock structural integrity is performed using fracture mechanics parameters. To assess its structural integrity, extensive testing of the full-scale prototype had been performed, including hydrostatic over-pressurizing, during the design phase. More recently, the Failure Assessment Diagram has been used to evaluate probability, whereas phenomenological analysis has been used to estimate consequence, in the scope of common risk estimation. It is shown that over-pressurizing has potential detrimental effect on pipeline safety, i.e. structural integrity.

KEYWORDS. Over-pressure; Pipeline; Structural integrity; Risk matrix.

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INTRODUCTION

Reversible Hydro Power Plant (RHPP) “Bajina Basta” is in operation since 1982, [1, 2]. Taking into account that the failure of its most critical part, the penstock, Fig. 1, would cause water overflow of the surge hub in the surrounding area, and the collapse of the entire plant, it is clear that special attention is still needed to prove its structural integrity.

This is especially important when it comes to the proof testing, now scheduled for 2022, since it has been shown that overpressure can cause significant damage and bring no benefit, [3]. Therefore, the basic aim of this paper is to make risk based analysis of the penstock structural integrity with focus of overpressure effect. Toward this aim, a simple engineering tool will be used to estimate probability, [4-10], and simple reasoning will be used to estimate consequence, [7, 11], so that risk will be evaluated as the product of these two. This approach is also adopted in the scope of ESIS TC12 activities, [12].

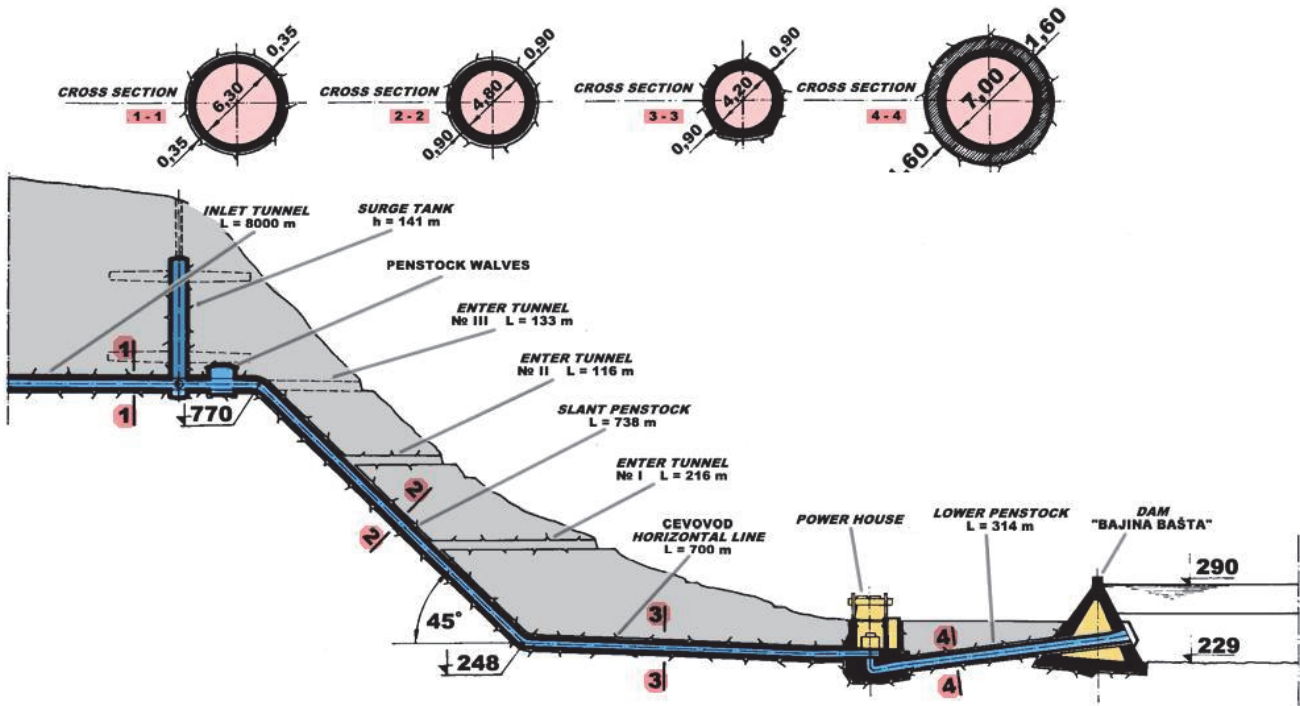


Figure 1: Disposition of penstock (upper and lower pipeline) "Bajina Bašta".

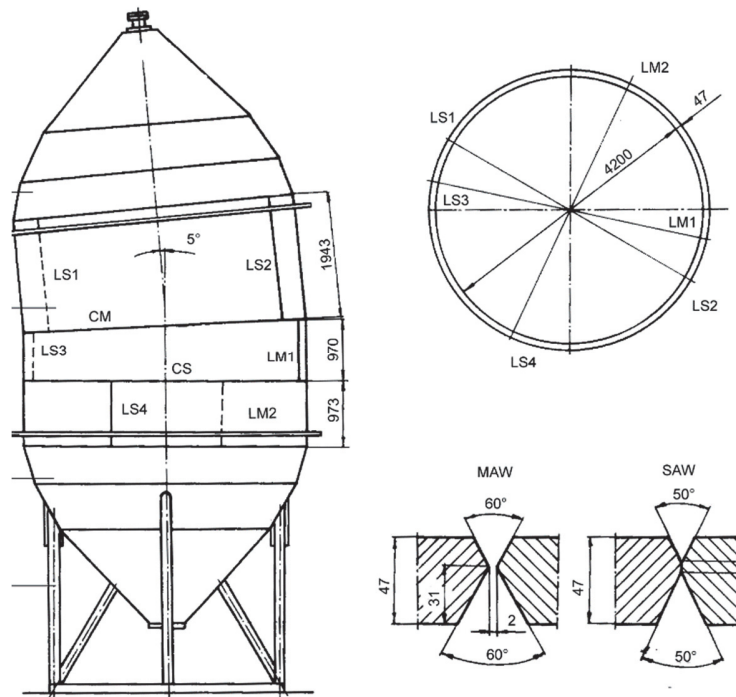


Figure 2: The full-scale model: L-Longitudinal, C-Circular; MAW – shielded manual arc welding; SAW-submerged arc welding



RHPP BAJINA BASTA – PENSTOCK DESIGN AND TESTING

Having in mind the importance of the penstock, special design procedure has been used, combined with extensive testing of the full-scale prototype, Fig. 2, including static, dynamic and fracture mechanics testing, based on the request to construct only one pipeline, made of steel with yield strength significantly higher than for the common structural steels. Therefore, SUMITEN HT80 was chosen, quenched and tempered weldable High Strength Low Alloyed (HSLA) steel, with nominal Yield Strength (YS) above 700 MPa, and Tensile Strength (TS) cca 800 MPa. Anyhow, welded joints made of such steels are well known for their susceptibility to cracking, making three stages hydrostatic proof testing of the model inevitable:

1. Loading from 0 to 3 MPa to check the measuring system.
2. Loading from 0 to 9.02 MPa, to reach the service stress.
3. Overloading (33.3%) from 0 to 12.05 MPa, as required by the regulation.

Full-scale model strains were measured by Strain Gages (SG) and Moiré grids, as described in details in [1,2]. In the base metal (BM) response was dominantly elastic, whereas plastic strain (0,24%) was registered in welded joint LS1 (SG2, SG34), indicating non-uniform, even strange behavior due to stress concentration and weld mismatching, as shown in [4].

		Potential consequences				Event Frequency				
		People	Property	Environment	Reputation	A	B	C	D	E
						Negligible	Low	Moderate	Medium	Large
0	No injuries	No losses	No damage	No harm						
1	Insignificant injuries	Loss up to 10 K€	Minor damage to environment	Insignificant consequences. Employees and population awareness.						
2	Minor injuries	Loss from 180 K€ to 540 K€	Minor consequence and damage to environment. Small costs..	Mild consequences. There is a concern at the local level.						
3	Serious injuries	Loss from 540 K€ to 1,8 M€	Moderate consequence. Short-term damage to environment..	Minor consequences. There is a concern at the regional level						
4	Permanent incapability	Loss from 1,8 K€ to 50 M€	Major consequences. Big damage to environment. Large costs.	Moderate consequences. There is a concern at the national level.						
5	Death	Loss over 50 M€	Dire consequences. Long-term and big damage. Huge costs.	Dire consequence. Concern and reaction at the international level.						

Table 1: Descriptive risk matrix, taken from [11].



RISK MATRIX

When observing the risk, possible consequences for the people, property, environment and reputation of the company should be considered. In the suggested model, we proposed a combination of qualitative and quantitative approach to the assessment of potential consequences, as given in Tab. 1 in the form of risk matrix, [7, 11]. Other aspects of risk based structural integrity assessment is given in [3-11].

As already shown in the case of pressure vessels that would cause air strike and significant damage, probably with fatalities, [7, 11], this is the case also with eventual penstock failure. The indirect damage would be the total stoppage of a reversible hydroelectric power plant for long period of time. Therefore, potential consequence in the case of penstock failure is certainly the highest one, category 5, since it would cause the collapse of the entire power plant.

Anyhow, the approach adopted here will not consider event frequency when probability is evaluated, since it has no relevance to the case considered. Instead, engineering approach will be applied, based on fracture mechanics concept, i.e. Failure Assessment Diagram (FAD), as described for different applications in [3-11].

FAILURE ASSESSMENT DIAGRAM APPLICATION

Failure Assessment Diagram, in its simplest form, i.e. level 1 as shown Fig. 3, enables one of the most efficient ways to assess structural integrity of a cracked component made of elastic-plastic material, such as HSLA steel. Basically, FAD indicates safe and unsafe position of a point corresponding to a given stress state for a cracked component, divided by so-called limit curve, Fig. 3:

$$K_r = S_r \left[\frac{8}{\pi^2} \ln \sec \left(\frac{\pi}{2} S_r \right) \right]^{1/2} \quad (1)$$

where $S_r = S_n / S_c$ and $K_r = K_I / K_{Ic}$, S_n stands for stress in net cross section, S_c for the critical stress (Yield Strength, Tensile Strength or any value in-between), K_I for the stress intensity factor and K_{Ic} for its critical value, i.e. fracture toughness.

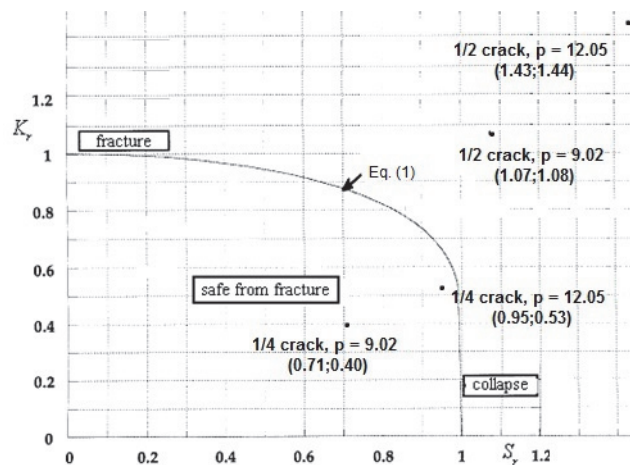


Figure 3: Failure Assessment Diagram, including assessment points for edge cracks.

Using experience and results of previous testing of the prototype, [1,2], two axial surface cracks are analysed here, both with length 90 mm, one with depth 11.75 mm (1/4 of penstock thickness, 47 mm), and the other one with depth 23.5 mm (1/2 of penstock thickness). Two loading cases are analysed, one being 9.02 MPa (design pressure), and the other one 12.05 MPa (hydrostatic proof testing pressure, 33.3% higher). Conservative assumption would be to consider cross-section as being just where the crack is, i.e. 90 mm wide and 47 mm deep (minus the crack depths), i.e. 3/4 or 1/2 of the original value, and use formulas for an edge crack, whereas S_c is taken as average value of YS and TS, i.e. 750 MPa:

- S_n is taken as **536 MPa**, for „1/4“ crack and **804 MPa** for „1/2“ crack, with remote stress **402 MPa** for $p=9.02$ MPa and **536 MPa** for $p=12.05$ MPa.
- $S_r = S_n / S_c = 536 / 750 = 0.71$ for $p=9.02$ MPa, **0.95** for $p=12.05$ MPa and „1/4“ crack.



- $S_r = S_n / S_c = 804 / 750 = 1.07$ for $p = 12.05$ MPa, **1.43** for $p = 12.05$ MPa and „1/2“ crack.
- $K_I = 1.39(pR/t)\sqrt{\pi a} = 1.39 \cdot 402 \cdot \sqrt{\pi} \cdot 11.75 = \mathbf{3402}$ MPa $\sqrt{\text{mm}}$ for $p = 9.02$ MPa and $a/t = 0.25$ or **4536** MPa $\sqrt{\text{mm}}$ for $p = 12.05$ MPa and $a/t = 0.25$.
- $K_I = 2.71(pR/t)\sqrt{\pi a} = 2.71 \cdot 402 \cdot \sqrt{\pi} \cdot 23.5 = \mathbf{9380}$ MPa $\sqrt{\text{mm}}$ for $p = 9.02$ MPa and $a/t = 0.5$ or **12507** MPa $\sqrt{\text{mm}}$ for $p = 12.05$ MPa and $a/t = 0.5$.
- $K_{Ic} = \sqrt{EJ_{Ic} / (1 - \nu^2)} = \mathbf{8548}$ MPa $\sqrt{\text{mm}}$ ($J_{Ic} = 316.6$ N/mm [13]).
- $K_r = K_I / K_{Ic} = 3402 / 8548 = \mathbf{0.40}$ ($p = 9.02$, 1/4), $4536 / 8548 = \mathbf{0.53}$ ($p = 12.05$, 1/4), $9380 / 8548 = \mathbf{1.08}$ ($p = 9.02$, 1/4), $12507 / 8548 = \mathbf{1.44}$ ($p = 12.05$, 1/2).

Therefore, the FAD coordinates obtained for cracks treated as through thickness cracks with depths being 1/4 and 1/2 half of thickness, are as follows, Fig. 1:

For 1/4 crack, $p = 9.02$ (0.71, 0.40), $p = 12.05$ (0.95, 0.53).

For 1/2 crack, $p = 9.02$ (1.07, 1.08), $p = 12.05$ (1.43, 1.44).

Clearly, this is overconservative estimation since both material and crack geometry are presented in conservative way. Anyhow, even this simple analysis indicates detrimental effect of over-pressurizing, since the points corresponding with it are way out of the safe region (1/2 crack), or very close to the limit curve (1/4 crack), Fig. 3.

Less conservative assumption would be to consider cracks as they are, i.e. treat them as surface cracks. In that case reduction of cross-section is negligible, so S_n and S_r are calculated as follows:

- $S_n = pR/t = 9.02 \times 2.1 / 0.047 = 402$ MPa,
- $S_n = pR/t = 12.05 \times 2.1 / 0.047 = 536$ MPa.
- $S_r = S_n / S_c = 402 / 750 = 0.54$
- $S_r = S_n / S_c = 536 / 750 = 0.72$

Stress intensity factor for surface edge crack in a plate can be evaluated using the following procedure from [14]. Plate is taken as better approximation than thin cylinder, since the ratio B/r_1 is just $47/2100 = 0.023$, i.e. much closer to 0 than to 0.1, which is the lowest value for cylinders in [14].

Geometry parameters F and Q are calculated for tensile plate with a surface crack ($a/2c = 0.13$ for 1/4 crack and ≤ 1) at the point of maximum stress intensity factor ($\varphi = 90^\circ$) as follows:

$$Q = 1 + 1.464 \left(\frac{c}{a} \right)^{1.65} = 1.08 \text{ for } 1/4 \text{ crack and } 1.22 \text{ and for } 1/2 \text{ crack,}$$

$$F = \left[M_1 + M_2 \left(\frac{a}{t} \right)^2 + M_3 \left(\frac{a}{t} \right)^4 \right] g f_\varphi f_w = 1.102 \text{ for } 1/4 \text{ crack and } 1.033 \text{ and for } 1/2 \text{ crack,}$$

$$M_1 = \left[1.13 - 0.09 \left(\frac{c}{a} \right) \right] = 1.106 \text{ for } 1/4 \text{ crack and } 1.108 \text{ and for } 1/2 \text{ crack,}$$

$$M_2 = 0.54 + \frac{0.89}{1 + a/c} = 1.39 \text{ for } 1/4 \text{ crack and } 0.7 \text{ and for } 1/2 \text{ crack,}$$

$$M_3 = 0.5 - \frac{1}{0.65 + \frac{a}{c}} + 14 \left(1 - \frac{a}{c} \right)^{24} = -0.589 \text{ for } 1/4 \text{ crack and } -0.355 \text{ and for } 1/2 \text{ crack,}$$

$$g = 1 + \left[0.08 + 0.15 \left(\frac{c}{t} \right)^2 \right] (1 - \cos \varphi)^3 = 1$$

$$f_\varphi = \left[\left(\frac{c}{a} \right)^2 \sin^2 \varphi + \cos^2 \varphi \right]^{1/4} = 1, f_w = \left[\sec \left(\frac{\pi c}{2W} \sqrt{\frac{a}{t}} \right) \right]^2 = 1$$

Now, for $a/t=0.25$ one can calculate $K_I=2837 \text{ MPa}\sqrt{\text{mm}}$ for $p=9.02 \text{ MPa}$ and $3777 \text{ MPa}\sqrt{\text{mm}}$ for $p=12.05 \text{ MPa}$, whereas for $a/t=0.5$ $K_I=4012 \text{ MPa}\sqrt{\text{mm}}$ for $p=9.02 \text{ MPa}$ and $5341 \text{ MPa}\sqrt{\text{mm}}$ for $p=12.05 \text{ MPa}$. Finally, assessment points coordinates in FAD are, Fig. 4:

For $1/4$ crack, $p=9.02$ (0.54, 0.33), $p=12.05$ (0.54, 0.46). Corresponding probabilities are 0.58 and 0.62.
 For $1/2$ crack, $p=9.02$ (0.72, 0.44), $p=12.05$ (0.72, 0.62). Corresponding probabilities are 0.75 and 0.82.

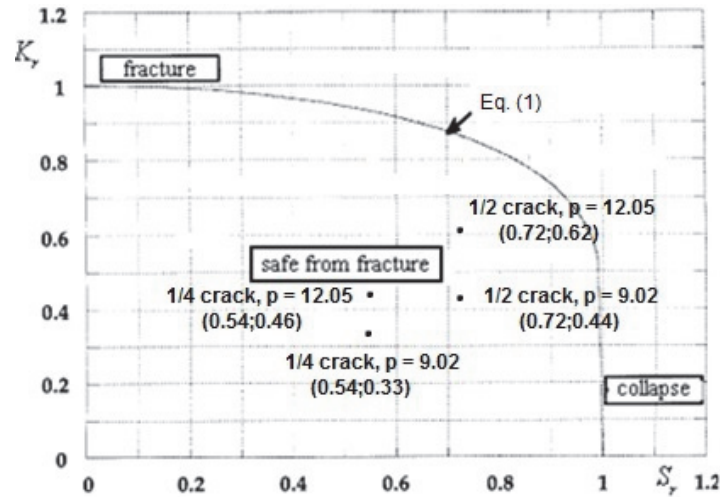


Figure 4: Failure Assessment Diagram, including assessment points for surface cracks

Now, one can get risk matrix in usual way, as presented in Tab. 2, indicating shift from high (0.58) to very high risk (0.62), for $1/4$ crack, or from very high (0.75) to extremely high risk (0.82) for $1/2$ crack.

Probability category	Consequence category					Risk legend
	1 – very low	2 - low	3 - medium	4 - high	5 - very high	
≤ 0.2 very low	Very low	Very low	Very low	Very low	Very low	Very low
0.2-0.4 low	Very low	Low	Low	Low	Low	Low
0.4-0.6 medium	Low	Low	Medium	Medium	1/4 crack $p=9.02 \text{ MPa}$	Medium
0.6-0.8 high	Medium	Medium	High	High	1/4 crack $p=12.05 \text{ MPa}$ 1/2 crack $p=9.02 \text{ MPa}$	High
0.8-1.0 very high	High	High	Very High	Very High	1/2 crack $p=12.05 \text{ MPa}$	Very High

Table 2: Risk matrix for $1/4$ crack and $1/2$ crack, $p=9.02 \text{ MPa}$ and 12.05 MPa .

DISCUSSION

The approach so far presented is the simplest one which takes into account crack geometry and material behaviour. Being the simplest it is not the most accurate one, lacking precise stress distribution, especially in weld joint zones. Namely, as shown previously, [1,2], stress concentration can cause local plastic deformation in welded joints made by SAW, in the case of overpressure, since they have the lowest Y_S (687 MPa). To take into account such effects, more sophisticated approach is needed, e.g. Japp vs. J-R curve analysis, based on more complex analytical solutions for J, [1,2]. Here, such an analysis is briefly presented, as shown in Fig. 5. Corresponding critical values (0.91· Y_S for WM and 0.92· Y_S for BM in the case of $1/4$ crack, or 0.82· Y_S for WM and 0.85· Y_S for BM in the case of $1/2$ crack, can be taken as inverse of

probability, but this is beyond the scope of this approach since its basic advantage, simplicity, would be lost. Anyhow, one can notice that overpressure in weld metal can reach the critical state, since only 563 MPa would cause unstable crack growth in SAW weld metal with $\frac{1}{2}$ crack, whereas operating pressure would not jeopardize penstock integrity even in that case.

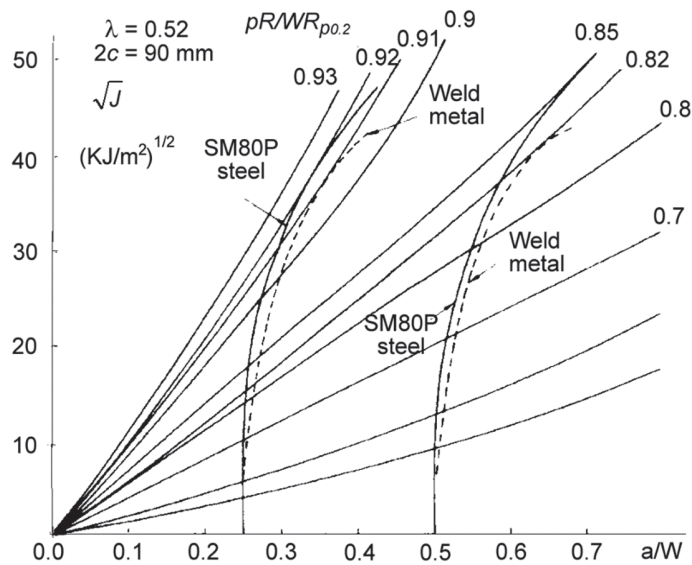


Figure 5: Crack driving force vs. J-R curves for BM and WM.

CONCLUSIONS

Based on the results shown here, one can conclude the following

- Risk based analysis using fracture mechanics parameters, as presented here, is efficient engineering method to assess structural integrity of a cracked component, especially if its geometry is relatively simple.
- Effect of over-pressure is detrimental from the point of view of structural integrity since it can cause unnecessary damage of welded joints, as the most crack sensitive regions. Both simple engineering method, as presented here, and previously performed more complex fracture mechanics analysis, lead to that conclusion.

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