Development, experience and qualification of steel grades for hydropower conduits*

Horst Cerjak, Norbert Enzinger and Milan Pudar

Kurzfassung

*Entwicklung, Erfahrungen und Qualifizierung von Stählen für Druckrohrleitungen von Wasserkraftwerken**

In dem vorliegenden Beitrag werden Entwicklungen und Erfahrungen bei der Anwendung von hochfesten Stahlsorten für Druckrohrleitungen und -schächte von Speicher- und Pumpspeicherkraftwerken zusammenfassend beschrieben. Die Ergebnisse der Untersuchungen von zum Teil spektakulären Schadensfällen machen deutlich, dass hochfeste Stähle äußerst sorgfältig hergestellt und verarbeitet werden müssen, um einen sicheren Betrieb zu gewährleisten. Dabei kommt dem Schweißen eine besondere Bedeutung zu.

Die Auswertungen dieser Erfahrungen führten zur Entwicklung und Durchführung von Qualifikationsprogrammen. Ziel ist die Bereitstellung von Vorgaben für die Auslegung und Herstellung für einen sicheren Betrieb. Aufgrund der dramatischen Veränderungen hinsichtlich der Anforderungen an die Betriebsbedingungen von Speicher- und Pumpspeicherkraftwerken bedingt durch die Netze und die zunehmende Verwendung von hochfesten Stahlsorten in den vergangenen Jahren, kommt der Berücksichtigung der dynamischen Belastung dieser Bauteile eine besondere Bedeutung für die Auslegung neuer und die Lebensdauerbeurteilung bestehender Anlagen zu.

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Authors

Em. Prof. Dr. Horst Cerjak
Assoc. Prof. Dr. Norbert Enzinger
Institute of Materials Science and Welding
Graz University of Technology
Graz/Austria

Dr. Milan Pudar
Magna Steyr Fahrzeugtechnik AG & Co KG
Graz/Austria

Historical development of steels for hydropower application in central Europe

Since 1900 penstocks for hydropower plants have been built in central Europe. As can be noticed from Figure 1, Table 1 and 2, mainly two grades of steels were used until the beginning of the 1950s. After that time, fine grain steels, normalized with higher yield strength up to 400 MPa were introduced. Since about 1960 quench and tempered fine grain steel grades (Q&T) appeared, displaying yield strength up to nearly 600 MPa. With the beginning of the 1980s, the Q&T steel grade S 690 QT was introduced.

Thermo-mechanically treated (TM) steel grades 500ML and 550ML were firstly used in Austria in 1988. The first high strength steel grades (HSS) S690 Q were applied in 2001. The HSS TM steel grade S 700 was firstly 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]. Similar progress was observed in Japan [4].

When discussing steel grades, the most important issue is the consideration of the joining procedure applied to perform a successful usable penstock. Figure 1 shows the history of the application of different joining procedures for penstocks and steel lined shafts.

Joining processes applied

Initially penstocks were made from plates and joined by riveting.

During the twenties of the last century, the so-called watergas welding procedure was applied for the production of pipes. After World War II, the semi-automatic and automatic welding processes MAG, SAW and MIG processes have been increasingly used in addition to the shielded manual arc (SMAW) process.

High-strength steels

When quenched and tempered (Q&T), fine grain steels started being used in the late 1950s, hydrogen induced cold-cracking in the heat affected zone (HAZ), the so-called type IV cracking appeared as the main problem when welding this type of steels (Figure 2). The maintenance of proper pre- and post-heating procedures in the cases of cold-cracking was widely underestimated, the same holds true for the necessity of the use of sensitive non-destructive testing methods [5].

The application of high-strength steels, types S690, and in the last decade also of S890 QT raised another welding problem: hydrogen-induced cold-cracking in the high-strength steel weld metal. The development of high-strength weldable steels made great progress in the last 20 years by the application of the combination of lean alloying concepts with the thermo-

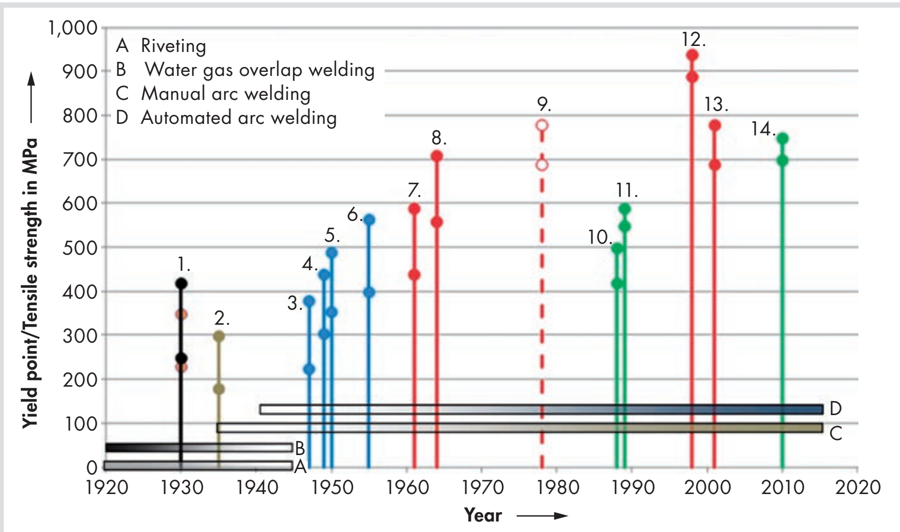

Fig. 1. Historical development of steel grades and joining processes for hydropower penstocks and steel lined shafts in central Europe [1, 2].

Tab. 1. Mild steel grades.

Position		Steel grade	Yield point [MPa]	Tensile Strength [MPa]
1.		M I steel	230 to 250	350 to 400
1.		M II steel	250 to 290	420 to 500
2.		SM steel	180 to 270	300 to 400

Tab. 2. Steel grades for fusion welded shafts of hydropower plants.

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

* Current standard DIN EN 10025-3

mechanical treatment of the materials. As a result of this successful development, steel grades showing excellent strength and toughness properties, but also good weldability appeared on the market. The risk of H–induced cold-cracking in the HAZ was dramatically reduced which, as a consequence, leads to the reduction of applied preheating temperatures. By the use of the traditional fusion welding procedures SMAW and SAW, the required strength in the weld deposit – adequate to that of the base material – can only be reached by the application of a higher amount of alloying elements in the consumables. By this, the risks of the appearance of H-induced cold-cracking moved from the HAZ region of the base material towards the weld deposit. The H-induced weld metal cold cracking appeared mostly as transversal but also as longitudinal cracks in the weld deposit as shown in Figure 3. These types of cracks were unexpected and therefore in many cases not detected by the applied traditional NDT methods.

The cause of these cracks is, as in the traditional HAZ-type IV cold-cracks, the combined interaction of microstructure, H-content and residual stresses. The maintaining and control of the necessary pre- and post-heating temperatures and durations, the control of the H-intake by the consumables, are in combination with the application of proper NDT-methods in the case of using high-strength steel grades of even greater importance as it was in the past.

The Cleuson Dixence case

One landmark of the underestimation of these basic requirements when using new high-strength grades is the Cleuson Dixence case in Switzerland, which happened in December 2000. [3] A brand new shaft, up to 3.5 m diameter and 36 mm wall thickness made from the steel S890 fractured catastrophically by the formation of a crack in the longitudinal weld of the shell, penetrated into the base materials of the both adjacent shells and stopped in the next circumferential welds (Figure 4 and 5). The mud caused by the water leakage went down the mountain, killed three people and caused heavy damage. Extensive investigations performed by different competent European laboratories devoted to that failure case came to the conclusion that this catastrophic failure initiated from an existing cold-crack in the weld deposit. The detailed results of these investigations are described in [3]. Other postulated failure mechanisms, like stress corrosion cracking, could not be confirmed by these investigations.

The selected reconstruction concept is based on the introduction of a new sleeving pipe in the existing pipe, made of steel grade S690. The reconstruction works started in 2007 and were finished at the end of 2009.

Qualification criteria for high strength steel grades for hydropower application

Based on these experiences, a new approach for the definition of qualification criteria when using high-strength steel grades for hydropower application was developed. Apart from weldability and application of adequate fabrication procedures, strength and toughness for static loading

Fig. 2. Type IV cold cracking on penstock Q&T fine grain steel [5].

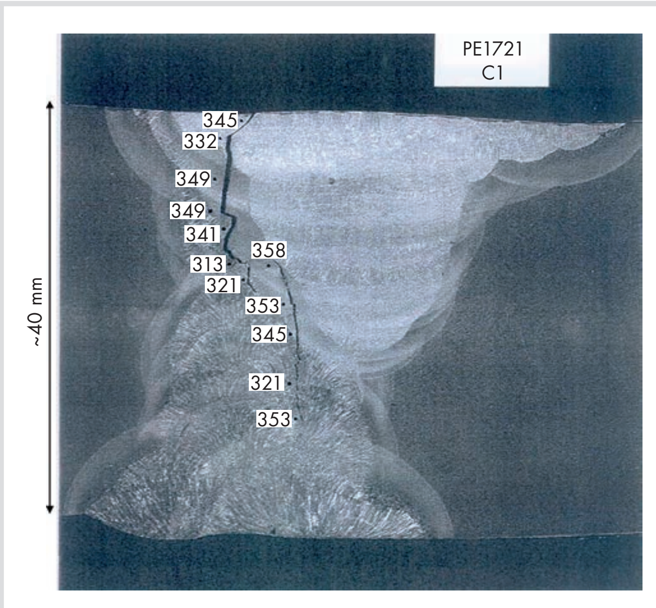

Fig. 3. H-induced cold crack in S890 steel weld deposit [3].

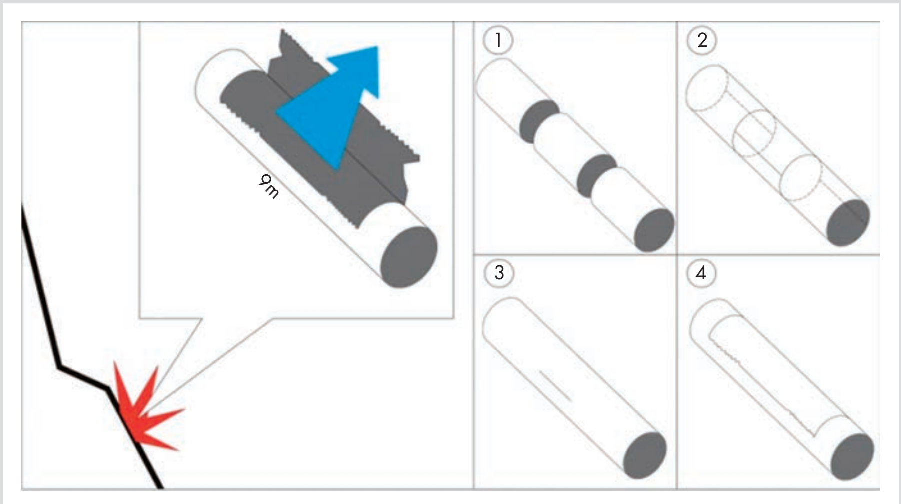

Fig. 4. Cleuson Dixence: crash appearance [3].
Through the crack of 9 meters length 27,000 m³ gushed out in a water jet of 100 meters
1 The pressure shaft consist of 3 m long shells, welded to each other
2 Each shell has a longitudinal weld which are arranged opposite to each other
3 It is concluded that in a 3 meter longitudinal weld a failure was present
4 The crack extended on each side to cause an opening of 9 meters to gush out 270,000 m³ of water

Fig. 5. Cleuson Dixence: view of mudslide [3].

conditions, fatigue properties for dynamic loading conditions, susceptibility for stress corrosion cracking and application of optimal non-destructive testing methods and sequences are the criteria which have to be considered for the selection of high-strength steel grades for the design, fabrication and service of penstocks and steel lined shafts to assure their integrity.

Static loading conditions: *Strength*

The designers and stress analysts see at their first criteria the strength properties which are very important and standardised 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 economists and lawyers.

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 but also for unexpected service events or even catastrophic natural disasters. This is necessary not only for the base material, but also for all different microstructures present in the component, caused by fabrication processes like welding, forming and repairs.

The material property which describes that behaviour is the toughness. Standards usually define toughness criteria by specified minimal notch impact values, which have to be fulfilled during the acceptance tests. 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 integrity of the component to bearing loads in presence of flaws, i.e. cracks.

Decisive influence on the toughness level of high strength steels has also the cleanliness of the plate material 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 to check the cleanliness of the steel plates is the application of through thickness tensile test by specification of a minimum value for the reduction of area value in accordance to DIN EN 10164. This requirement shall anyway be applied when welds perpendicular to the plate surface are foreseen, to prevent the appearance of lamellar tearing effects.

Qualification programmes to allow integrity analysis

For the representation of the qualification criteria so-called qualification programmes were developed and performed to allow an Integrity analysis [3, 6 to 8]. Safe design of components shall be based on the principles of the integrity analysis, briefly described in Figure 6 [6].

The detectable crack size always has 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 applied qualifiedly, 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 sharp cracks.

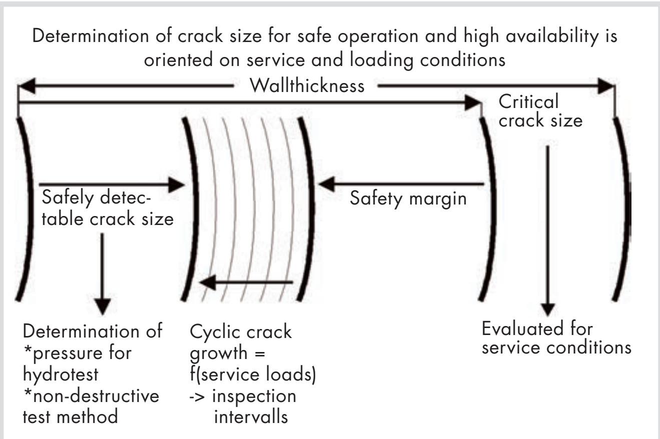

Fig. 6. Integrity analysis [6].

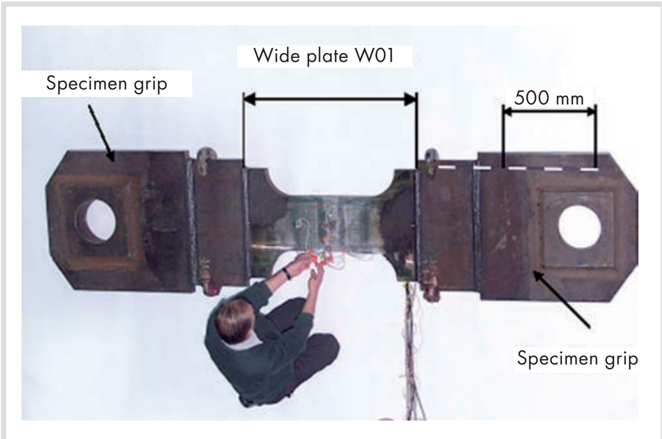

Fig. 7. Wide plate investigations [6].

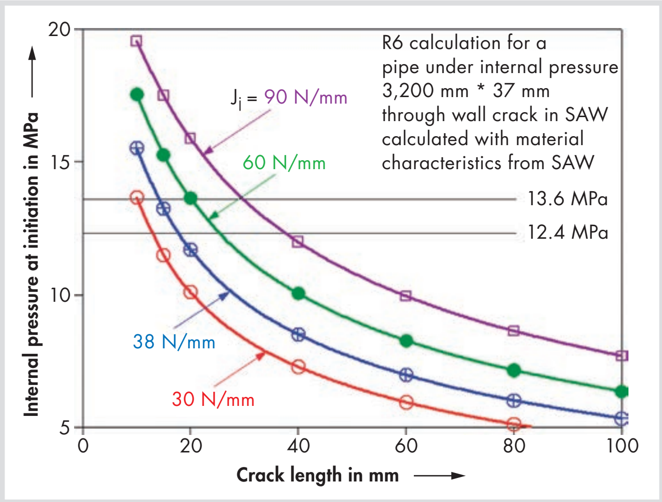

Fig. 8. Initiation pressure of a pipe depending of through wall crack length and different initiation values calculated with R6 method [6].

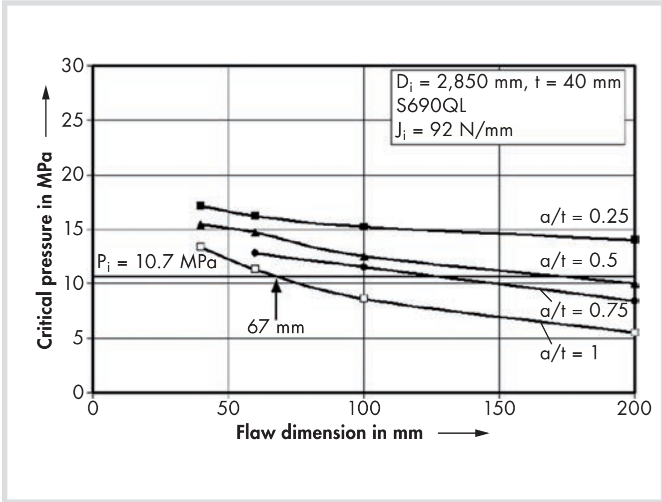

Fig. 9. Critical crack size calculation using R6 routine [7].

The results obtained from the qualification programmes allowed to define the material properties of the new grades of high strength steels which allow quantifying the integrity of components in presence of flaws, which can safely be detected by non-destructive tests applied.

During those qualification programmes not only small fracture mechanics samples were tested, but also the integral behaviour of welded plates by testing of wide plate tests, Figure 7.

Figure 8 as an example depicts as a result from such a programme 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 fracture mechanics tests, critical crack sizes for the different positions in the shaft can be estimated and therefore allow a quantitative integrity analysis.

Figure 9 displays a result as an example of application of that approach for the steel grade S 690QL [7].

This approach also allows to compare the basic behaviour 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 and S 890 QL (quenched and tempered) are compared under the following assumptions:

A penstock with an inner diameter of 2,850 mm and a wall thickness of 40 mm is pressurised with 10,7 MPa. The software IWM Verb (Version 2011) [9] was used for calculation. The R6 routine in the standard level was applied [10]. The Young's modulus is 210 GPa for all materials. The relation between the measured Ji-value and the calculated KIC is based on the assumption of a plane stress state (Table 3).

For a safe service these effects have to be quantified and considered by appropriate monitoring programmes.

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 the static loading approach [2]. Because of the dramatic change of the requirements on the service programme of stored power plants (SP) and pump stored power plants (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 lifetime assessment of existing penstocks. 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. Recent investigations showed (Figure 10) [11,12] that additionally to the needs to aqcuire more knowledge about the quantitative fatigue behaviour of these materials as base material 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. When using the common approach of the International Institute of Welding (IIW) [13, 14], the calculated lifetime exhaustion factor, described by a Miner damage sum, taking into account a given service programme of pressure fluctuations, is therefore also very much dependent on the geometric situation of each single welded shell. The calculation reveals that even an angular misalignment which is in accordance with the widely used CECT recommendation [15] can reduce the calculated lifetime in relation to an ideal circular cross section of the pipe significantly.

Tab. 3. Comparison of calculated critical crack length 2c for different grades of high strength steels [6, 7, 8].

Material	Ji	KIC	$R_{p0.2}$	Rm	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

Stress corrosion cracking

In the course of the failure case analyses Cleuson Dixence and the subsequent qualification programme for the high strength steel S890, stress corrosion cracking as one potential danger was investigated in detail [16]. 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 mechanical 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.

Non-destructive testing

The use of HSS for penstocks and steel-lined shafts requires, according to the experience of the authors, in addition to the common and generally applied NDT procedures (when fabricating safety-related

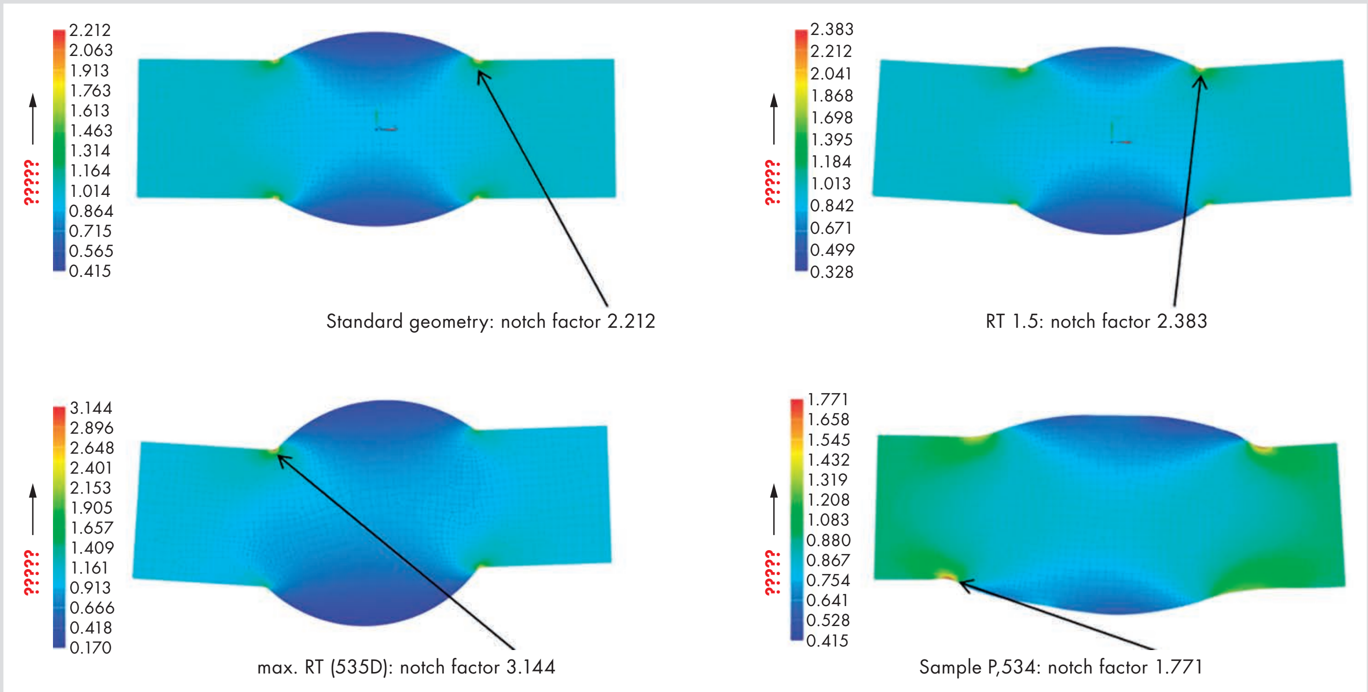

Fig. 10. 2D-Simulation of notch factors of different weld geometries showing different roof toppings (RT) [11].

designs), some additional measures to assure the needed homogeneity of the welded joint. The appearance of H-induced cracking in the weld deposit and the possibility of delayed cracking have to be considered by application of additional and delayed UT procedures.

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 persons involved in that business shall acknowledge this fact and accept their responsibility. They have to bear in mind that apart from the specified service programme, 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 persons involved, have to respect not only the existing design-materials- and testing standards but also have to consider the experiences, which were made worldwide in the past. The event which was the nucleus for the new approach of qualification of new grades of HSS for hydropower plants is a very good example of respecting that experience.

In the last decades outstanding developments in the field of strength of high-strength steels grades happened and allowed the design, fabrication and erection of huge SP and PSPs. Also because of the new requirements coming from the grids, new challenging dynamic service conditions appeared requiring higher exploitation grades of the penstocks and lined shafts. In addition to the static load also the dynamic loading conditions have to be considered. Extensive qualification programmes were performed to quantify the fabrication and service properties of the materials applied.

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 be adhered to in order to assure that all requirements necessary during design, material selection, planning and performance of the fabrication steps, especially welding, assembly and testing as well as in service are met. If these conditions, based on an integrity analysis, are completely fulfilled, successful and safe service for a long time can be assured.

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