THE NEW PENSTOCK FOR THE HIGH HEAD HYDROPOWER PLANT KAUNERTAL

Part 2

Analysis methods and material properties for the high ductility concept

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Abstract: This paper shows how the analyses with fracture mechanic methods for the penstock of the high head hydropower plant Kaunertal have been made. Besides the analyses the experiences of material testing, welding and the connection to well-known standards for steel building will be presented. The main goal was to ensure the integrity of the penstock for the whole service life of 100 years. A high strength ductile material had to be found which allows high possible deformations and withstands cracks and failures which may grow under variant loading conditions. These cracks have to be noncritical until the end of the service live.

1 Introduction

Due to the high head and the size of the penstock the realization of the steelworks are challenging. Besides the static stress analyses and the fatigue strength analyses also fracture mechanic analyses were carried out to ensure the integrity of the structure.

Fracture mechanics has to be seen as a tool to deal with cracks and flaws in a construction. In 1983, the National Bureau of Standards and Battelle Memorial Institute estimated the costs for failure due to fracture to be $119 billion dollars in the United States per year. This study estimated that the annual cost could be reduced by $35 billion if the current technology from 1982 were applied, and that further fracture mechanics research could reduce this figure by an additional $28 billion [1].

Failures have occurred for many reasons, including uncertainties in the loading or environment, defects in the materials, inadequacies in design, and deficiencies in construction or maintenance. Design against fracture is an important part of the design process. The designers should be cautioned about the need to consider absolutely as many factors as possible that might lead to failure, especially when life is at risk.

The basic structural analysis is carried out by comparing the applied stress with the allowable stress. The allowable stress is normally defined as a fraction of the yield strength or the tensile strength. In fracture mechanics the applicable load depends on the fracture toughness of the material and the flaw size in the structure. This correlation is better known as the fracture mechanics triangle (Fig. 1).

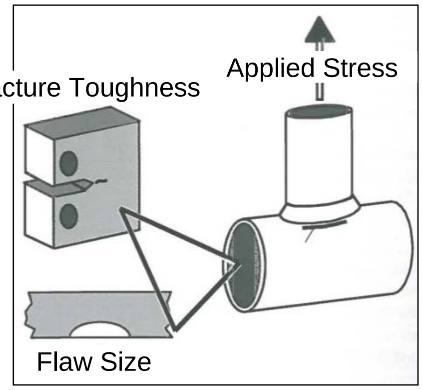

Fig. 1. Fracture mechanics triangle [2]

2 Fracture Mechanic Analysis by FAD

To determine if a crack may cause a structural failure, the failure assessment diagram (FAD) method uses two ratios: brittle fracture and plastic collapse. The FAD method is described in the FKM-Guideline “Fracture Mechanics Proof of Strength for Engineering Components” [3].

The axes of the FAD chart use the non-dimensional ratios Lr (plastic collapse ratio) on the x-axis, and Kr (brittle fracture ratio) on the y-axis. The evaluation points inside the FAD curve indicate acceptable cracks, and the evaluation points above the FAD curve are unacceptable cracks that indicate a predicted structural failure. The plastic collapse ratio is computed using the reference stress divided by the yield strength. The brittle fracture ratio is computed from the crack front stress intensity, obtained by the crack geometry and the stresses at the crack.

An example of the default FAD curve and crack evaluation points in the diagram is shown in Figure 2. An evaluation point on the FAD curve is a critical crack on the verge of failure, which can be useful to determine if residual stresses in component are harmful. When an analysis for a specific structural component and a stress-strain curve is available, a material specific FAD can be computed.

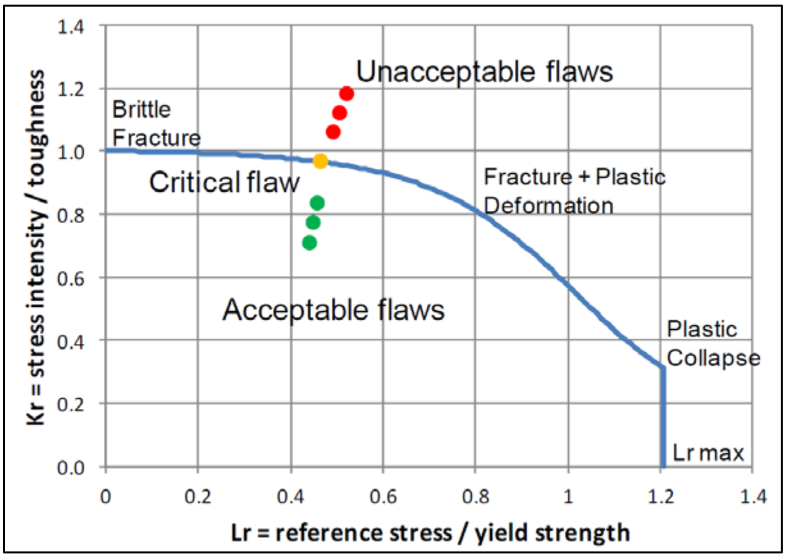

Fig. 2. Example of the FAD and crack evaluation points [4]

3 Detail design consideration

In the detail design for the shaft and its elements e.g. bifurcations, bends, thrust rings etc. it is necessary to take additional stresses into account. Influences like bending effects, notch effects, residual stresses and other components have to be considered to get realistic stresses for the fracture mechanic analysis.

In production and assembly relevant defects and cracks are found by NDT and all intolerable defects are repaired to receive an almost faultless structure. The tolerable or undetected defects are far too small to be significant in a static fracture mechanic analysis. But in a dynamically stressed structure these defects are subjected to growth. Therefore the relevant crack size to be analysed comes from the grown crack at the end of the service life.

Eurocode 3 Part 1-10 [5] gives recommendations on the required number of main inspection intervals to find growing cracks in the operation period (equation 4). To avoid main inspections (NDT of all important welds) during the service life the partial safety coefficients should be at least $\gamma_F = 1.2$ and $\gamma_M = 1.1$ for the fatigue analysis.

$$n = \frac{4}{(\gamma_F \gamma_M)^5} - 1$$

n ... number of main inspections γ ... partial safety coefficients

The crack size considered in the analysis has to be selected in an appropriate way. In a background document to the EC3-1-10 the initial crack size and the size of the design crack at the end of service are defined according to table 1 and figure 2. The table gives the crack geometry for a detailed fracture mechanic analysis dependent on the wall thickness.

	Initial crack size		Design crack size	
t mm	a_0 mm	$2c_0$ mm	a_d mm	$2c_d$ mm
30	1.7	8.5	5.3	10,6
50	2.0	9.8	9.1	18,2
90	2.2	11.2	19.0	38,0
120	2.4	12.0	28.8	57,6

Table 1: Initial crack size (a_0, $2c_0$) and design crack size (a_d, $2c_d$) [5]

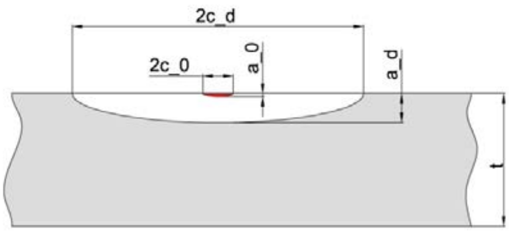

Fig. 3. Initial crack size (a_0, $2c_0$) and design crack size (a_d, $2c_d$)

To calculate the stress intensity in the detail design the equations for a plate in tension and bending are used. These equations assume a defined half-elliptic surface crack.

The examination of the longitudinal and circumferential welds for the cylindrical part of the shaft can be done easily. In these welds the additional stress components are mainly caused by residual stresses of the welding procedure. For the welds in "as welded condition" (AW) the residual stresses are conservatively assumed to be 100% of the yield strength. For welds with post weld heat treatment (PWHT) the residual stresses are reduced to 25% of the yield strength.

Other stress components are depending on the production standards. Bending stresses due to misalignment of weld edges are negligible because the misalignment is restricted to 1 mm or 5% of the wall thickness whatever is lower (e.g. Δt = 1mm for t = 50 mm and $\sigma_m = 0.6\ R_{p0,2}$ gives $\sigma_b = 0.02\ R_{p0,2}$).

4 Fracture mechanic analysis example

Especially for special components like bifurcations and segment-bends a fracture mechanic analysis can be very useful to decide if post weld heat treatment is necessary.

In this paper I want to show you the analysis on the bifurcation which connects penstock and surge tank. The design and structural mechanic analysis was made by our contractor for the steelworks - Andritz Hydro GmbH in Linz. In Figure 4 the bifurcation and the segment bend to the surge tank is shown.

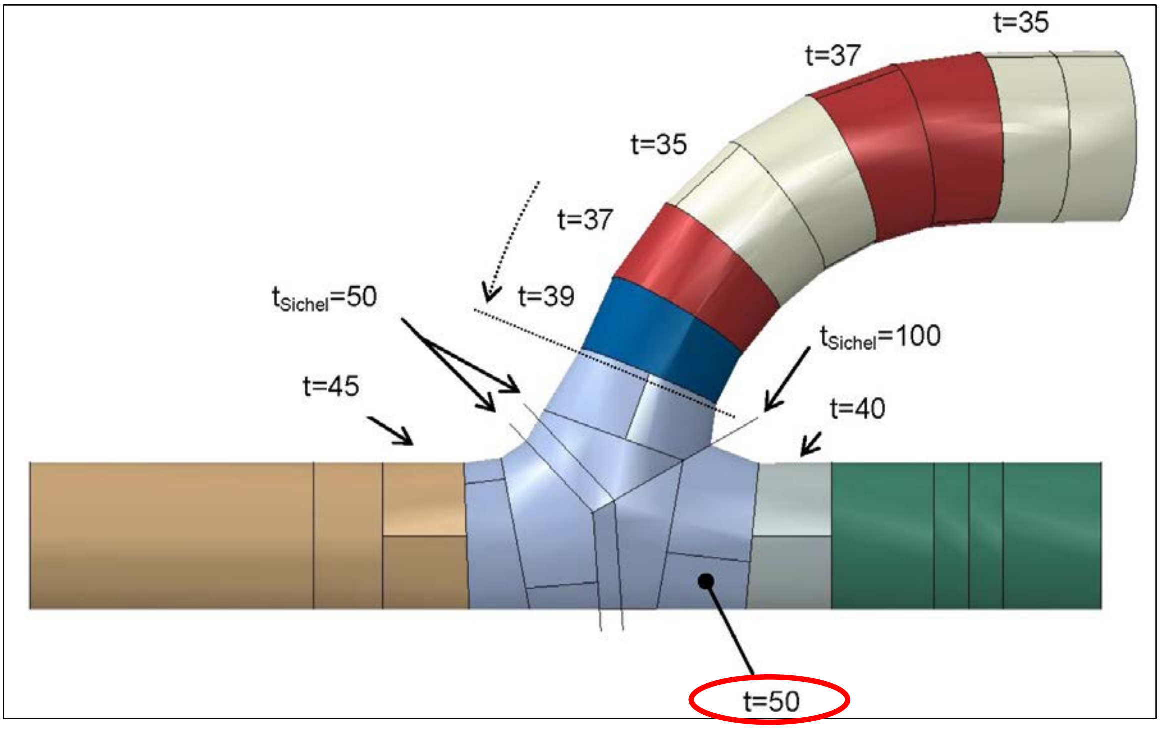

Fig. 4. Bifurcation to the surge tank - wall thicknesses

The structural mechanic analysis under maximum static pressure and dynamic pressure fluctuation was made by Andritz Hydro. The numerical calculations are made with ABAQUS 6.12, a standard finite element program.

To find the maximum load case many simulations had to be done. In Figure 5 you can see the result for the maximum principal stresses in the worst load case.

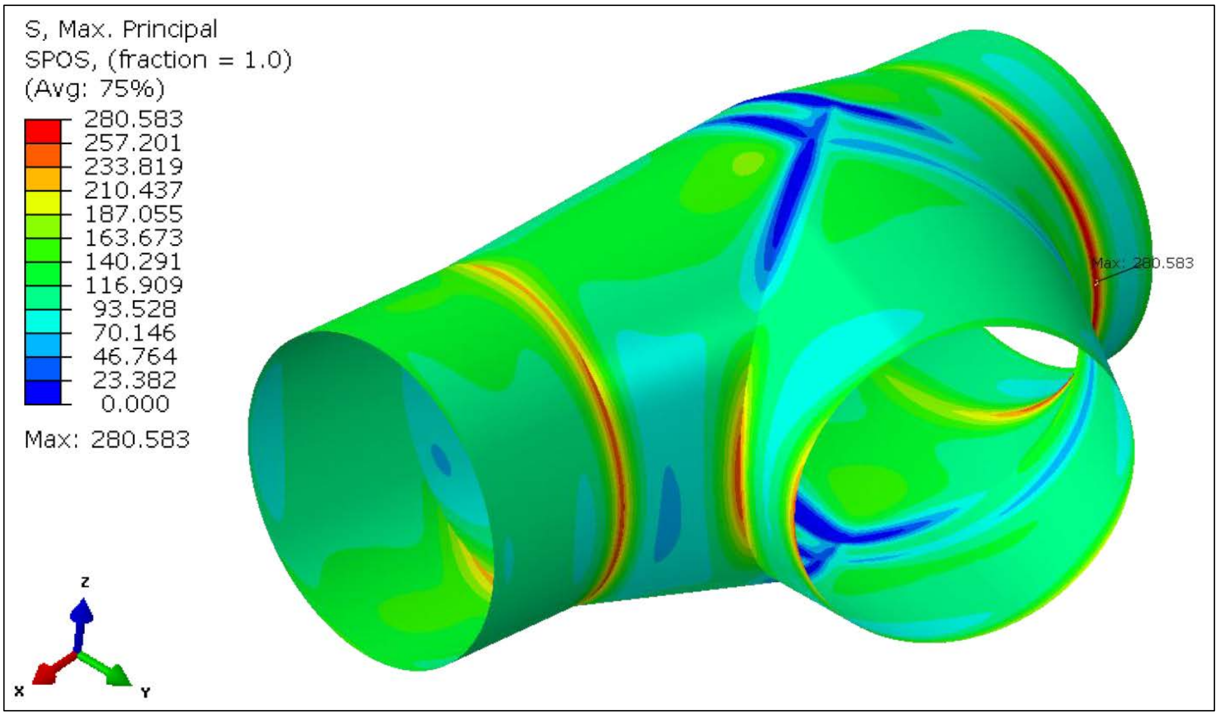

Fig. 5. Bifurcation to the surge tank - maximal principal stresses calculated by finite elements

The maximum stress in the outer section of the shell model is σ_{max} = 280,6 MPa. To be conservative it is assumed that this stress is constant over the wall thickness. Besides the stress the material properties are needed for the analysis.

Material	Aldur 580/820QL		
Yield strength [min]	$R_{p0,2}$	580	MPa
Tensile strength [min]	R_m	820	MPa
Yield ratio [max]	$R_{p0,2}/R_m$	0,92	-
Wall thickness	t	50	mm
Welding procedure	MAG		
Crack resistance [min]	$J_{0,2}$	80	N/mm

Table 2: Material properties for the bifurcation

For the known wall thickness the design crack can be defined by Table 1. It’s a 9,1 mm deep and 18,8 mm long crack on the surface. The brittle fracture ratio Kr takes primary stresses from external loads like internal pressure and secondary stresses like residual stresses from welding. The assumed residual stresses are about the yield strength of the base material. The calculation is summarized in Table 3.

Crack analysis			
Primary Stress (Internal Pressure, …)		280,6	N/mm²
Secondary Stress (Residual Stress, …)		580,0	N/mm²
Form Factors (depending on crack geometry and configuration)	M1	1,040	-
	M2	0,202	-
	M3	-0,106	-
	g	1,000	-
	Q	2,464	-
	f_phi	1,000	-
	p	1,309	-
	H1	0,918	-
	H2	0,755	-
Primary Stress Intensity Factor - K_p		1000	MPa√mm
Secondary Stress Intensity Factor - K_s		2066	MPa√mm
Plasticity	zeta	0,028	-
	a_{eff}	9,763	mm
	K_{s_pl}	2141,6	MPa√mm
	beta	3	-
	$K_{s\_p} / (K_p / L_r)$	1,049	-
	psi	0,092	-
	phi	0,682	-
	rho	0,116	-
Brittle fracture ratio - K_r		0,83	-
Plastic collapse ratio - L_r		0,49	-

Table 3: Fracture mechanic analysis according to FKM [3]

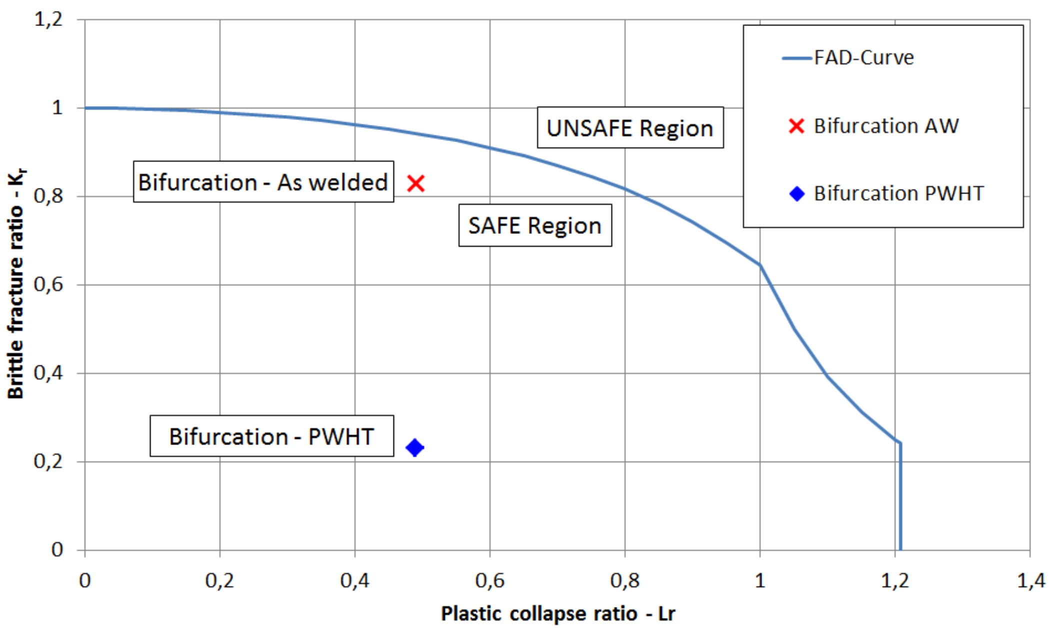

Fig. 6. FAD for the Bifurcation to the surge tank – AW and PWHT

Figure 6 shows that a post weld heat treatment for the bifurcation welds is not necessary. The effect of the residual stress in the weld is not critical for the bifurcation.

5 Material properties

As a big part of the quality assurance for the penstock a lot of material testing was made. All assembled steel sheets were tested on its mechanical properties and every heat also on its chemical composition. The following figure shows how the uniform elongation relates to the Strength for the Alform 580/820M. This steel grade was used for a big part of the penstock. Voestalpine satisfied the specification very well.

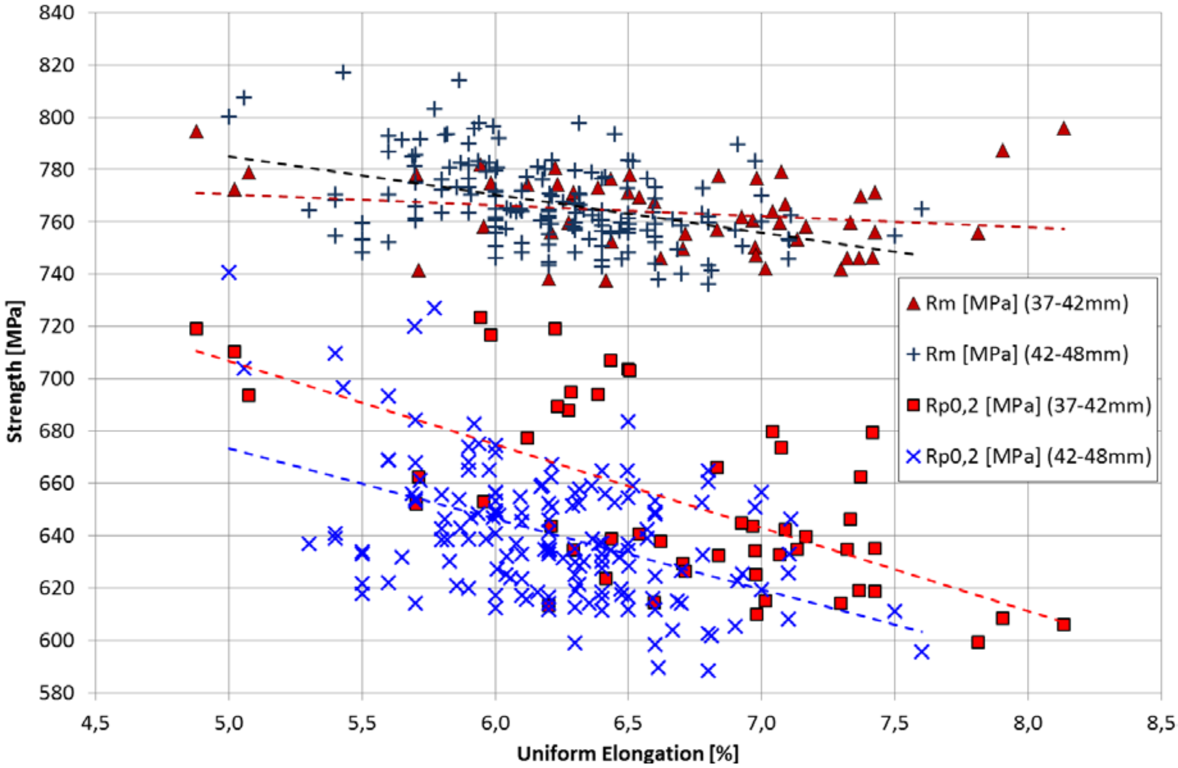

Fig. 7. Relation of Uniform Elongation to Strength – Alform 580/820 from voestalpine

For every welding procedure a qualification WPQ had to be made to prove the specified characteristics. Whenever a new charge of welding material was used it had to be tested again. Also if welding parameters were changed the characteristics had to be tested again. From all this qualification, charge and working tests a pool of test results was gathered for every welding procedure.

Almost 90% of the 14.300 m of welds were made in the workshop with submerged arc welding (SAW). In Figure 9 and Figure 10 the correlation of uniform elongation to strength and ductility (notch impact energy and crack resistance $J_{0,2}$) is shown. These are the result from several tests (positive and negative) for SAW. The results are divided in high strength welds (mean value of tensile strength > 830 MPa) and low strength welds (mean value of tensile strength > 700) [6].

Similar to the results from the base material it shows that ductility and strength are correlating. But the variation of the results is very high. Most of the test satisfied the specification we made and were positive tested.

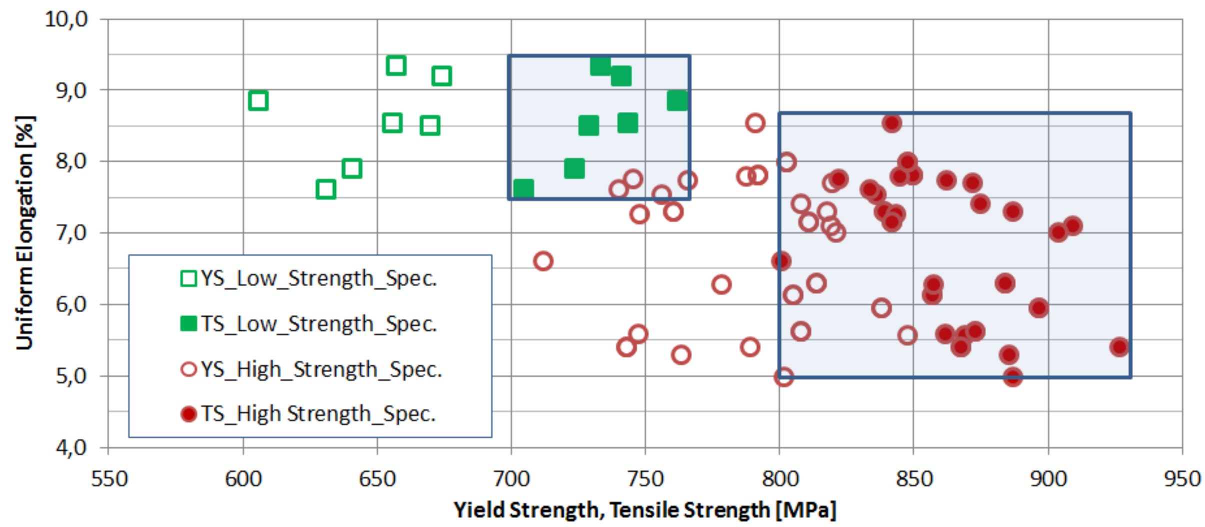

Fig. 9. Relation of uniform elongation to strength (SAW)

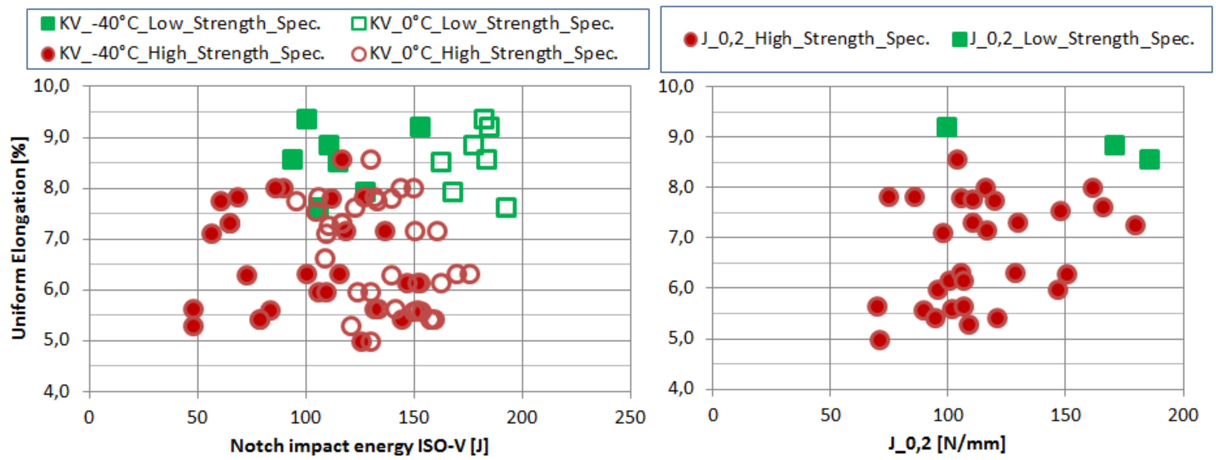

Fig. 10. Relation of uniform elongation to Notch impact energy and fracture toughness as $J_{0,2}$ (SAW)

6 Conclusion

Due to the high head and the size of the penstock the realization of the steelworks is challenging. With fracture mechanic analyses the integrity of the structure was evaluated for the whole service life. Additionally these analyses demonstrated that post weld heat treatment is only necessary for parts over 50 mm thickness. Therefore the heat treatment was only necessary for the bifurcations and some longitudinal welds near the powerhouse.

Besides it's important to specify the material properties properly and do tests on the materials to ensure its characteristics. For this purpose a defined number of tests on mechanical properties, chemical composition and fracture resistance has to be carried out. Based on a universal quality assurance program with continuous adaption to extraordinary occasions the integrity of the penstock is granted.

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