Development, Experiences and Qualification of Steel Grades for Hydro Power Conduits

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Abstract

The history of the development of steels grades for penstocks and steel lined shafts for SP and PSP hydro power plants and experiences made on existing plants by comprehensive programs to check the further usability of existing prior penstocks is discussed briefly.
Because of the progress made by the steel industry in the past 50 years, the Yield Strength of steels for SP and PSP raised from 400 MPa for normalized fine grain steels to 890 MPa for Q&T steels. Since 30 years TM grades are in service, recently showing Y.S. up to 700 MPa. The new high strength steel grades behave increasingly sensitive in its behavior during welding; especially the problem of hydrogen induced cracking is a crucial issue. The H induced crack appearance moved from the HAZ in the weld deposit area of the joint when welding HSS grades.
Extensive Qualification Programs have been established to quantify the materials behavior of the new grades of regarding their fabrication and service behavior. The results out of that programs allowed to establish sound criteria for material selection based on a fracture mechanics, fatigue properties and stress corrosion susceptibility for an Integrity Analysis.
Because of the development in the European energy market, in the recent period the influence of dynamic loading on penstocks and steel lined shafts became an additional challenge.
When using high strength steel grades these findings have to be considered for successful design, fabrication, testing procedures as well as for service and monitoring conditions for existing penstocks and steel lined shafts.

Historical Development of steels for Hydropower Application in Central Europe

Since 1900 in Central Europe penstocks for hydropower plants has been built. As can be noticed from Figure 1, Table 1 and 2, mainly two grades of steels where used until begin of the 1950ies of the last century. After that fine grain steels, normalized, showing higher yield strength up to 400 MPa were introduced. Since about 1960 quench & tempered fine grain Steel grades (Q&T) appeared, showing yield strength up to nearly 600 MPa. With begin of the 1980ies the first Q&T steel grade S 690 QT was introduced.
Thermo mechanically treated (TM) steel grades 500ML and 550ML firstly were used in Austria in 1988. The first high strength steel grades (HSS) S690 Q were applied in 2001. HSS TM steel grade S 700 was first applied in the Verbund - AHP Reisseck II Scheme 2010 [2]. In Switzerland for the Cleuson Dixence Scheme the High Strength Steel S 890 QT was used [3].
When discussing steel grades, the most important issue is the consideration of the joining procedure applied to perform a successful usable penstock. Figure 1, also depicts the history of the sequence of the application of different joining procedures for penstocks and steel lined shafts.

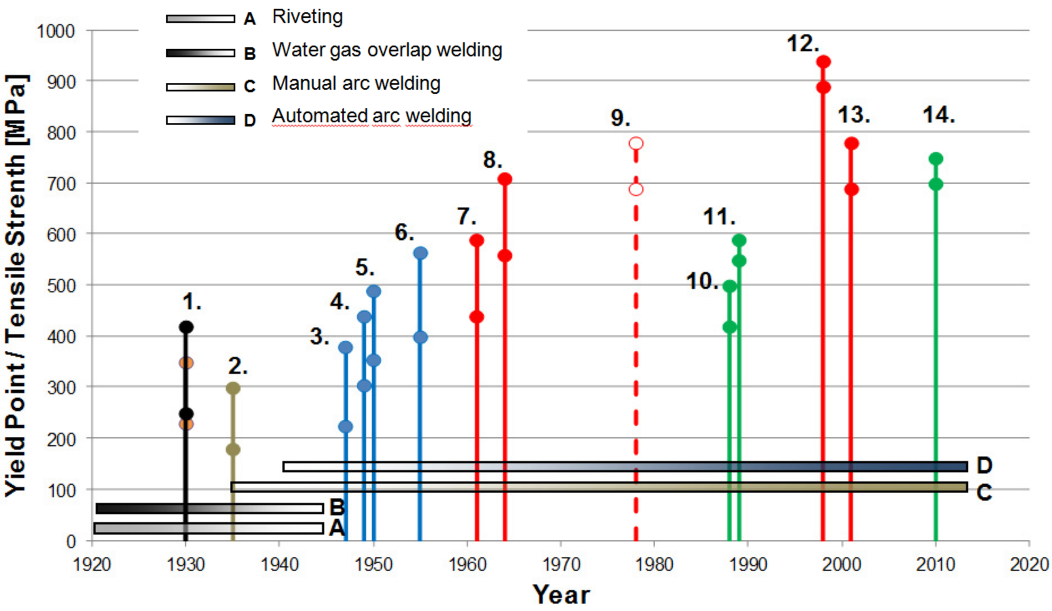

Figure 1: Historical Development of steel grades and joining processes for Hydropower Penstocks and steel lined shafts in Central Europe [1, 2]

Table 1

Position		Steel grade	Yield Point [MPa]	Tensile Strength [MPa]
1.	black	M I Steel	230-250	350-400
1.	black	M II Steel	250-290	420-500
2.	olive	SM Steel	180-270	300-400

Table 2

Position		Steel	Steel grade	Standard	Yield Point min. [MPa]	Tensile Strength min. [MPa]
3.	blue	Normalized Steel Grades	StE255	DIN17102* (10/1983)	255	360
4.			StE315		315	440
5.			StE355		355	490
6.			StE420		420	530
7.	red	Quenched and Tempered	S460Q	DIN EN 10025-6	460	550
8.			S550Q		550	640
9./13.			S690Q		690	770
10.	green	Thermomechanically Rolled	S420MC	DIN EN 10149-2	420	480
11.			S550MC		550	600
12.	red	Quenched and Tempered	S890Q	DIN EN 10025-6	890	940
14.	green	Thermomechanically Rolled	S700MC	DIN EN 10149-2	700	750

* current standard DIN EN 10025-3

In the beginning penstock were made from plates, and joined by riveting.

During the twenties of the last century, the so called watergas welding procedure became applicable for the production of pipes. Bended plates where hammered in the region of overlapping which was heated by watergas flames. A forge welding joint was produced and the pipe was normalized after the forging procedure. Figure 2 shows typical behavior of such joints under tensile load. The problem was that the fused zone regularly was contaminated with residual scale, which could cause lack of fusion, and further loss of strength. The test applied to represent the strength of the pipe was a water pressure proof test.

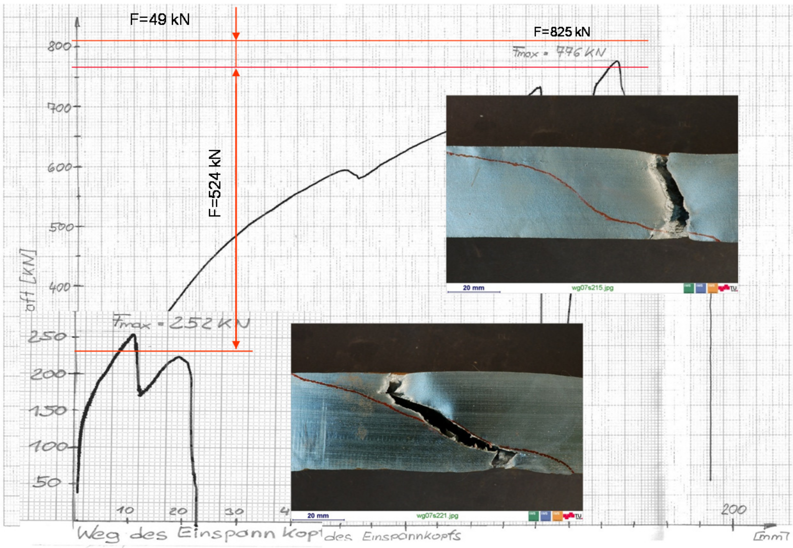

Figure 2: Mechanical behavior of watergas welds [4]

Experiences made by evaluation of prior penstocks

During reconsidering activities performed since 1980 on numerous penstocks, successfully in service since decades, many investigations were performed to quantify the safety and the further usability by comprehensive investigation programs [5]. The general condition of the penstock and its surroundings, the material properties and the presence of possible flaws in the material were investigated. For these projects, for the first time fracture mechanics approaches, considering the interaction between toughness of the material, service stresses in the penstock and flaw sizes, were applied.

- For the determination of the material properties strength and toughness but also for checking its microstructure and chemical composition it was tried, to gain some surplus material from the penstock always considering its integrity. Limited results from toughness tests revealed partially very low values. A relative brittle behavior of the material could be expected.
- The service stresses have been calculated under consideration of static and dynamic load cases.
- For the determination of flaw sizes and shapes Ultrasonic (UT) and Magnetic Particle (MT) tests were performed. On watergas welded pipes often heavy indications during MT testing were observed. The problem at that time was to define the depth of these indications, because all UT methods available at this time were developed for fusion welds only. By application of mobile metallographic investigations it was revealed, that in no case of comprehensive investigation a crack propagation caused by fatigue could be observed. This observation was a very important input for further safety evaluations.

However, under consideration of the results of these investigations und the successful service behavior of the penstocks during decades for the plants investigated, it was concluded, that a limited and controlled service time for planning and execution of a new scheme can be accepted under fulfillment of the following recommendations

1. Service conditions regarding the pressure fluctuations have to be, compared to the procedures used in the last decades of dynamic service loadings, changed towards “smoother” gradients.
2. The appearance of additional stresses caused by i.e. settings of supports, uneven support etc. should be controlled continuously and considered by counter measures.
3. In spite of that mandatory measures it cannot be fully excluded, that caused by impacts from outside, like avalanches, mudslides, earthquake etc. a sudden collapse of the relative brittle penstock can happen. For this case, measures for limitations of secondary damages should be foreseen in the layout and in the vicinity of the plant.

It is to report, that in Austria steel penstocks are generally successful in service since more than 100 years. In that period in one lined shaft (Gerlos I) three cases of brittle fracture of the pipe material in the years 1945, 1946 and 1948 happened. The pipe was produced during WWII, using very low quality steels available at this time. Comprehensive investigations and studies of that failure cases [5, 6, 7, 8], were performed which came to the conclusion, that the brittle fracture observed was caused by the very low toughness of the plate made from unkilled steel grades, partly used for this conduit. Impact tests, performed on fractured parts revealed Impact values of 10 J and lower. The material showed Widmanstaetten microstructure and high aging susceptibility. In addition the influence of welding residual stresses and also unequal bedding situation of the pipe in the tunnel was mentioned in these reports. In that cases the fracture were released by a water hammer, caused by valve closing maneuvers. Unfortunately, after the first fracture, the sleeve pipe applied to bridge the fractured zone was welded against the existing brittle pipe. This position fractured already during the first refilling attempt. The further repair measures used tight pressing procedures to assure tightness of the connection to prevent welding. The shaft has been successfully in service for 40 years until it was replaced in the year 1989 [2].
As a conclusion of the experiences made on penstocks and lined shafts built in the first half of the twenties century in Austria, it can be stated, that our antecessors engineers made, compared to the possibilities and hard- and software tools available to them at that time, a very tough job. Many of the penstocks designed and fabricated by them are still successful in service today.

Experiences made during steel development for penstocks and steel lined shafts

Fine grain steels normalized
The development of Stored Power Plants (SP) and Pumped Stored Power Plants (PSP) at the beginning of the 1950ies exploitation higher water heads and greater installed capacities asked for the use of higher strength steel grades for penstocks. At this time normalized fine grain steels showing higher yield strength (Y.S.) up to 400 MPa and wall thickness up to 80 mm appeared on the market and were highly appreciated by Engineers, OEMs and Owners of SP and PSP.
The power plant industry was one of the main drivers and pushers of that development. The manufacturers of the penstocks were asked to develop adequate shop - and site fabrication procedures, to realize the advanced designs. Additionally to the manual welding procedures, matured at this time, the semi-automated welding processes like submerged arc welding (SAW) and metal active gas welding (MAG), including the adequate welding consumables were developed. This development was accompanied by the appearance of a number of quality problems. These were mainly flaws in thicker welds, the appearance of hardening effects in the heat affected zones (HAZ) of the weld and problems in fulfilling the adequate

material requirements of the weld deposit and HAZ. Parallel to and because of these quality problems, the development of nondestructive testing (NDT) procedures like X-ray, ultrasonic testing (UT), surface checking by dye penetrant (DP) method as well as by magnetic particle testing (MT) matured to accepted and standardized Quality Assurance (QA) procedures.
Post weld heat treatment (PWHT) of welded wall thicknesses higher 30/36 mm became mandatory to reduce HAZ hardening as well as to reduce welding induced residual stresses. This requirement often could not be fulfilled because of the fact of limited or impossible access to the welded areas in the tunnels.

Quench and tempered steel YS < 600 MPa
The appearance of high strength fine grain quenched and tempered steels (Q&T) with a yield strength up to 600 MPa in the middle of the 1950ies allowed the realization of even larger facilities of SP and PSP and were widely used for the erection of penstocks and lined shafts. The advantages of using high strength steels are obvious: allowing design of higher water head plants and higher plant capacity by the same or even smaller wall thickness compared to former designs, saving welding time and consumables demand and limit bending forces for the realization of the shells [9].
In addition, lighter components are much easier to transport and to handle under severe site conditions in the mountains.
Because of the susceptibility to hardening effects in the HAZ as well as to the sensitivity to softening effects in the outside vicinity of the HAZ and the susceptibility to cracking phenomena these steel grades requires very strict control of welding parameters. This has to be considered for design welds as well as for auxiliary welds and is important for heat input, pre and post weld heat procedures as well as for the controlled treatment of welding consumables to be applied. The planning and performance of NDT procedures and their application in the right sequence of the fabrication process is extremely important too.

Hydrogen induced cold cracking
Hydrogen induced cold cracking (also called toe cracking) is the most observed failure mechanism when welding Q&T high strength steel grades. It mostly appears in the coarse grain zone of the HAZ of the top layer. This not only on longitudinal and circumferential welds, but also preferably in fillet welds, often used for auxiliary attachments. The depth of these cracks normally does not exceed 2-3 mm [10]. Figure shows a typical example of cold cracking in a penstock design.

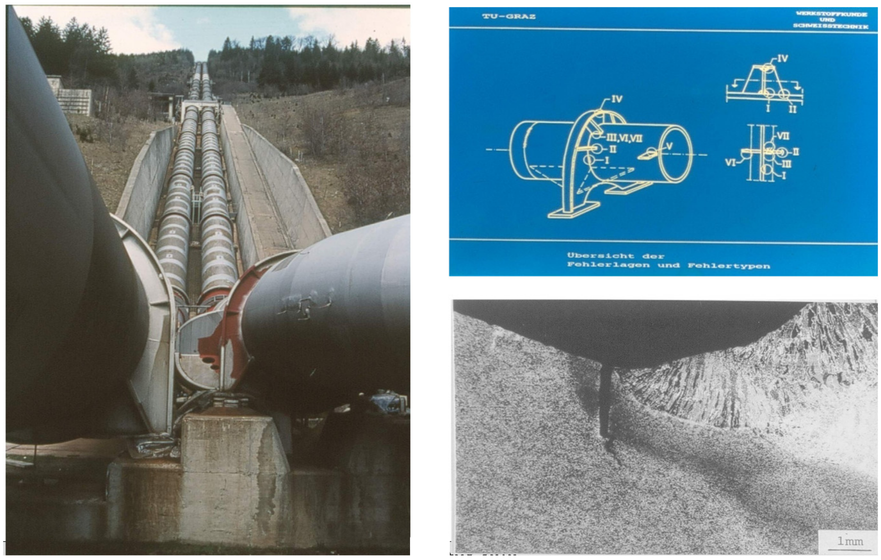

Figure 3: Appearance of Hydrogen induced cold cracking on a penstock [10]

The reason for appearing of H induced cold cracking is the combination of a sensitive hard microstructure in the coarse grain region of the HAZ of the top layer, the presence of hydrogen, stemming from the consumables flux or electrode coating and from the surrounding environment, in addition, from stresses, depending on the design of the weld under consideration and the local restraint working condition. The cracks appear after cooling down from welding, sometimes hours or even days after cooling, also called delayed cracking. This phenomenon was widely investigated and many tests and formulas have been proposed by many researchers to tackle that problem. Nearly 200(!) cold cracking tests and formulas have been proposed in the literature [11]. Out of that it can be concluded, that up to now none of these tests will really be able to give quantitative advice for procedures for 100% preventing cold cracking for each single case of application.
After the experience obtained from many relevant penstock projects the adequate principal measures to prevent that phenomenon are:

- Keeping and continuously control the selected preheating temperature during the whole welding process, also during interruption of the work.
- Application of a post heat treatment, so called soaking, acting as hydrogen effusion process, some hours at temperatures above 250°C in uninterrupted sequence after welding preheating.
- Apply adequate drying and handling procedures of the welding consumables, proposed by the supplier.
- Application of a so called temper bead technique during welding to anneal the HAZ of the top layer of multilayer welds.
- NDT surface checking control on the welds by use of MT on a notch free grinded weld surface. Welding caused notches can also hide cold cracks or produce fake indications. UT tests are not sensitive enough to detect toe cracks. The test should be performed after a waiting time of at least 48 hours after cooling of the component to cover also the delayed cracking phenomena.

High strength steels Y.S.>600 MPa
The increasing demand on energy in the years from 1990 on leads to the development of larger SP and PPS in the range of 800 to 1300 MW capacity and water heads close to 2000 m [3, 12].

For the realization of penstocks and steel lined shafts for that advanced designs, the use of even higher strength steel grades, yield strength larger 600 MPa became necessary.
Because of high efforts by the steel industry in cooperation with the research community, new grades of high strength steels could be developed and produced industrially on science based research results since the 1980ies. Under consideration of the fact, that for the application in hydropower plants plates showing wall thickness up to 100 mm and more had to be provided, two lines of production were followed in parallel:

1. The further development of quench and tempered grades of high strength steels (yield strength higher 600 MPa)
2. The application of thermo-mechanical treatment during the rolling process.

Both development lines has been successfully accomplished leading to standardization of that grades (Figure 1), Table 2.
For the performance of products from both development lines extremely qualified and equipped production facilities in the steel plants have to be available. Not surprising, these types of steels only could be offered by a limited number of qualified steel plants in Japan and Europe i.e. [9, 13].

Thermomechanically treated steels
Tremendous R&D activities where undertaken by the steel industry to develop the new grades of thermomechanically treated (TM, TMPC) steel grades from beginning of the 1980ies. By the use of controlled thermo mechanical rolling and cooling process the high strength- and toughness properties which are typical for these products could be achieved. Because of that specialized forming process very low amounts of alloying elements, also of carbon, a complex combination of controlled microstructure is produced, which combines effects of fine grains, dislocation density, transformation and precipitation behavior to develop the very good toughness properties of that steel family. Therefore these grades are less susceptible against cold cracking and hardening effects in the HAZ need limited precautions regarding preheating and post heating procedures. Because of weakening effects in the HAZ region (soft zones), the qualified welding parameters representing controlled heat input, have to be kept strictly [9, 13].

Welding of high strength steels Q&T and TM
Additionally to the guaranteed mechanical properties strength and toughness, main focus of that development was to accomplish the weldability of these new grades and the development of suitable welding consumables as well as to fulfill the demands of proper behavior of the welded joints [3, 14, 15].
As mentioned before, to assure cold crack free welds, preheating of the parts to be welded have to be provided. Under consideration of very severe site conditions i.e. in tunnels, the preheating temperature makes it difficult to assure acceptable working conditions for the welders. Also the application of reliable preheating facilities and the welding consumable management on site causes big efforts. These are very big challenges for the fabricator in the shop as well on the partly severe site conditions
The higher the strength of Q&T grade steels is maintained, the higher the amount of alloying elements is needed. This causes a higher cracking susceptibility, which requires great precaution during the fabrication process to perform sound safe welds. This very simple approach has to be considered when using higher strength steel Q&T steel grades.
Q&T high strength steel grades need to be, depending on the strength level, in the alloy design adequate chemical composition to maintain the mechanical properties specified. To

assure sound welds and keeping the expected mechanical properties, very strict compliance of the required preheating and soaking management and the qualified welding parameters, is mandatory.
These requirements makes the fabrication process more complicated, needs more time and causes additional costs.
The appearance of the new grades of high strength steels containing slim alloying concepts, released at a first glance the feeling, whether the strict keeping of the requirements regarding pre and post heating procedures are still necessary. This is, because the community traditionally was used to adjust the pre and post heating requirements on the effect of the hardening elements of the base material, i.e. based on the different formulas regarding carbon equivalent. Unfortunately, the problem of cold cracking, when using advanced high strength steels, is still present: Since the susceptibility of the advanced base material could be reduced dramatically, the weld deposit, which have to keep the same strength and toughness level as the base material, now became the critical area of the welded joint. The mechanical properties of the weld deposit cannot be influenced by Q&T or TM procedures. It gains its properties mainly from a higher amount of alloying elements, which make the microstructure now sensitive against cold cracking.
When using these high strength steel grades one have to take in account that the susceptibility to H induced cold cracking move from the HAZ into the weld deposit. In most cases H-induced cold cracks in high strength weld metals usually appear perpendicular to the weld direction, sometimes also in longitudinal direction. The experience made at the Cleuson-Dixence case is a very sad representative example of that effect. To remember: The reason for the catastrophic collapse of the Cleuson-Dixence shaft in December 2000, which was the starting event for establishing the conference series High Strength Steels for Hydropower Plants [3], was the presence of hydrogen induced cold cracks in the weld metal of longitudinal welds (Figure).

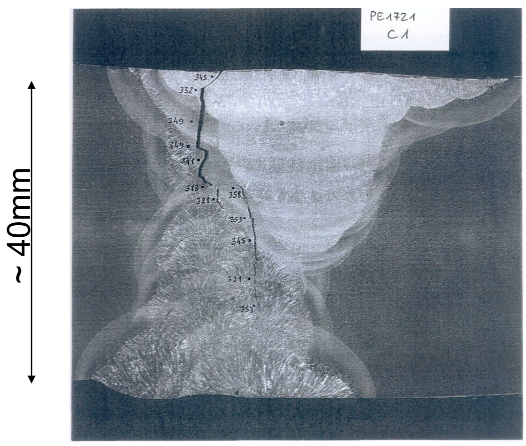

Figure 4: Cross section of longitudinal H-induced Cold Crack in Weld Deposit of Steel Grade S 890 QT [16] Source IS Paris report No. 36088, 25.5.2000

As a conclusion: When using advanced HSS-grades, Q&T as well as TM, the precautions regarding pre and post heating procedures and NDT testing techniques and procedures have in addition to the traditional experiences also to be oriented on the behavior of the weld metal properties and the typical possibilities of appearing of flaws under this conditions.

Qualification criteria for high strength steel grades for hydropower application

Penstocks and steel lined shafts for SP and PSP are engineering designs which are exposed to high loadings during service and keep an inherent high risk potential for human life and goods in case of collapse or leakages. In addition a lifetime up to 100 years is expected.

These criteria make penstocks and steel lined shafts of SP and PSP in relation to many other engineering to palmary designs in the history and practice of engineering services.

When planning, designing, ordering and fabricating such components the responsible people involved in that business shall acknowledge these facts and accept their responsibility. They have to have in mind, that beside of the specified service program, many unexpected situations during the very long service period can happen which have to be carried by the component.

Regarding the penstocks and lined shafts, we as the responsible engineers involved have to respect not only the existing design, materials and testing standards. We also have to recall the experiences, which were made in the past worldwide. The event, which was the nucleus for our conference series [3, 12] is one of the known examples, and the contributions to that conference series irea very good examples of respecting that experience.

The criteria which have to be considered for the selection of high strength steel grades for design, fabrication and service of penstocks and steel lined shafts to assuring its integrity are, beside of the weldability, strength and toughness for static loading conditions, fatigue properties for dynamic loading conditions and susceptibility for stress corrosion cracking as well as non-destructive testing.

Static Loading Conditions

Strength

The designers and stress analysts see at the first criteria the strength properties: They are very important and standardized in the codes. Allowable stresses and so called safety factors are relatively easy to control and derivations from the specified values are easy to observe, even for economic people and lawyers.

From the personal, nearly 50 years of practical experience of the lead author, no single component failed because of a limited fall below the value specified of strength values. The statistical distribution of strength properties is quite well known.

Toughness

Much more important for the integrity of the component is the capability of the material to keep local overstressing through plastic deformability by the inherent high toughness; this not only for the specified service conditions as well as during unexpected service events or for even catastrophic natural disasters. This is necessary not only for the base material, but most important, also for all different microstructures present in the component, caused by fabrication processes like, fabrication welding, forming and repairs. The material property which describes that behavior is the toughness. Standards usually define toughness criteria by specified minimal notch impact values, which have to be fulfilled during the acceptance tests. Figure depicts the wide scattering of Charpy impact values reported in the QA documents of plate testing on a steel lined shaft material S 890 QT.

Charpy impact testing is a very sensitive and valuable test method to check the proper production procedure of the material. But the results of that test cannot represent quantitatively the the integrity of the component to bearing loads in presence of flaws, i.e. cracks.

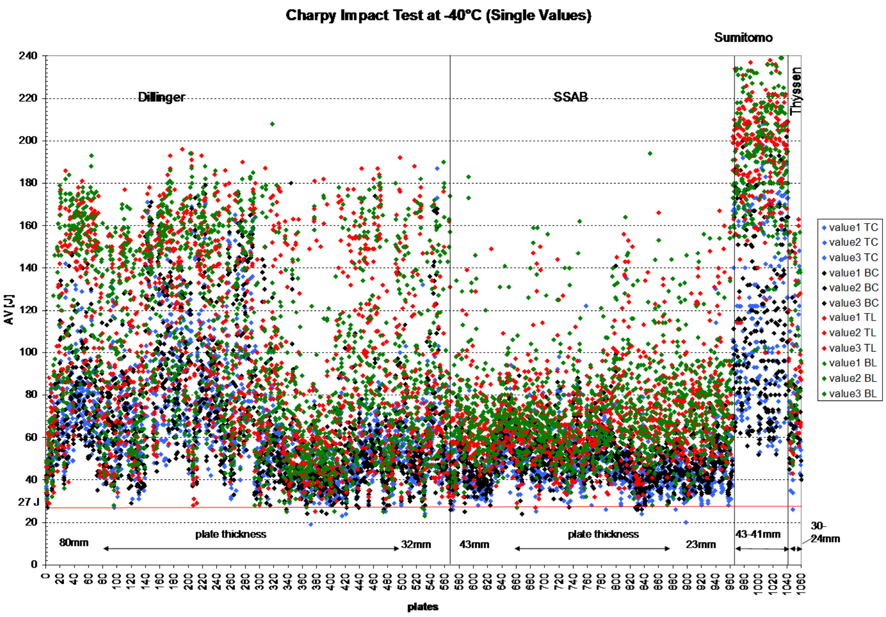

Figure 5: Charpy - V Values of Plates S 890 of Cleuson Dexence Shaft [16]

Decisive influence on the toughness of high strength steels has the cleanliness of the plate regarding residual elements and non metallic inclusions. The cleanliness depends on the metallurgical treatment of the molten steel and the pouring process in the steel plant. A quite simple method do check the cleanliness of the steel plates is the application of through thickness tensile samples by specification of a minimum value for the reduction of area value in accordance to DIN EN [17]. This requirement shall anyway be applied when welds perpendicular to the plate surface are foreseen, to prevent the appearance of lamellar tearing effects.
Safe design of components shall be based on the principles of the Integrity Analysis, briefly described in Figure [18].

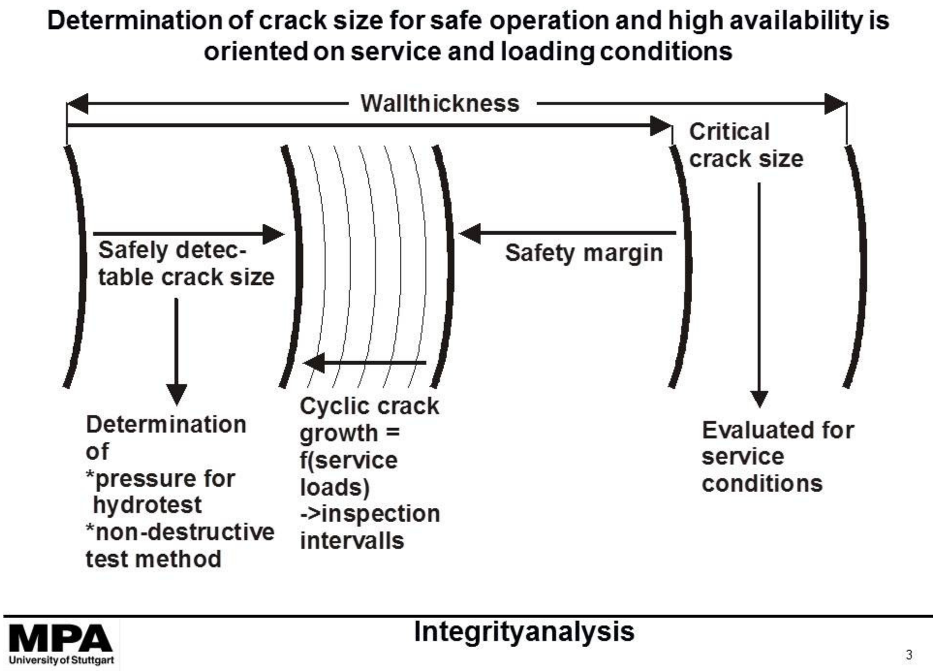

Figure 6: Integrity Analysis [18]

The detectable crack size have always to be smaller compared to the critical crack size in the fabricated condition of the component as well as in service, in case of the propagation of an existing crack or evolution of a fatigue crack.
Fortunately in the last decades the fracture mechanics approach matured and gives, when qualified applied, very helpful advice about the integrity of components containing flaws under given loads. This is valid not only for homogenous material, but also for the fact of the presence of flaws in the material, represented conservatively by cracks.
For that reason, so called Qualification Programs where developed to define the material properties of new grades of high strength steels which allow quantifying the integrity of components in presence of flaws, which can safely be detected by nondestructive tests applied [3, 18, 19, 20].
During those Qualification Programs not only small fracture mechanics samples were tested, but also the integral behavior of welded plates by testing of wide plate tests, Figure.

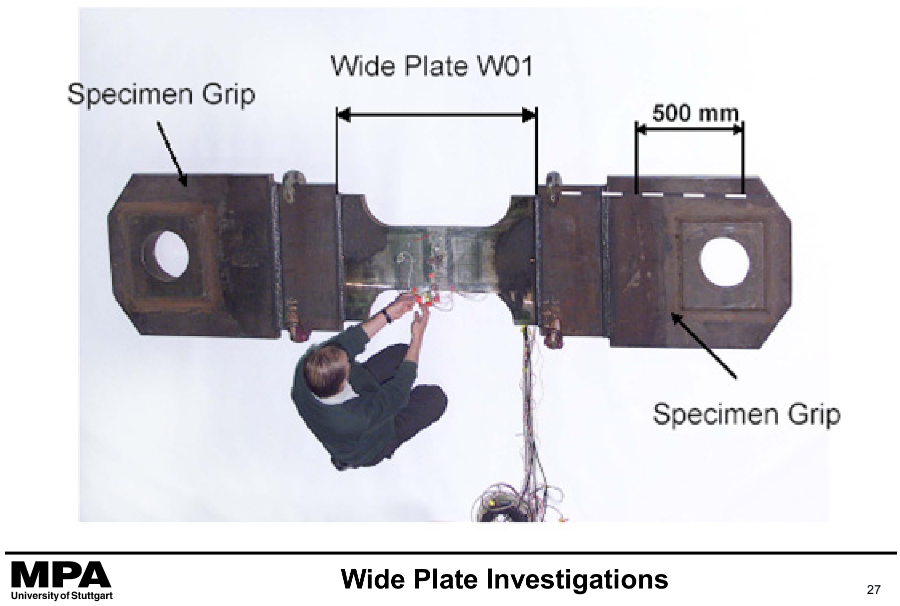

Figure 7: Wide Plate Investigations [18]

Figure as an example depicts as a result from that program the influence of different toughness levels on the critical crack size in a pipe under given design and pressure assumptions.
By using the material data achieved by such a qualification program critical crack sizes for the different positions in the shaft can be estimated and therefore allow a quantitative integrity analysis.

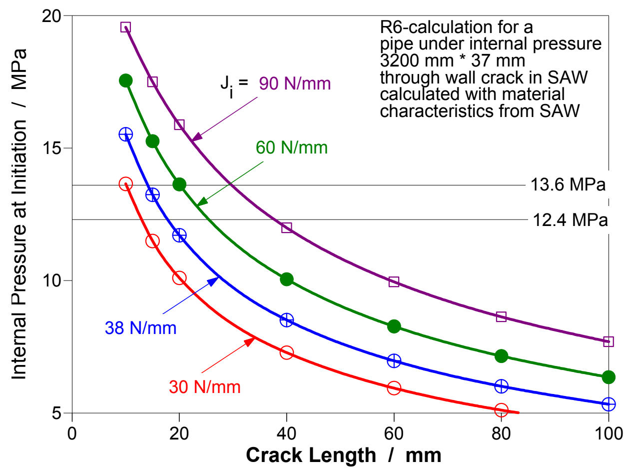

Figure 8: Initiation Pressure of a pipe depending of through wall crack length and different initiation values calculated with R6 method [18]

Figure: gives an example result of application of that approach for steel grade S 690QL [19]

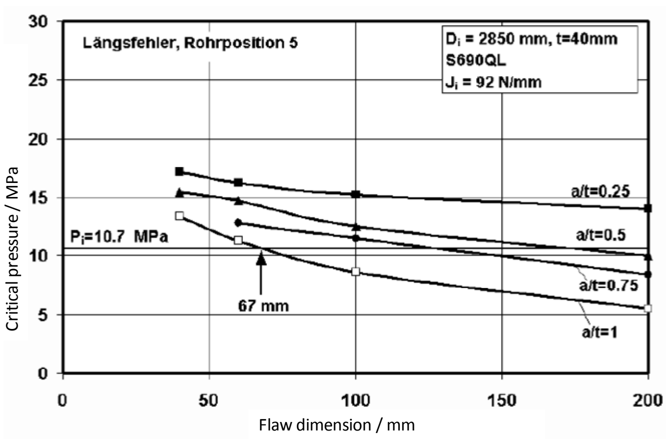

Figure 9: Critical Crack Size Calculation using R6 Routine [19]

This approach also allows to compare the basic behavior of different steel grades regarding their critical crack length to be carried under comparable load conditions. As an example the three grades S 690 ML (TM Treated), S 690 QL (quenched and tempered) and S 890 QL (quenched and tempered) are compared under the following assumptions:
A penstock with an inner diameter of 2850 mm and a wall thickness of 40 mm is pressurized with 10,7 MPa. The calculation was done by means of the software IWM Verb (version 2011) [21]. The R6 routine in the standard level was applied [22]. The Young's modulus is constant 210 GPa for all materials. The relation between the measured J_i-value and the calculated K_{IC} is based on the assumption of a plane stress state (Table 3).

Table 3: Comparison of calculated critical crack length for different grades of High Strength Steels [18, 19, 20]

Material	J_i	K_{IC}	$R_{p0.2}$	R_m	2c
	N/mm	$MPam^{0,5}$	MPa	MPa	mm
S690ML	175	191,7	690	870	112
S690QL	92	139,0	690	750	64,0
S890QL	90	137,5	890	940	67,2

For a safe service these effects have to be quantified and considered by appropriate monitoring programs.
It is to mention, that the qualified use of fracture mechanics tools available need basic understanding of the principles to prevent misinterpretation of the results.

Dynamic Loading Conditions

In the past the design of penstocks and conduits at least in Austria, was based mainly on static loading approach [2]. Because of the dramatic change of the requirements on the service program of SP and PSP coming from the power grids, the increasing use of high strength steels in the recent years the item of dynamic loading of penstocks and steel lined shafts became nowadays one of the main issues for the design of new as well as for the life time assessment of existing SP and PSP. Because the fatigue strength of high strength steels is more or less independent from the yield strength of the steel in the endurance domain, penstocks and lined shafts made from high strength steels are more sensitive to undergo fatigue damage compared to lower strength materials.

Influence of the fabrication quality on the fatigue behavior of pipes

Recent investigations showed [23, 24] that beside of the needs to know more about the quantitative fatigue behavior of that materials as base material properties itself as well as in the welded condition, the influence of the fabrication quality of the penstocks and steel lined shafts has decisive influence on the fatigue lifetime of such components. Angular as well as linear misalignment of the welded shells can have dramatic influence on the local stresses in the notch region of welds, Figure. When using the common IIW Approach [25, 26], the calculated life time exhaustion factor, described by a Miner damage sum, taking into account a given service program of pressure fluctuations, is therefore also very much dependent from the geometric situation of each single welded shell. The calculation reveals that even an angular misalignment which is in accordance to the widely used CECT Recommendation [27] can reduce the calculated life time in relation to an ideal circular cross section of the pipe significantly.

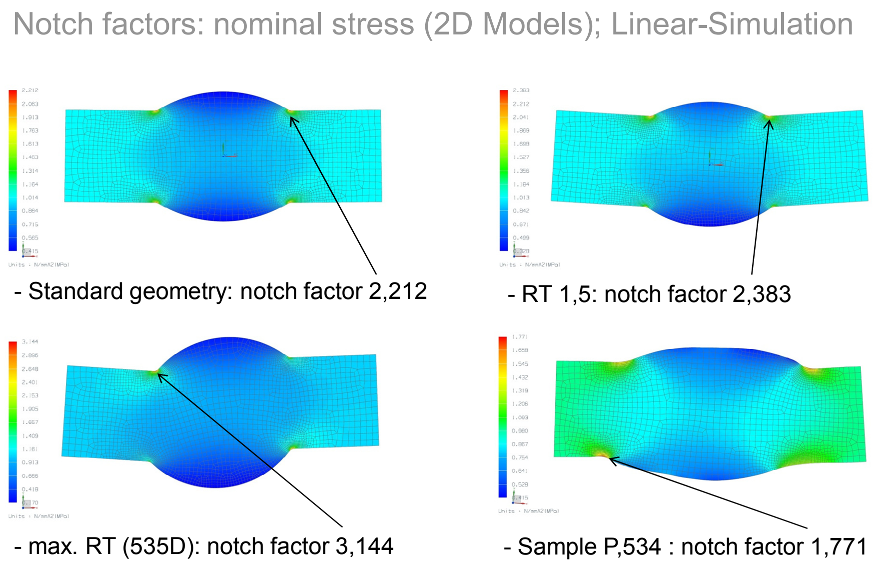

Figure 10: Simulation of notch factors of different weld geometries showing different root toppings (RT) [23]

This lifetime fatigue calculation based on the IIW approach [25, 26] takes into account a crack free starting condition of the weld.
It is important to know, that the lifetime of a component can be reduced dramatically, when in the notch of the weld, which is definitely the point of highest local stresses (Figure) small cracks are present. This is also the position were cold cracks (toe cracks) see Figure 3, normally appear, when the fabrication condition was not adequate as discussed above.
If, for certain reasons i.e. no adequate MT testing on grinded surface after welding was performed, very small cracks can be present at this position. These existing cracks can act as starting point for fatigue crack propagation.
The calculated fatigue life time calculation consider the crack initiation period, which consumes, after basic knowledge, about 90% of the lifetime. So it is not surprising to find cold cracks acting as fatigue crack starter, if fatigue cracks in components appear already after a short service time

Differentiation Cold Cracking – Fatigue Cracking
As discussed in the chapter above, penstocks nowadays are heavily exposed to dynamic loading cases, which lead, when the lifetime is consumed, to the formation of instable fatigue cracks. If a fatigue failure case occurs during service after a very short period it is very recommendable to investigate the cause of the failure in order to introduce the right conclusions and remedies. As an example the results of an investigation of a failure case in a penstock will briefly be given:

Already after 5 years of service fatigue cracks caused leakage in a penstock. This case was investigated on a sample cut out of a damaged area.
Figure shows the fracture surface of the forced opened crack after chemical removal of the corrosive layer [10]. By application of Scanning Electron microscopic (SEM) investigation it could be observed that that on the inner surface of the pipe a H-induced cold crack existed. This surface area, depth about 1-2mm was heavily covered by corrosion pits. The rest of the surface showed typical traces of high cycle fatigue crack propagation (Figure 12).
This observation was supported by metallographic examination of the cross section which revealed, that in the region of the existing cold crack heavy corrosive product are visible. (Figure 13).
By this observation it could be explained why the fatigue damage of that pipe occurred so early.

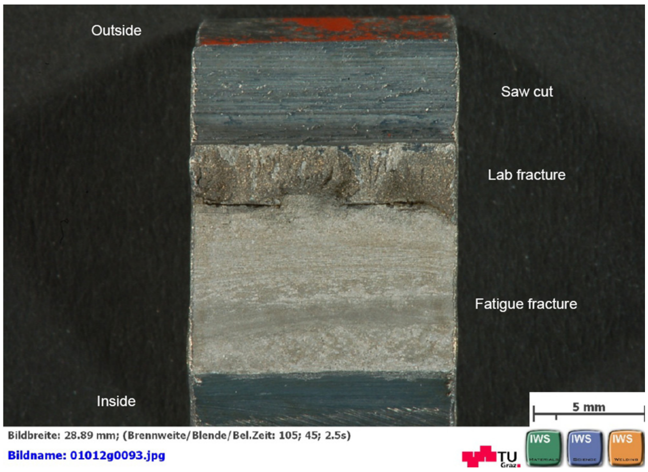

Figure 11: Surface of forced opened fatigue crack after chemical removal of the corrosive layer

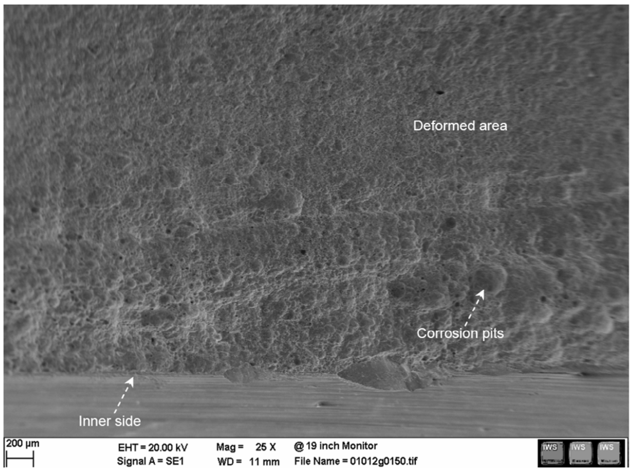

Figure 12: SEM investigation of fracture surface. Area with corrosion pits are caused by cold cracking, deformed area is caused by fatigue crack propagation.

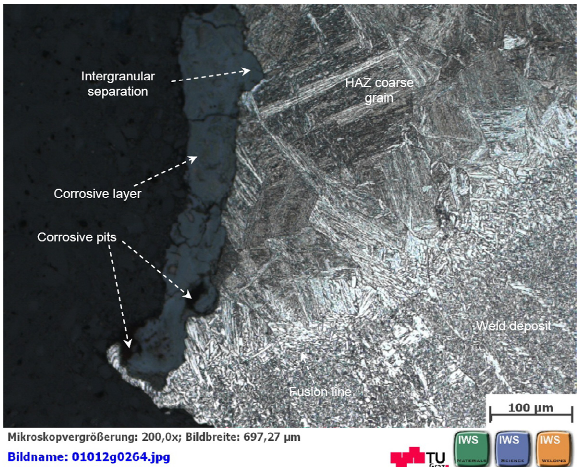

Figure 13: Cross section crack start showing heavy corrosive attack at the inner surface region of the pipe

To reduce the risk of fatigue failures during service, this example support the necessity of application of sensitive surface crack MP-testing in the course of the fabrication QA program.

Stress corrosion cracking

In the course of the failure case analyses Cleuson-Dixence and subsequent qualification program for the high strength steel S890, stress corrosion cracking as one potential danger was investigated in detail [28]. Numerous samples from the base material and different weld metals were tested on their susceptibility to stress corrosion cracking under service conditions of penstocks and steel lined shafts. The tests were conducted in air, water and H_2S saturated water as a worst case condition. Tensile tests, slow strain rate tests and fracture mechanics tests were elaborated and compared with reference results obtained from well-known and less strength materials.

It was found that the high strength steel S890 and it welds behave very similar to materials like S690Q and P355NL1 and is not prone to stress corrosion cracking. Ductile cracking was observed in air and water condition with a general corrosion attack in the latter case, which did not lead to hydrogen uptake and stress corrosion cracking. Only in the worst case situation (long term exposure in H_2S saturated water) all tested materials showed a brittle behavior.

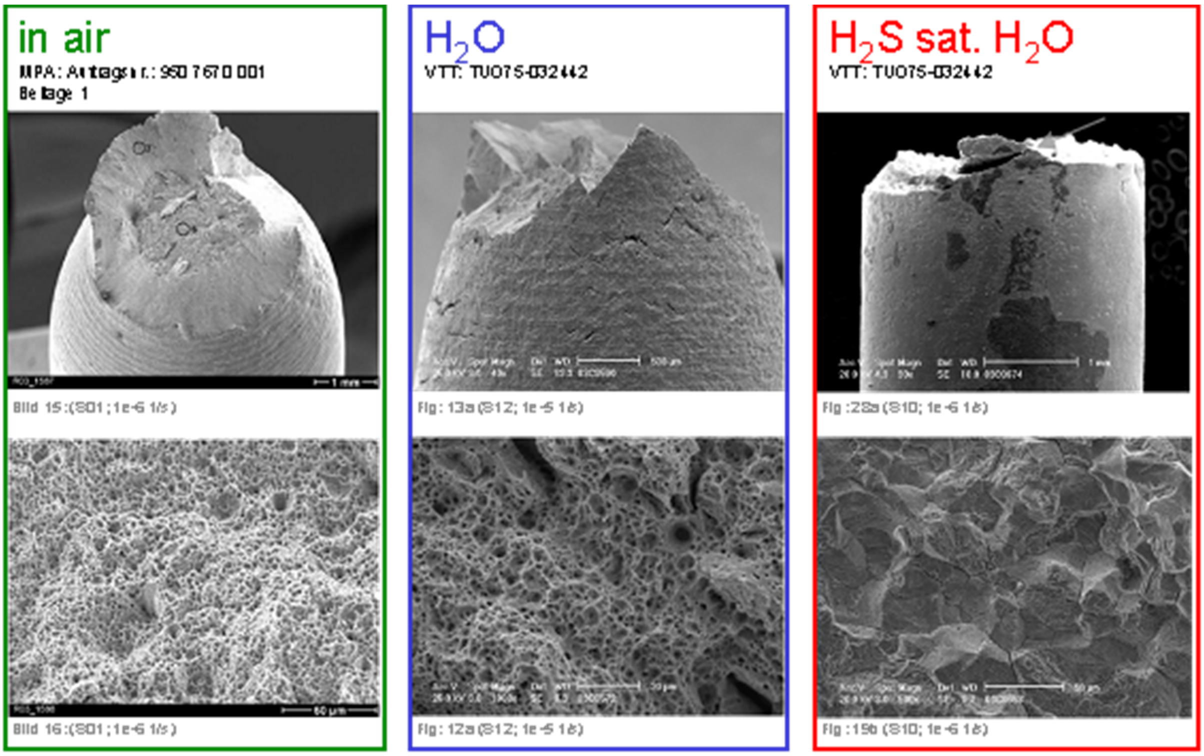

Figure 14: Results of Low Strain Rate Tests Steel Grade S 890QL [28]

Non Destructive Testing

The use of HSS for Penstocks and steel lined shafts requires, after the experience of the authors, in addition to the common NDT procedures generally applied when fabricating safety related designs, some additional measures to assure the needed homogeneity of the welded joint:

- Because of the mentioned susceptibility of fused weld deposit to hydrogen induced cold cracking when welding these steel grades, special attention should be focused to that phenomenon. As mentioned above, the susceptibility to hydrogen induced cold cracking moves at these grades from the HAZ into the weld deposit. As experience made during, the Cleuson-Dixence case, Hydrogen induced cold cracks can appear in vertical direction in the weld deposit in transversal and longitudinal direction. Its fracture surface can be quite unruffled. This effect could lead to misinterpretation of UT indications because of a so called “Mirror Effect” which can lead to dangerous underestimation of the UT result.
- It is recommended to qualify and calibrate the UT test procedure by the application of a special test piece, which contains so called mirror flaws.
- NDT application should start after a waiting period of 48 hours after cooling down from preheating/soaking treatment, to consider the delayed cracking phenomena.
- In addition, as mentioned above, the surface checking should be applied by the use of MT procedure on grinded, notch free welding surfaces. This treatment has also a very positive additional effect by remarkable improving the resistance of the welded joint against fatigue damage [23].

Conclusions and Recommendations

Penstocks and steel lined shafts for SP an PSP are engineering designs which are exposed to high loadings during service and keep an inherent high risk potential for human life and goods in case of collapse or leakages. In addition, traditionally a lifetime of 100 years is expected. These criteria make penstocks and steel lined shafts of SP and PSP in relation to many other engineering to palmary designs in the history and practice of engineering services. When planning, designing, ordering and fabricating such components the responsible people involved in that business shall acknowledge this fact and accept their responsibility. They have to have in mind, that, beside of the specified service program, many unexpected situations during the very long service period can happen which have to be carried by the component. Regarding the Penstocks and lined shafts, we as the responsible people involved have to respect not only the existing design, materials and testing standards. We also have to recall the experiences, which were made in the past worldwide. The event, which was the nucleus for our conference series is a very good example of respecting that experience. In the last decades outstanding developments in the field of high strength steels grades happened and allowed the design, fabrication and erection of huge SP and PSP`s. Also because of the new requirements coming from the grids, new challenging dynamic service conditions appeared and requires higher exploitation grades of the penstocks and lined shafts. The design has to consider in addition to the static also the dynamic loading conditions. Extensive Qualification Programs where performed to quantify the fabrication and service properties of that materials.

The conclusions out of these investigations as well as of the first fabrication experiences show that these new HSS grades behave very sensitive. This requires a fully new approach to assure that all precautions necessary during design, material selection, planning and performance of the fabrication steps, especially welding, assembly and testing, as well as in the service adhered. If these conditions are completely fulfilled, a successful and safe service for a long time, based on Integrity Analysis which strictly has to be applied, can be assured.

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