The Renewal of the Pressure Shaft for the High Head Hydropower Plant Kaunertal in Austria
Part 2: Material Properties – Analysis, Testing and Specification

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Abstract

The new shaft for the HPP Kaunertal will be highly stressed and strained due to its size and water head. The high static pressure and the exceptional dynamic loads from the plant operation require particular considerations, which were unusual in the past. To support steel lining design and material specifications development prior to contract award, the tolerable steel strength vs. ductility, the compatibility between pipe material and welding material and the brittle fracture behaviour was investigated. In particular the high performing steel and welding materials require detailed fracture mechanic analysis to determine if selected materials fit into project requirements.

Extensive tests were carried out on sample pipes by the bidders to select steel and welding materials. Substantial parts of these tests were made on a full-size model of the pipe to simulate realistic welding conditions. Analysis of the tests brought interesting results and dependencies on material strength, welding process, filler material and other parameters.

Introduction

The new underground pressure shaft is designed as the conduit for the existing HPP Kaunertal and the planned extension HPP Prutz 2. The nominal flow will be 122 m^3/s under a geodetic head of 896 m. It comprises an inclined and a horizontal section, followed by the bifurcation with branches and adit pipes to the powerhouses. The branch for the future extension will get a blind cover. The adit for the HPP Kaunertal will be connected to the existing conduit with a second bifurcation.

The construction concept for the pressure shaft is a steel liner embedded in rock, backfilled with concrete and grouted. The inclined section is bored with a TBM, the rock is supported with precast concrete segments that are grouted with mortar. The horizontal sections are excavated by conventional drill and blast and the rock supported with shotcrete and bolts. The branches of the bifurcations need access for the future connecting installations, so they are arranged without embedment.

The main data for the steel liner are:

- Inclined section: length 1,430 m, inner diameter 4.3 m, slope 60 %;
- Horizontal section: length 180 m, inner diameter 4.3 m
- Adit pipe to the existing HPP Kaunertal: length 100 m, inner diameter 3.1 m
- The maximum internal pressure is 100 bar
- The embedment is considered to bear a maximum of 30 % of the internal pressure

In this paper we describe the steps to find the optimum material for the steel-lining, the bifurcations and the welds. The design and basic material specifications are described in [1].

Basic considerations

The dimensioning of steel pipes or bifurcations under internal pressure is normally done with the consideration of idealized behaviour for steel plates and its welds. Faults and defects implemented during the pipe manufacture or the welding process, potential for crack initiation or propagation due to loads, load concentrations and non-uniform load distribution are not considered in the standard design process.

The criteria for high ductility are substantial uniform elongation (A_g) and high notch impact energy (Charpy-V-test), but these properties are not directly used in the dimensioning process since only material properties within the elastic stress-strain region are considered.

Driven by economic benefits and by the need to limit the steel plate thickness in order to prevent post weld heat treatment at the site of erection, steel of higher strength is preferred. It is obvious that for high-tensile steel the uniform elongation A_g decreases significantly as the yield strength rises, and it is also known that other ductility criteria decrease approximately in the same manner.

The consequences of faults and defects were investigated thoroughly by TIWAG and external experts. The first aim was the prevention of defects as far as possible with reasonable measures. This aim will be regarded in the manufacture of the steel plates and in the welding process. The second aim was to specify materials which promise reasonable high resistance against initiation and propagation of cracks. The third aim was to ensure detection of small defects with Non Destructive Testing (NDT).

Fracture mechanic analysis

For many applications, it is sufficient to determine the maximum static or dynamic stress the material can withstand and to design the structure in such a way that the stresses remain below acceptable limits. This involves fairly routine constitutive modelling and numerical or analytical solutions of appropriate boundary value problems. More critical applications require some kind of defect tolerance analysis. In these cases, the material or structure is considered to contain cracks due to fabrication or loads. For this assumption a fracture mechanic analysis has to be carried out.

The resistance against crack initiation and crack propagation is lower for high strength steel in comparison to lower strength steel of the same quality standard. Therefore the allowable size of defects (i.e. cracks) decreases significantly for high strength steel due to the lower crack resistance and the higher allowable stress level.

Preliminary design with a “through-wall-crack”

In the preliminary design fracture toughness-values are calculated based on circumferential membrane-stress to identify the criticality of brittle fracture for the penstock and bifurcation pipes. Initially wall thickness is calculated based on the allowable stress (equation 1). A standardized “through-wall-crack” is introduced into the design model. The length of the assumed through- wall crack is twice the thickness of the wall.

$$t = p \frac{D}{2 \cdot k \cdot R_{p0,2}} \quad (1)$$

t ... wall thickness [mm] p ... rated pressure [N/mm²] D ... internal diameter [mm]
k ... load factor [-] $R_{p0,2}$ ... yield strength [N/mm²]

The stress intensity factor K for the trough wall crack can be determined with fracture mechanics analysis [2]. K depends on the applied stress from internal pressure, the crack size and the form factor F_m. So if equation (2) is true the material withstands the supposed crack under the load of the membrane stress in the pipe.

$$p \frac{D}{2 \cdot k \cdot R_{p0,2}} \leq \frac{1}{\pi} \left[\frac{K}{0.6 \cdot R_{p0.2} \cdot F_m} \right]^2 \qquad F_m = f\left(\frac{c_0}{\sqrt{r_i \cdot t}}\right) \quad (2)$$

K ... stress intensity factor [MPa√mm] $2c_0$ ... crack size (width) [mm]
r_i ... internal radius [mm] F_m ... form factor [-]

$$J = \frac{K^2}{E/(1-\nu^2)} \quad (3)$$

J ... J-Integral [N/mm] E ... Young's modulus [N/mm²] ν ... poisson ratio [-]

The stress intensity factor K required to fulfil equation 2 and the corresponding J-Integral from equation 3 gives a raw estimate of the required steel quality for the envisaged lining. The criticality of brittle failure at a certain point in the steel lining can be evaluated depending on diameter, pressure and the J-Integral (Fig. 1).
Two examples for the Kaunertal-shaft DN3100 (adit pipe) and DN4300 (pressure shaft) are indicated, which would suggest that the fracture toughness of the steel material shall have J > 80 N/mm for the adit pipe and J > 110 N/mm for the pressure shaft.

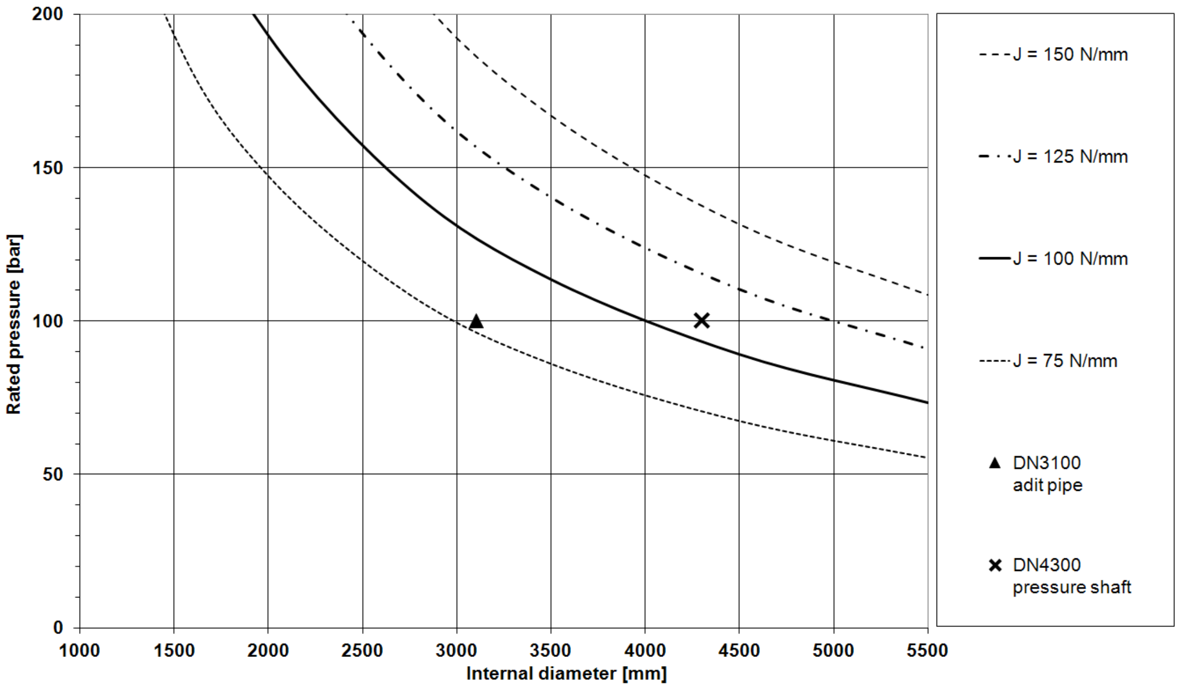

Figure 1: J-Integral for through wall cracks ($2c_0 = 2_t$, hoop stress σ = 0.6*580 N/mm²)

Detail design consideration to avoid brittle fracture

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 [3] 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.

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

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 [4] 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.

Table 1: Mechanical properties of the pipe material

	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	26.3
50	2.0	9.8	9.1	45.4
90	2.2	11.2	19.0	95.1
120	2.4	12.0	28.8	144.1

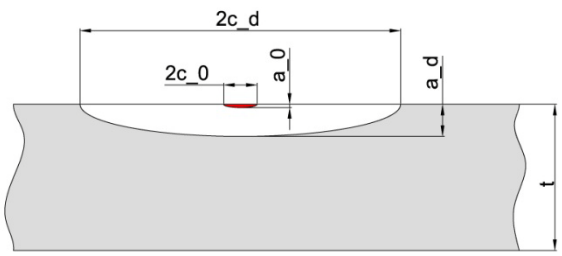

Figure 2: Initial crack size (a0, 2c0) and design crack size (ad, 2cd)

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 [2].

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 $\sigma_b = 0.02\ R_{p0,2}$).

Table 2: J-Integral [N/mm] for longitudinal welds ($\sigma_m = 0.6\ R_{p0,2}$)

Wall thickness \ Residual stress	100% AW	75%	50%	25% PWHT	0%
30 mm	59	42	28	17	8
50 mm	102	73	48	29	14
90 mm	217	155	103	61	31
120 mm	336	239	159	95	47

J > 120 N/mm

Table 3: J-Integral for circumferential welds ($\sigma_l = 0.3\ R_{p0,2}$)

Wall thickness \ Residual stress	100% AW	75%	50%	25% PWHT	0%
30 mm	39	25	15	7	2
50 mm	67	44	25	12	4
90 mm	143	94	54	26	8
120 mm	222	145	84	40	12

J > 120 N/mm

The calculated J-Integral values in table 2 and 3 define the crack tip load for the analyzed cracks and stresses. To ensure safety against brittle fracture these values have to be lower than the allowable material parameter. In the specification for the new Kaunertal-shaft the target value for the J-Integral is taken $J_{0,2}$ = 120 N/mm (table 4).

Material Testing

Extent of testing
For the new Kaunertal Pressure Shaft a large number of material tests were executed. The program included tests of mechanical properties, toughness properties and chemical composition of the materials.
To meet realistic boundary conditions the testing program started with a pilot test on a full-scale model. This pilot test in advance of the contract signing led to clearer specifications.
For each welding method used in the production of the penstock a qualification for the welding procedure was made. Special interest was given to the fracture mechanic behaviour.

During the main assembly works, welded work samples will be tested on their fracture mechanic characteristics similar to the pilot test to ensure the quality and to get experience in the variation of results to be expected. To assure that fracture mechanic properties are met, steel plates with more than 40 mm thickness will be tested as well.

Pilot Test
Near to site-conditions were defined for the pilot-tests. The tests should indicate the main parameters for high and repeatable welding-quality, quality-proving, sound and save working conditions as well as optimum working-progress.

The pilot-test covered:

- rolling of steel plates
- longitudinal welding of pipes with a diameter of 4300 mm
- 30°inclination of pipes and test plates
- joining of four pipes by circumferential welding
- proving the quality of steel and welds by destructive and non-destructive testing

Three bidders took part in the pilot tests, their expenses were remunerated by TIWAG with a lump sum. TIWAG bought various grades of steel plates from three different steel-mills. The tests were supervised by testing personnel authorized by TIWAG. Also were the representatives of the state authority invited to visit the tests.

The bidders work covered all welding methods anticipated for the completion of the shaft lining. Factory welding tests involved

- longitudinal and circumferential welds of pipes with submerged arc welding (SAW)
- welds on other components (e.g. bifurcations) with gas metal arc welding (GMAW)

In the case of site welding representing the work in the shaft, the welding procedure depended on the bidders choice covering

- circumferential welds produced by shielded manual arc welding (SMAW); manual or semi-automatic gas metal arc welding (GMAW); manual or semi-automatic flux-cored arc welding (FCAW); gas tungsten arc welding (GTAW) with hot wire (HW) and with narrow gap (HW-NG)

The value t8/5 representing the cooling time [s] from 800° to 500°C was measured in the tests. It was found for the selected test specimen (D*L*s = 1000*500*40 AW, D*L*s = 2000*500*≥50 PWHT) that the heat input and heat transfer at the plain plate (Figure 3) was the same as on the rolled plate. It was therefore decided that test results for plates were also valid for the finished pipe.

Figure 3: Welding of plain plates in upwards position and 30° inclination

Requirements defined for the pilot-test

During the execution of the pilot-test all processes were consequently surveyed and recorded by the TIWAG Testing Engineer. Each single component, the rolled steel pipe, the weld material, the welding procedure, the quality process and the personnel working on the product was tested. This created a closed loop of information on the whole product.

Requirements for the steel plates:

- mechanical properties to be tested at a temperature of 0°C
- tensile strength Rm for the steel plates to be limited, in order to provide over-matching of the filler material

Requirements for the filler material:

- assure over-matching of the filler material in terms of yield strength and tensile strength
- align mechanical properties with the properties of the pipe material

Requirements for the welding processes:

- high ductility
- little introduction of hydrogen
- ensure a low defect rate (unavoidable defects must be noncritical)
- ensure a high level of repeatability (automation, low exposure of welding personnel)

Requirements for the quality control:

- complete record of all working processes and test results
- measurement of cooling time t8/5
- ultrasonic scanning of welds with TOFD/phased array systems
  (which allow detection of nearly all defects, recording on data-loggers and post-processing of defects is enabled)

Material characterization for the fracture mechanic analysis

Several fracture mechanics tests were carried out to find the achievable crack resistance. To characterize the fracture resistance for the Kaunertal pressure shaft the $J_{0.2}$ value is used. This value is the vertical intersection at $\Delta a = 0.2$ mm with the crack growth resistance curve (Polynom) shown in figure 4. The value is dependent on material, size and geometry. With respect to a limited multiaxiality [5] it is convenient to use this value as the allowable value for the material characterization. The test results suggested to reach the values presented in table 4 in the works to assure acceptable material performance.

The only way to characterize fracture resistance independent of size and geometry would be to record J_i by measuring the SZW (Stretch Zone Width), which defines the actual crack initiation, with a scanning electron microscope. To investigate each specimen in such a way would be too time consuming for the large number of samples and the ongoing test during production.

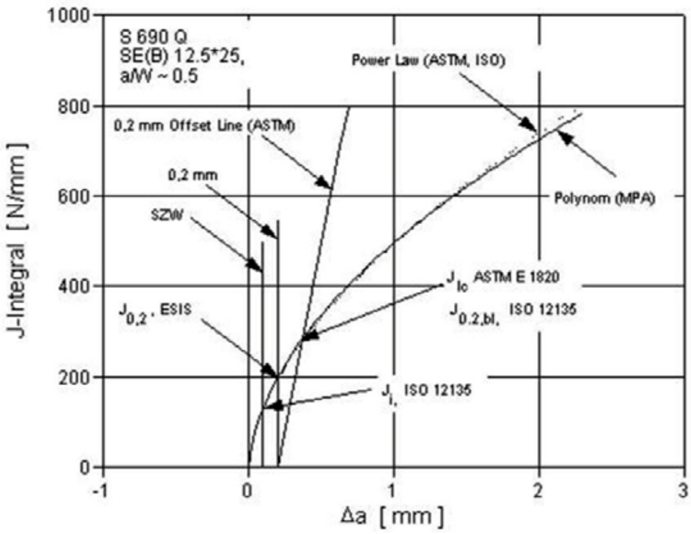

Figure 4: Different crack initiation and resistance values [6]

Material Specification

Specification of the pipe material

The specification for the steel plates was based on DIN EN 10025 [7], however adjustments were made as a result of the material tests.

- Maximum and minimum values were defined for mechanical properties.
- The allowed minimum impact energy was defined for the “Charpy V-notch specimen” (the lowest single value (SV) as well as the mean value of the test was taken at zero degrees and -40 degrees).
- Fracture toughness was defined as a minimum target value.

The specified mechanical properties for the new Kaunertal shaft lining are presented in table 4.

Table 4: Mechanical properties of the pipe material

		Properties in longitudinal direction					Impact Energy Charpy V - lateral		Fracture Toughness
Steel Grade	t [mm]	$R_{p0,2}$ Minimum [MPa]	R_m Minimum [MPa]	R_m Maximum [MPa]	A_{gt} Minimum [%]	(R_e/R_m) Maximum [-]	K_V Minimum (0°C) [J] MV / SV	KV Minimum (-40°C) [J] MV / SV	$J_{0,2}$ Target (0°C) [N/mm]
S620/820 QL	50-100	580	650	820	5	0,95	130 / 100	70 / 50	120
S620/820 QL	101-140	560	630	820	5	0,95	130 / 100	70 / 50	120
S580/820 M	30-50	580	650	820	5	0,93	200 / 175	100 / 70	120
S620/820 M	46-51	620	690	820	6	0,93	200 / 175	100 / 70	120
S500/770 M	20-50	500	560	770	6	0,93	200 / 175	100 / 70	120
S460/700 M	20-50	460	515	700	6	0,93	200 / 175	100 / 70	120
S355/630 M	20-50	355	400	630	6	0,93	200 / 175	100 / 70	120

Specification of the weld connections

To get the desired quality and properties of the weld connection it is also important to define the properties of the filler material. The specified properties for the weld connections are listed in table 5.

Table 5: Mechanical properties of the weld connection

		Properties in welding direction				Impact Energy Charpy V - lateral		Fracture Toughness
BM Strength Yield/Ultimate	t [mm]	$R_{p0,2}$ Minimum [MPa]	R_m Minimum [MPa]	R_m Maximum [MPa]	A_{gt} Minimum [%]	K_V Minimum (0°C) [J] MV / SV	KV Minimum (-40°C) [J] MV / SV	$J_{0,2}$ Target (0°C) [N/mm]
≤ S460 / 700	20 - 50	600	720	850	5	130 / 100	70 / 50	120
> S460 / 700	30 - 50	700	830	900	5	130 / 100	70 / 50	120
> S460 / 700	60 - 140	700	830	900	5	130 / 100	70 / 50	120

Requirements for test specimens

During the thermo-mechanical rolling the fine grain is stretched in the rolling direction. This means the plate receives a texture, thus the mechanical properties are direction-dependent. The tensile-testing specimens are therefore taken in longitudinal direction whereas the impact testing specimens and the fracture mechanic specimens are taken in transverse direction. The notch and hence the corresponding crack is orientated in longitudinal direction.

Conclusion

The preliminary analysis of the new pressure shaft for the HPP Kauntertal showed that brittle fracture could be a critical aspect because of the high pressure and large diameter. Initial defects in the steel lining can grow to a size critical for failure if they are subjected to dynamic loads when considering fracture mechanics.

To learn more about the ductility of the selected materials and to avoid that brittle fracture could become a problem for the shaft lining, it was necessary to start a comprehensive testing program for pipe steel and weld connections. With the tests fracture toughness values were identified for each steel grade and weld connection used on the Project. The steel and the weld connections were specified based on the results of pilot tests ahead of contract award to the steel provider to assure the required quality standard for the entire production. To keep the quality standard high testing will continue during the production process as well.

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