Key parameters for safe steel constructions for the new penstock of the high head hydropower plant Kaunertal

Andreas Hammer
Plant Planning Department
TIWAG – Tiroler Wasserkraft AG
Eduard Wallnöfer Platz 2
Austria - 6020 Innsbruck
Tel.: +43 50607 21392
Mobil: +43 699 12572392
Email: andreas.hammer@tiwag.at

Rainer Maldet
Plant Planning Department
TIWAG – Tiroler Wasserkraft AG
Eduard Wallnöfer Platz 2
Austria - 6020 Innsbruck
Tel.: +43 50607 21592
Mobil: +43 699 12572592
Email: rainer.maldet@tiwag.at

Introduction

The renewal of the steel lined pressure shaft for the high head hydropower plant Kaunertal is necessary as a result of the heavy hydraulic loading from power station peak operation and due to the fact that parts of the pressure shaft were constructed in a then unknown landslip and have since been subjected to additional loading from creep movement of the rock mass.

The critical parameters as well as the safety level and the risk level for a penstock or pressure shaft have to be defined in the beginning of the construction process. The product of internal pressure and diameter gives the designer a number for the criticality of a pipe. A comparison of many steel penstocks by this number shows that the new penstock of the HPP Kaunertal is besides Cleuson-Dixence one of the most critical penstocks built. The additional dynamic load from the known operation mode made the design more difficult.

To ensure the integrity of the penstock for the whole service life of 100 years some important parameters have to be ensured.

- Ductile Material:

To build in an economical way designers have to consider high strength steels. The increase of strength saves you thickness and so material costs and welding time. But with rising strength the ductility decreases. To be safe against low deformation fracture the uniform elongation has to be specified in a proper level. Therefore the tensile strength has to be limited with an upper bound.

- Fracture Toughness:

To achieve safety against brittle fracture it is necessary to assure high fracture toughness values for the base material and for the weld connection. To ensure the targeted values quality assurance has to be done on a high level from steel production over the workshop manufacturing and up to the onsite assembling.

- Fatigue Strength

The dynamic load provides stress variations in the penstock. Therefore an analysis about the structures fatigue strength over the service life has to be done. First of all the dynamic load has to be determined. Either the pressure pulsation can be measured in an existing plant or a numerical analysis for the transient hydraulics has to be done.

This paper gives you an overview on the safety concept for penstock of the high head hydropower plant Kaunertal. Besides the safety concept experiences in material testing, weld characteristics and the different analysis are shown.

1. Project Overview

The Kaunertal hydropower plant was constructed by TIWAG – Tiroler Wasserkraft AG in the years 1961 to 1964 as a highhead storage plant. With its power of 390 MW and a regular annual energy production of 660 GWh, it was the most powerful hydropower plant in Austria at the time. A 13 km long headrace tunnel followed by the 1.6 km long inclined pressure shaft with an internal diameter of 3.30 m to 2.85 m (maximum gross head 895 m, generation flow quantity 52 m³/s) is situated between the Gepatsch reservoir and the powerhouse at Prutz.

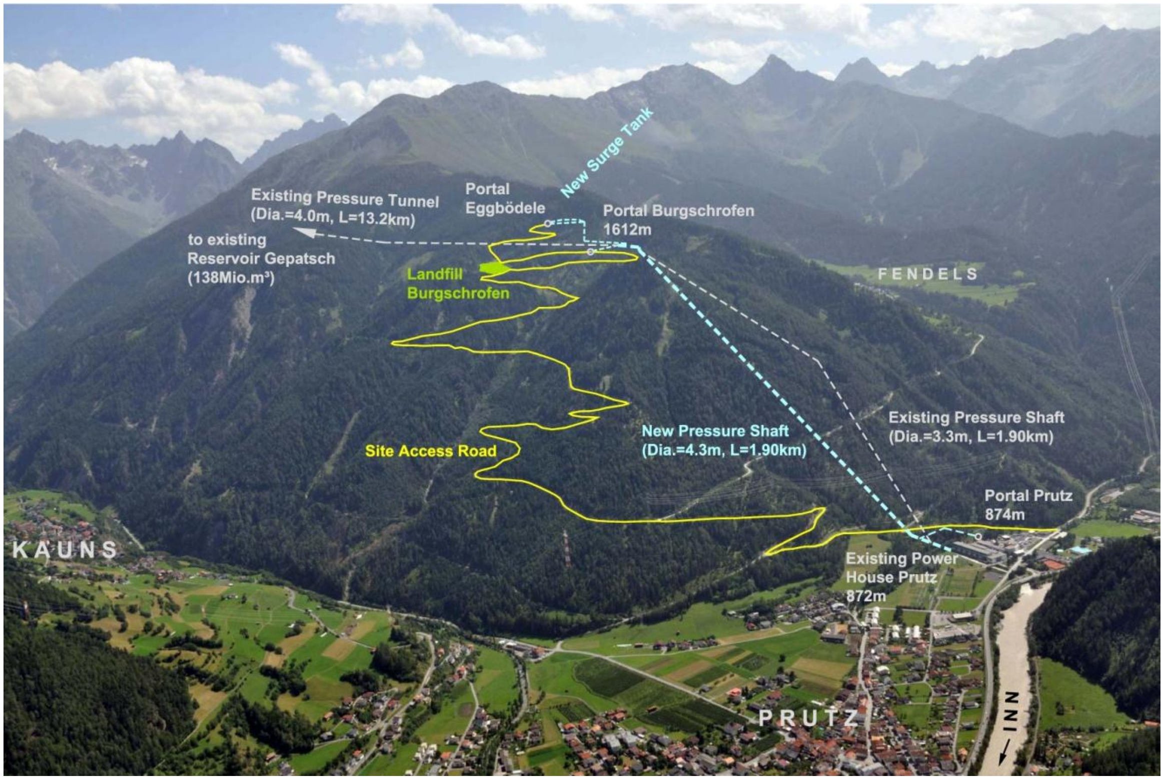

Figure 1: Project Overview

The renewal of the steel lined pressure shaft (Figure 1) is necessary as a result of the heavy hydraulic loading from power station peak operation and due to the fact that parts of the pressure shaft were constructed in a then unknown landslip and have since been subjected to additional loading from creep movement of the rock mass.

The design and sizing of the new pressure shaft and the surge tank take into account a planned expansion of the Kaunertal hydro power plant to twice the nominal flow quantity which will be implemented in a future project state.

2. Design of the penstock

Steel lining design for straight embedded pipes is based on plane pipes tightly embedded in the rock mass. The internal pressure in the pipe is shared between the pipe steel and the rock mass according to the stiffness ratio of lining and rock mass [1]. Such steel lining design requires that the gap between steel and shaft wall is back-filled with concrete and grouted.

The dimensioning of the steel lining is defined according to the k-factor-concept $s_d = k\ s_y$ (factored yield strength) on an infinite length of steel pipe. The authorities require a k-factor of k = 0.6 for embedded pipes and s_y the yield strength defined as the steel material characteristics $R_{p0.2}$ or 0.90 R_m whichever is smaller. For the rock mass, the stiffness of V_f^* = 3840 MPa (“grey Bündner schist”) and V_f^* = 1280 MPa (“variegated Bündner schist”) are found the calculated representative values. To limit the rock mass contribution in restraining the internal pressure, k = 0.9 has to be satisfied even without taking the beneficial reaction of the rock mass into account (V_f^* = 0 MPa). A rock mass contribution for bearing the internal pressure in the order of 30% is hence considered at maximum.

External ground water pressure and grouting pressure is analysed according to the design concepts and formulas of Amstutz/Jacobsen [2] and [3]. A design factor of 1.5 is defined by the authority. The tolerances of the lining are taken into account with an initial gap of j = 0.0003 r and a non-circularity (50° template) of u = 5 mm. Tolerable grouting pressure is determined as a result of the analysis for j = 0.001 r.

For embedded pipe bends the same principles are applicable in circumferential direction as for the straight embedded pipe. Additional stresses at the connection of polygonal pipe sections in the bend are considered according to Wieser/Green/Emmerson/Greiner [4]. Branch pipes whether embedded or not are analysed without taking the beneficial contribution of the rock mass into account. The steel thickness is determined for the self-supported case, which is capped on all sides and the particular site arrangement is modeled to find potentially worse loading conditions of the more realistic embedded case. Individual k-factors are defined for different combinations of membrane-, peak- and bending stresses in the branch pipes. Special regard is given to pipe accessories like pipe rings to improve buckling, openings and auxiliary steel plates for maintenance access, survey and grouting which are installed in the steel lining in substantial numbers. The shape and size of these openings is optimized using analysis and test results by recently performed research at the Technical University of Graz [5].

Dynamic loads generated by power plant operation are considered according to the Eurocode. The specified amplitude of 5 bar at a frequency of 8 x10^7 load cycles in 100 years as derived from operation history turns out to be the decisive load case for many partitions of the steel lining and pipe accessories. The design requirements for the Project are normally met in case the welding detail and weld treatment satisfies category 112 according to EN 1993-1-9.

3. Material Specification for high ductility

The dimensioning of steel pipes or bifurcations under internal pressure is 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. But especially for penstocks and shafts with a high criticality (Figure 2) the requirements are high to bear discontinuities from the production and the mounting.

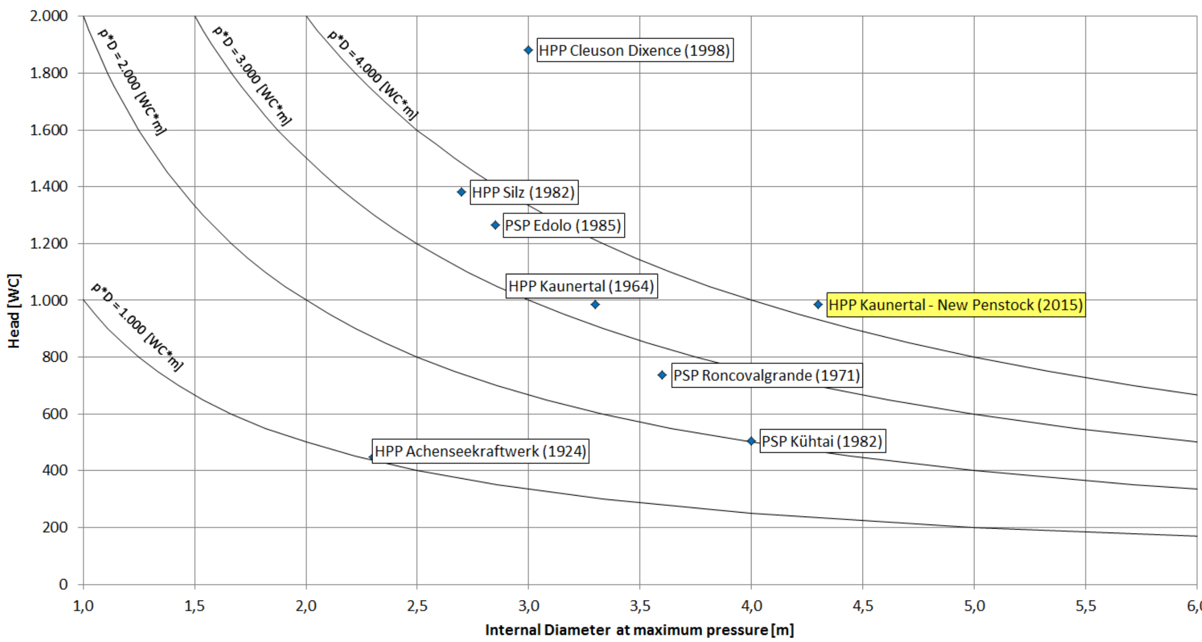

Figure 2: Criticality of penstocks due to pressure and size

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 as the yield strength rises (Figure 3), and it is also known that other ductility criteria decrease approximately in the same manner.

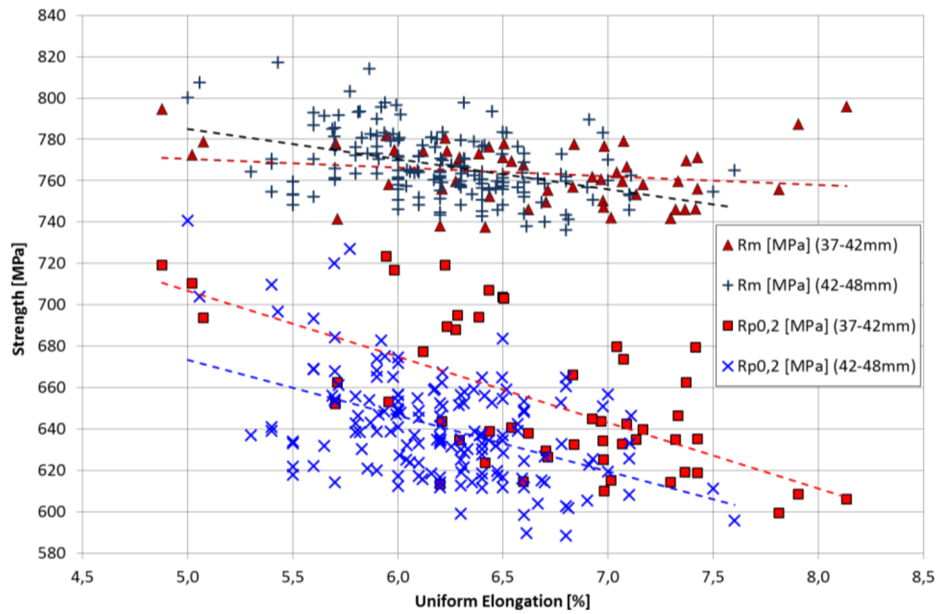

Figure 3: Relation of Strength and Uniform Elongation on TM-Steel Alform580/820 for the Kaunertal penstock

The preliminary engineering comprised an investigation of the available steel grades for plates and welding filler and a pilot test simulating welding and mounting at near-site-conditions. TIWAG participated in an Austrian research project Betriebssicherheit von geschweißten hochfesten Pipelines und Druckrohrleitungen. The understandings and experiences gathered are described in [5].

The steel lining requires high ductility in base material and weld to compensate for eventual weak bedding conditions. It also requires over-matching, which means that the minimum yield strength of the deposited weld shall be higher than the maximum yield strength of the plates, allowing for eventual movement of the surrounding rock.

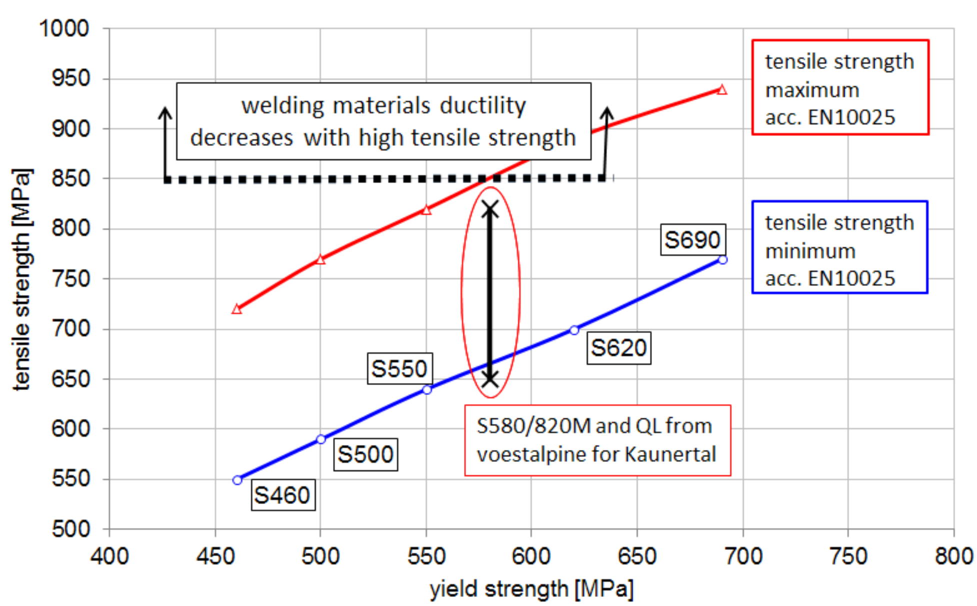

Figure 4: Standard specification of strength according to EN10025[6]

The diagram depicts minimum and maximum tensile strength versus yield strength for steels according to EN10025.

3.1. Specification of the pipe material

The specification for the steel plates was based on DIN EN 10025 [6], 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 1.

Material (GW) specification Kaunertal:										
		mechanical properties longitudinal					toughness transverse		fracture mechanics	
							guarantee	goal	guarantee	goal
sign VOEST Alpine	Thickness [mm]	$R_{p0,2}$ min [MPa]	R_m min [MPa]	R_m max [MPa]	A_{gt} min [%]	(R_e/R_m) max	MW / EW AV [J] (0°C)	MW / EW AV [J] (-40°C)	$J_{0,2}$ min [kJ/m²] (0°C)	CTOD min SEB10 [mm] (0°C)
Dillimax 620 QL	100 - 151	560	630	820	5	0,93	130 / 100	70 / 50	150	0,56
Dillimax 620 QL	50 - 101	580	650	820	5	0,93	130 / 100	70 / 50	150	0,56
Aldur 560/820 QL	101 - 140	560	630	820	5	0,95	130 / 100	70 / 50	120	0,56
Aldur 580/820 QL	50 - 100	580	650	820	5	0,95	130 / 100	70 / 50	120	0,45
Alform 620/820 M	46 - 51	620	690	820	6	0,93	200 / 175	100 / 70	120	0,45
Alform 580/820 M	30 - 50	580	650	820	5	0,93	200 / 175	100 / 70	120	0,45
Alform 500/770 M	20 - 50	500	560	770	6	0,93	200 / 175	100 / 70	120	0,45
Alform 460/700 M	20 - 50	460	515	700	6	0,93	200 / 175	100 / 70	120	0,45
Alform 355/630 M	20 - 30	355	400	630	6	0,93	200 / 175	100 / 70	120	0,45

Table 1: Mechanical properties of the pipe material

3.2. 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 2.

Weld (SG) specification Kaunertal:								
strength class welded connection	welding process	mechanical properties guaranteed				hardness	toughness	fracture mech.
						guarantee	guarantee	goal
		PWHT (°C)	R_{p02} min [MPa]	MW/EW R_m min [MPa]	A_{gt} min [%]	MW/EW HV10 max	MW / EW AV min [J] (0°C)	$J_{0,2}$ min [kJ/m²] (0°C)
≤ S460 / 700	UP	510±10	580	700 / 680	5	350 / 380	130 / 110	110
	MAG	510±10	580	700 / 680	5	350 / 380	100 / 80	120
	E	510±10	580	700 / 680	5	350 / 380	100 / 80	120
	WIG-man	510±10	580	700 / 680	5	350 / 380	130 / 110	120
	WIG-HD NG	510±10	580	700 / 680	5	350 / 380	130/110	120
≥ S500 / 770 ≤ S620 / 820	UP	510±10	710	830 / 810	5	350 / 380	130 / 100	80
	MAG	510±10	710	830 / 810	5	350 / 380	120 / 90	80
	E	510±10	710	830 / 810	5	350 / 380	80 / 60	70
	WIG-man	510±10	710	820 / 800	5	350 / 380	130 / 100	120
	WIG-HD NG	510±10	710	820 / 800	5	350 / 380	130 / 100	120

Table 2: Mechanical properties of the weld connection

4. Fracture Mechanics

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, and it is a very active area of current research. 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 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

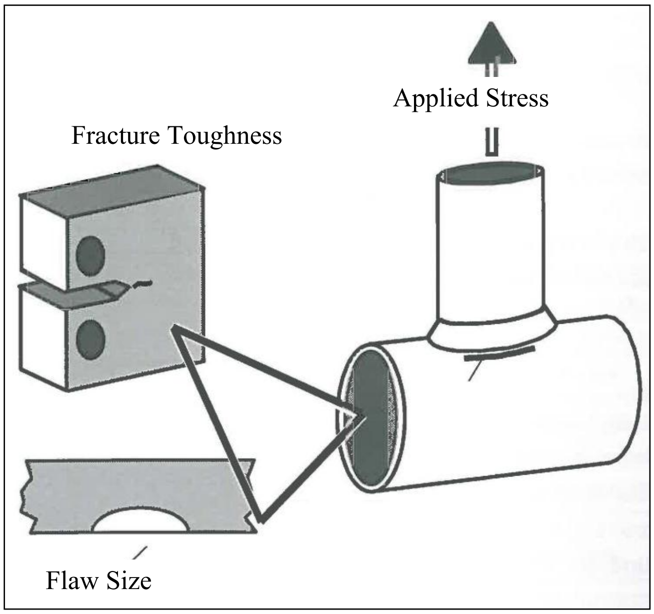

Figure 5: Fracture mechanics triangle [7]

Due to the fracture mechanic analysis the above mentioned specification were defined as lower border for the used steel and weld materials. In the pre-project and the weld qualifications many test specimens were made and tested. Hence the relation between uniform elongation and fracture toughness was noticed for the automated welding procedures in the Kaunertal project like Submerged Arc Welding (SAW) and Gas Tungsten Arc Welding (GTAW or TIG). The manually produced welds e.g. Metal Active Gas welding (MAG) showed high variations in the results. So it wasn't possible to find a correlation. All the fracture mechanic tests were made according to ISO12135 with the compliance method to gain the fracture resistance curve from every single specimen. The recorded curves give you the possible crack resistance as the J-Integral over the crack extension which is a value for the deformation energy absorbed near the crack. The curve depends after the crack initiation on the specimen size and crack configuration. Therefore the J-Integral value at 0.2 mm crack extension is used for the fracture mechanic analysis. So the error for structures with normal multiaxial stresses is very low. In case of high multiaxiality of the stress tensor the exact J-Integral value for crack initiation has to be determined (Figure 6).

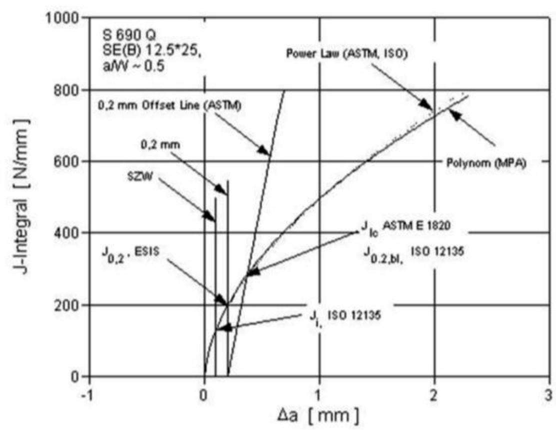

Figure 6: Different crack initiation and resistance values [6]

5. 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. To keep the quality standard high testing continues during the production and mounting process.

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The Authors

The authors are with TIWAG-Tiroler Wasserkraft AG, Division Engineering Services. The scope of work for the 125 staff members ranges from the assessment of existing plants and their rehabilitation to the planning for the erection of new plants.

A. Hammer graduated in Mechanical Engineering from the Vienna University of Technology and works for the TIWAG – Tiroler Wasserkraft AG since 2011. His main tasks are fracture mechanics and structural analysis. He was involved in several structural integrity analyses of TIWAG hydropower plants. At the moment the Kaunertal penstock is his main project. He works mainly on the quality assurance for the planning and the execution of the steel works.
Dipl.-Ing. Andreas HAMMER; TIWAG-Tiroler Wasserkraft AG; Division Engineering Services
Eduard Wallnöfer Platz 2; 6020 Innsbruck; T: +43 50607 21392; M: andreas.hammer@tiwag.at

R. Maldet is a senior engineer in the team “Maschinentechnik”. He is responsible for hydraulic machines and devices with the main emphasis on steel structures. He is an experienced European welding engineer. In 1984, he graduated with a degree in Mechanical Engineering from the HTL Innsbruck. Actually he is a member of the working group “Materials” within Oesterreichs Energie, previously Verband der Elektrizitätsunternehmen Österreichs (VEÖ), an independent advocacy group for the Austrian electricity industry.
Ing. Rainer MALDET; TIWAG-Tiroler Wasserkraft AG; Division Engineering Services
Eduard Wallnöfer Platz 2; 6020 Innsbruck; T: +43 50607 21592; M: rainer.maldet@tiwag.at