THE APPLICABILITY OF STRATEGY FOR RISK BASED MAINTENANCE TO A PENSTOCK

Tamara Sedmak[1], Stojan Sedmak[2], Ljubica Milović[3]

[1]University of Belgrade, Faculty of Mechanical Engineering, Serbia

[2]Society for Structural Integrity and Life (DIVK), Belgrade, Serbia

[3]University of Belgrade, Faculty of Technology and Metallurgy, Serbia

Email adress: tamarasedmak87@hotmail.com

Abstract: The risk of brittle fracture of pumping up penstock was recognized in an early stage of design. To reduce the cost of penstock construction one tunnel was accepted. For that most stressed penstock section HSLA steel, 700 MPa yield stress, 47 mm thick, was selected. Two problems were induced regarding brittle fracture. Cold cracks in welding could be avoided applying undermatching approach. This required to specify welding procedure and to qualify it for used thickness. Designed thickness might produce plain strain condition. For detailed analysis of cracks effect and stress state it was accepted to produce two full-scale prototypes of penstock most stressed part. Obtained results by fracture mechanics methods have shown sufficient crack resistance of PM, WM and HAZ in welded joints. It was necessary to assure structural integrity of welded joints and penstock involving corresponding approach for maintenance and repair. Maintenance procedures are in continuous development, and most promising is probably risk based approach, developed in last years. In the paper the base requirements of this approach are considered, and the possibility and convenience to apply them for penstock is evaluated.

Key words: brittle fracture; welded joint; undermatching; penstock; prototype model; risk based maintenance

1. INTRODUCTION

Hydro-electrical power plant (HEPP) systems might require large amount of water in the Storage Lake and high fluid flow rate for the operation. For such a system the consequences of unexpected failure can be catastrophic, producing a great risk in service. In order to avoid the failure, preventing measures have to be applied /1/.

One of very important component in HEPP is a penstock, which can be exposed to high stresses, and for that be susceptible to failure. To reduce the risk level, operational safety of individual components in HEPP system, including penstocks, must be at very high level, This requirement comprises the assurance of high quality of produced components.

The failures of penstocks and pipelines are not frequent. Mechanical damages observed before and during service, fatigue, corrosion defects, welding imperfections and environment effect are referred as most important causes. Plastic collapse and brittle fracture are not cited often as failure cause, because applied steels for pipelines are ductile, and pipelines are used in the region above nil-ductility transition temperature.

However, cracks, brittle fracture and leakage had been experienced in penstocks produced of weldable high strength low alloy (HSLA) steels, developed and applied for reducing manufacturing costs by lower wall thickness /2/. Proof pressure test is required before acceptance for service, in some cases also testing of model is necessary.

2. EXAMPLES OF BRITTLE FRACTURE AND LEAKAGE

Two examples of failures /2/ are selected to illustrate the significance of risk analysis for penstocks. They also have shown the significance of welding procedure specification (WPS) for maintenance system and possible risk in service of a penstock.

Typical example of fast brittle fracture is catastrophic failure of penstock (length 2640 m, hydrostatic water pressure 864 m), occurred in 1973 year during pressure proof test in one knee close to machine house in HEPP „Santa Isabel“ in Bolivia. Failure occurred at pressure 735 m, e.g. at 84% of design pressure. Water jet passed through hole 1 m long and 0.7 m wide, and destroyed tropical vegetation along 130 m and 10 m in width. About 6000 m^3 of water leaked for one hour, before the closing the valve in surge tank. The penstock was repaired by new segments for the knee. The tubes were produced of quenched and tempered steel Aldur 50/65D. This steel is designed for penstocks. In damaged knee pipe diameter was 1.15 m, plate thickness 22 mm. Mechanical properties, tested after failure, corresponded to specification. Metallographic examination revealed that failure cause is brittle fracture, initiated in the heat-affected-zone (HAZ) of longitudinal welded joint, performed by sub-merged arc welding (SAW) procedure. Crack developed from the initiation point on both sides in the directions parallel to weld, and arrested at transversal manual arc welded joint, where continued to grow in direction normal to the weldment. It is evaluated that the possible failure cause is weld repair, since the preheating had not been applied according to welding procedure specification (WPS). Since involved steel is ductile, tough and crack resistant, the presence of high level of welding residual stress due to improper welding technology reduced penstock strength. After repair, in repeated test, penstock passed pressure 30% above design pressure, corresponding to 1170 m.

The next example, failure of penstock of „Peručica“, due to partial leakage, showed the significance of quality assurance in welding. Neither brittle fracture nor complete leakage occurred, but the occurrence of cracks in welded joints required measures for preventing of the break of power plant operation. Cracks occurred in welded joint of a ring, 100 mm wide, consisting of 6 circumferential segments (pos. 104 in Fig. 1). The diameter of penstock (pos. 103 left) is reduced from 4000 mm to 3400 mm in inlet line for turbine (pos. 103 right). Two pipelines were produced by different manufacturers, and significant misalignment and end distance occurred, what was solved by the collar (pos. 105), welded before the ring and accepting the loading by fillet welds. The ring served to fill the gap. After welding, the tunnel was filled with the concrete outside penstock, and penstock was protected inside by lacquer. Steel of 450 MPa yield stress, microalloyed by vanadium, was selected for collar and ring. After 10 years of service numerous cracks were revealed, several hundreds millimeters long, in both ring welded joints „A” and „B“ (Fig. 1), some of them passing through the weld and reaching fillet weld of pos. 105, i.e. the space between collar and ring. During the examination of empted penstock the water was found in cracks, confirming that crack depth reached the thickness of the ring, i.e. tube. The monitoring of cracks showed that they did not grow, or grow slowly.

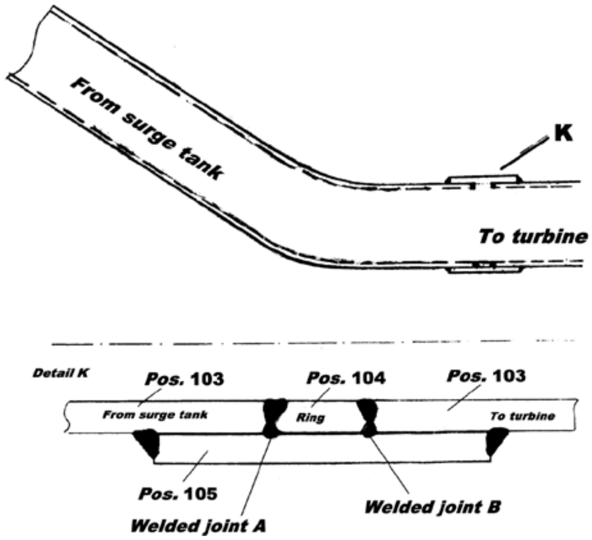

Figure 1. Design of collar (pos. 105) and ring (pos. 104) for joining the penstock

Examination had shown that cold cracks are in question, occurred due to improper preheating and the rigidity of penstock at ring welding. Once initiated, they developed due to corrosion. Significant for their occurrence was an overloading of penstock in early stage of service, followed by vibrations. Cracks did not endanger directly the integrity of structure, but affected the contact of inner welded joints of collar with the water, what, in addition to acting stress concentration, could initiate cracks also in loaded welded joint of collar. For this reason the repair is performed by change of all segments of a ring.

3. DEVELOPMENT OF MAINTENANCE SYSTEM

Maintenance of technical systems has been developed and improved during the years. Corrective maintenance, which implies to eliminate the effects of experienced failures, is the first generation of maintenance strategies, simple, bur no more attractive. Second generation was the scheduled maintenance, which considers higher plant availability, longer equipment life and lower costs. Past thirty years many complex strategies have been developed as third and fourth generation. Those include TPM (total productive maintenance), LCC (life-cycle costing), RCM (reliability centered maintenance), RBI (risk based inspection), and RBM (risk based maintenance) /3/. Nowadays most attractive are risk based maintenance and inspection, because they can assure best practical results

Risk is defined as the combination of the probability of an event and its consequences. Risk analysis can provide information for different type of consequences that can arrive from failures of equipment, like environmental, health, safety and business consequences. This is very important for large and complex industrial systems, like oil refineries, petrochemical and chemical plants, steel production and power plants.

However, current practice of inspection and maintenance planning in power plants is still mostly time oriented and based on prescriptive empirical rules and experience rather than being an optimized process where risk measures for safety and economy are integrated /4/.

The major challenge for a maintenance engineer is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures a safe and environmentally friendly operation, and minimizes the total cost of the operation. This can be achieved only by adopting a structured approach to the study of equipment failure and the design of an optimum strategy for inspection and maintenance /5/.

For the selection of a maintenance strategy using a risk-based approach is essential to develop cost effective maintenance polices for mechanized and automated systems because in this approach the technical features (such as reliability and maintainability) are analyzed considering economic and safety consequences, according to Kumar, /5/.

Further more, the use of risk-based methods in inspection and maintenance of piping systems in power plants gives transparency to the decision making process and gives an optimized maintenance policy based on current state of the components.

Lack of unique standard for RBM results in various methods and techniques for analyzing risk and making inspection decisions based on those analyses. According to Ref. /6/ there is no unique way to perform risk analysis and involve RBM. Different approaches are reported, ranged from only qualitative to complete quantitative /5/.

Only available applicable risk based standard is American Petroleum Institute standard (API 581, Risk Based Inspection-Base Resource Document). However this is standard for American industry and applicable only for process plants.

Extensive European project RIMAP /7/, started in 2001 and finished in 2004, had been induced to offer a European standard for RBM. It has produced four industry specific workbooks for the petrochemical, chemical, steel and power generation industries, aimed to provide more specific guidance on how to apply the RIMAP approach in these sectors. However, this approach is to complex, and will not be considered in this paper.

In this paper it is accepted that the level of failure consequences is very high /1, 2/, and for that the probability of failure should be very low. Relevant parameters for failure occurrence are required, and they can be established by theoretical and experimental analysis, and, when possible, supported by a numerical analysis /8/.

3.1. Risk based maintenance optimization

A qualitative risk assessment ranks system and components relative to each other. When a qualitative risk assessment should be perform, relative failure probability and consequence severity can be classified in broad groups, assigned as ‘high’, ‘medium’ and ‘low’. Although any number of groups could be applied, probably maximum five failure probability and consequence severity groups can be accepted with sufficient confidence. Qualitative analysis uses words to describe the magnitude of potential consequences and the likelihood that those consequences will occur. These scales can be adapted or adjusted to suit the circumstances, and different descriptions may be used for different risks /9/.

Quantitative analysis includes acquisition and elaboration of the data, related to the equipment history and failure modes and consequences. It is necessary to quantify probability of failure occurrence and consequences, which product represents risk value.

According to API, as well as to RIMAP, this can be performed on three different levels, depending on detail of analysis. In API approach the levels are categorized as qualitative, semi-quantitative and quantitative analysis, categories in RIMAP are at screening, intermediate and detail levels.

It is well known that there are also other different scales for consequences and likelihood, and corresponding risk matrix. Scales and matrixes can be defined in respect to specific analyzed problem, with no strict rules. For that it is difficult to select a proper matrix.

First, i.e. qualitative level is based on one general matrix, presented in Table 1, which is applied in the Project Risk NIS /10/. In this matrix, consequences are categorized, based on several parameters (health, safety, environment, business, security) as A to E, A indicating low, almost negligible consequences, and E fatal and serious consequences. Probability categories are graduated by 1 to 5, category 1 representing very unlikely detrimental event, once in more than 100 years ($1x10^{-4}$), and 5 representing very probable event occurring at least once in a year ($1x10^{-1}$).

Table 1. Scheme for risk based qualitative evaluation of maintenance

		Consequence category				
		A	**B**	**C**	**D**	**E**
Probability category	**5**					**Very high risk**
	4				**High risk**	
	3			**Medium risk**		
	2		**Low risk**			
	1	(Very low, negligible risk)				

As it has been mentioned, the consequences of penstock failure can be extremely serious /2/, indicating category E. For safe and reliable use of penstock it is of utmost importance to assure extremely low frequency of detrimental event, measured as 1×10^{-4}, or once in more than 100 years. This can be achieved by special measures in all steps of construction and operation. On the other hand, very strict requirements have to be posed for such a structure, complex regarding design and manufacturing, to prove that detrimental events are unlikely to occur. This might be possible only with sufficient and confident data, experimentally verified.

3.2. Peculiarities for risk-based approach to penstock

Dominant failures of pressure equipment are fast fracture, leakage and corrosion. Fast fracture could be brittle fracture under plane strain condition or ductile fracture due to overloading in plane stress condition. Leakage is a consequence of through wall crack, achieved as time dependent stable crack growth. Corrosion can be developed in specific environment condition, and stress corrosion is supported by applied stress. Common feature of these three failure modes is the existence of crack. Welded joints are prone to cracking, and they are most critical regions of welded structure. For that the quality level of performed welded joint has to be assuring following strict requirements during manufacturing, according ISO 9000 series standards.

Structural integrity depends of crack behavior. For the control of a crack two aspects are important. It is necessary first to detect crack and to identify its location and size by different non-destructive testing (NDT) methods. Then crack significance has to be assessed applying convenient parameter and method based on fracture mechanics. To assure safe operation according to European directives for pressure equipment (PED) these two aspects should be considered before the equipment is accepted for European market, since the welding quality can not be verified on final product but has to be induced during manufacturing /11/. Welded joint quality in service has also to be controlled by inspections in maintenance system.

However, penstock is in service not available for inspection in short time distances or by continuous monitoring, but only when it is emptied. Accepted inspection interval for HEPP is ten years, and NDT of penstock should be performed then on selected critical welded joints. For that, from risk point of view it is necessary to assess the risk level for all welded joints before inspection, and perform the inspection only on joints of high risk.

4. PROTOTYPE MODEL OF A PENSTOCK

Pumped-up storage HEPP "Bajina Bašta"in design period, about 40 years ago, represented the solution of world's highest head and water speed. Design is performed by „Toshiba", Japan, based on single-stage two units Francis type reversible pump-turbine of maximum output 315 MW at maximum head and revolving speed of 428.6 rpm. Pumping rate is maximum 621.3 m, discharge 50.8 m^3/s, maximum pump input 310 MW. Rotor runaway speed is 650 rpm. Maximum pressure in penstock corresponds to the water height level of 900 m.

The failure in HEPP „Santa Isabel"in Bolivia /2/ was clear warning to investor regarding the risk of brittle fracture when penstock is produced of HSLA steel. Accordingly, it was decided to perform experimental testing of two full scale prototype models of the penstock. Prototype, produced of quenched and tempered HSLA steel SUMITEN 80P (SM 80P), 47 mm thick, "Sumitomo", Japan. (Yield strength 700 MPa, ultimate tensile strength above 800 MPa), presented the most stressed part of the penstock (Fig. 2).

Penstock welding had to be partly performed in the field. i.e. in tunnel, and requirements could be satisfied only by educated, skilled and approved welders. Due to limited experience with this class of steel, certification of welders, welding procedure specification (WPS) and its qualification were required by user, similar to nowadays standards EN287 and EN288. The second problem was adopted safety margin of only 1.7 regarding steel yield strength according to German specification /12/ for HSLA steel. In other specifications, higher safety margin have to be accepted, in Japan for this steel grade recommended safety margin is 2.07. Full scale test is the most informative and serves as final proof for the quality and safety of a welded structure, giving realistic response of loaded welded joints behavior. For that, fitness for service (FFS) assessment was required, in order to understand better crack significance, resistance to brittle fracture and stable crack growth /13, 14, 15/.

It is to emphasize that the main motivation for full scale model testing was to gain sufficient data for risk significance assessment, based on experience and available knowledge in that time. These data are helpful also in the actual analysis based on risk. For that, most important information about the design and manufacturing of the prototypes, including welding and welded joints properties, are presented here sufficiently to explain possible application of experimental results for determination of parameters relevant for risk, at least on qualitative level. Extended experimental investigation according to specified programs regarding brittle fracture, stable crack growth and welded joints properties enabled to assess confident data about material and welded joints behavior under operational loading /8/.

Two prototypes manufacturing (Fig. 2), was also used to gain necessary experience in welding.

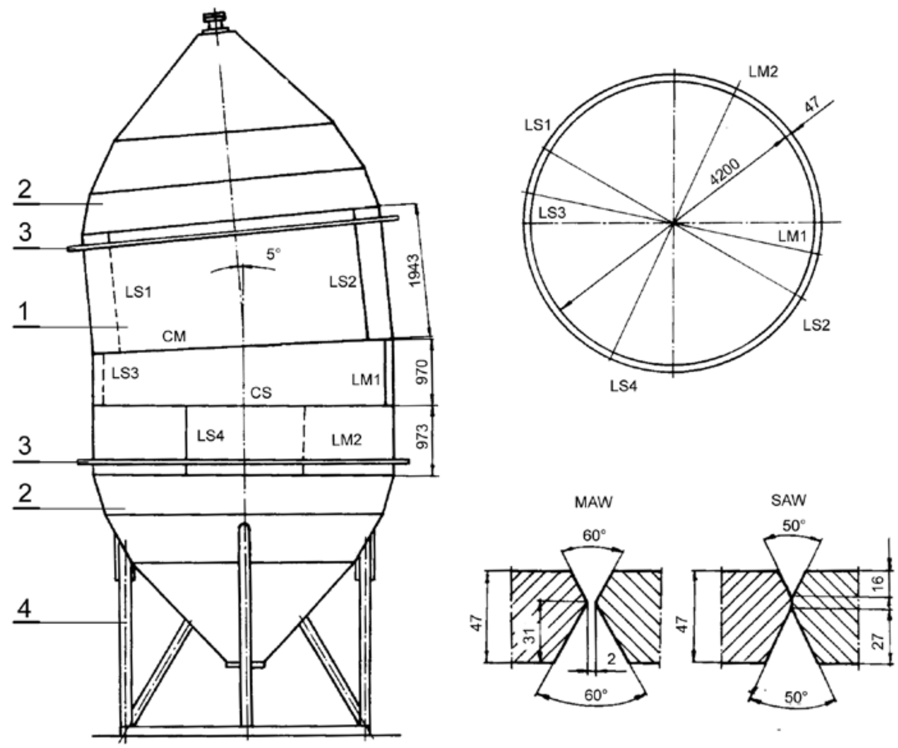

Figure 2. Full-scale model of penstock most-stressed segment:
1-mantle; 2-lid; 3-stiffener; 4- supports of leg L-longitudinal, C-circular;
MAW - manual arc welding (M); SAW-submerged arc welding (S)

Matching between strengths of parent metal (PM) and weld metal (WM) has an important role in the service of welded structures, since high stress should cause local plastic strain due to applied undermatching and stress concentration. Welded joints are generally designed as overmatched, with t

WM superior in strength compared to PM, with plastic deformation localized in PM. The situation turns to be complex in high strength steel which should be welded as undermatched to prevent cold cracking. In undermatched welded joint plastic deformation will start in WM, and PM can start to yield when WM strain hardening capacity is partly exhausted /16/. Anyhow, in welded joints microstructure of HAZ is heterogeneous. In non-uniform microstructure the straining can be constrained and plane strain can prevail, critical for brittle fracture. Stress concentration and residual stress, inevitably present in welded joints, can contribute to plain strain condition.

The overall behavior of a welded penstock under load was analyzed based on results of three approaches (crack initiation, crack propagation and arrest, stable crack growth), allowing an evaluation of crack significance. Obtained data in experimental investigation of prototype, together with the data about material properties and heterogeneity effect /15/, can also serve to select crack parameters and to calculate and specify their referent values for risk based inspection and maintenance strategies. To achieve this, additional analysis is necessary, generally followed by numerical modeling,.

4.1. Manufacturing of penstock prototype

Cylindrical mantle of full-scale model, consisting of 3 segments, 973 mm, 970 mm and 1943 mm long, designed with 5° knee corresponding to the penstock transition segment, was covered with two shaped lids (Fig. 2). The steel plates, two for each segment, were rolled and welded.

Welded joints, designed for penstock longitudinal (L) and circular (C) weldments with preparation given in Fig. 2, were MAW and SAW welded, using basic low hydrogen electrode LB118 for MAW and core wire U8013+M38F flux for SAW welding, produced by "Cobe Steel", Japan. To minimize the influence of the lids on the stress state in the mantle, two ring stiffeners were welded near circular weldments. Certified welders welded the prototype models and later the penstock. Specified and qualified manual arc welding (MAW) and submerged arc welding (SAW) procedures were used, also applied in subsequent penstock fabrication.

4.2. Burst test - resistance to fast crack propagation

The burst test was performed on the first model, produced by "Metalna" company. Here will be presented only some details of testing, main results and conclusion. More details about this test can be found in Ref. /17/.

Three additional longitudinal SAW welds were made on cylindrical mantle bottom shell (Fig. 2), providing three crossings with circular MAW weld metal. Two artificial surface cracks, sized 180×4.3 mm and 50×6 mm, were produced in longitudinal welded joints with the tip positioned in HAZ, and one crack (40×3 mm), was embedded in third longitudinal weld. The instrumentation consisted of two crack opening displacement (COD) gages over surface cracks, 22 strain gages, 9 Moiré grids, 3 acoustic emission sensors, pressure transducer and a measuring system of outer periphery.

The full-scale model was first statically pressurized by uniformly raising water pressure in two steps, achieving maximum level of 117 bar, which corresponded to the hoop stress σ_t = 518 MPa in an ideal cylindrical vessel. Next test was dynamic, to simulate water hammer, was performed by two successive explosions of controlled rate, after the static pre-loading of 60 bar (σ_t = 265 MPa). The plastic deformation followed the explosion loading rate, indicating stable crack growth.

The non-destructive examination showed that longer surface crack extended for 28 mm in length, 10 mm and 18 mm on sides, and the second surface crack did not propagate in length. Two small new cracks initiated in testing. Detailed analysis revealed that fracture developed through brittle region in HAZ, close to fusion line. No one crack passed the wall thickness.

The conclusion was that full-scale model and penstock can safely withstand the working pressure (90 bar) and effect of water hammer pressure in the presence of large flaw (6 mm deep, 50 mm long) and imperfection, caused by misalignment of weldments.

Burst test has shown that penstock is resistant to fast fracture. In that test an approximate answer is obtained for critical crack size and crack behavior during loading, similar to possible working loading.

4.3. Hydro-pressure test - resistance to stable crack growth

The hydro-pressure test of the second model with no crack enabled the post-yield analysis of weldments. Trial samples for additional testing were welded simultaneously with the model, see Ref. /18/.

The analysis of the behavior of crack free penstock under design loading and expected overloading, and the effect of initial plastic deformation on welded joint toughness, was the aim of the experiment, performed by GOŠA company. This was achieved by comparing the results of mechanical and fast fracture tests of corresponding specimens (Charpy V impact, drop weight – DW, and explosion bulge tests of MAW and SAW welded joints), taken from the prototype after hydro-pressure test and local plastic deformation in weldments, and from non-deformed trial samples.

Hydro-pressure test was performed at an ambient temperature (between +6°C and -3°C). Strains were monitored by strain gages, and controlled by moiré grids. Acoustic emission sensors in the critical regions enabled the control of large plastic strains or crack initiation, to prevent a catastrophic fracture during pressurizing. In the first testing step the pressure reached 90.2 bar (σ_t =399 MPa), corresponding to operating pressure. In the second step pressure was 120.6 bar (σ_t =533 MPa), that is close to the total operating and water hammer load. The measured values of strains for selected location and strain gages (SG) (2; 34; 53; 59) enabled to quantify residual plastic strains, ε_{pl}, (Fig. 3). The level b corresponds to maximum strain achieved in first step, level a indicates residual strain; level d is maximum strain in the second step, and level c indicates total residual strains. Strain developed uniformly in PM (53) and circular SAW WM SC (59). Total plastic strain of 0.1% after pressurizing is found on circular CS WM (59). Plastic strain 0.24% was found in WM LS1 (2, 34). The loop in Fig. 3 is attributed to the combined effect of undermatching, WM strain hardening and strain redistribution in unloading and reloading due to stored elastic energy release in PM.

Differences in tensile properties (yield strength; ultimate tensile strength; □ elongation of weld metal) for welded joints and WM were remarkable, regardless that the results fulfilled specification. The results of hardness measurement were acceptable. There are two basic reasons for differences in mechanical properties in tested prototype. Stress concentration is the first, global, due to 5° knee, and local, due to weldment shape that affected strain distribution. The second reason is level of undermatching, which is different for SAW and MAW welded joints. Longitudinal welded joints are more stressed then circular, and this produces more pronounced difference in stress and strain distribution. It is also necessary to take into account the tendency of pressure vessel to take under pressure simplest form of sphere or cylinder to achieve more uniform stress distribution. With all this in mind it is possible to conclude that the yielding will start first in position of lower material strength, in undermatched weld metal, and at the location of highest stress concentration in the vicinity of knee and where it is caused by imperfection of welded joint shape.

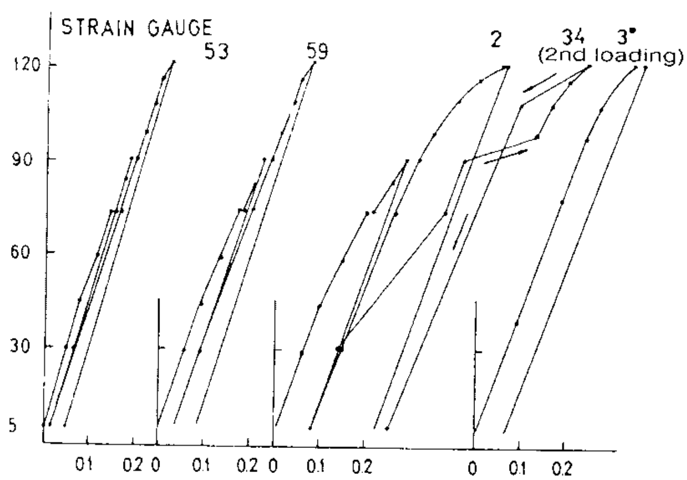

Figure 3. Typical relationships between pressure and strain

Important conclusion from performed test is non-uniform behavior and different local plastic deformations (Fig. 3), indicating complex material response to loading. But it is not critical, since the behavior of plastically deformed material in next loading will behave elastically.

4.4. Prediction of stable crack growth resistance

Next step was the assessment of residual strength of model cracked in PM and in WM, and resistance to stable crack growth, by J integral, comparing crack driving force (CDF), obtained by numerical Ratwani-Erdogan-Irwin model (REI), and material J-R curve /19/.

Set of CDF, calculated for the prototype (Fig. 2) is given in Fig. 4. for different pressures, defined by the ratio $pR/WR_{p0.2}$. (p is pressure, R radius, W wall thickness). CDF depends on material yield strength $R_{p0.2}$. Resistance curves for PM (steel SM80P) and SAW WM had been obtained by three point bend specimens (SENB) 22.5x45x180 mm (ASTM E1152). They are transferred to the CDF plot in Fig. 4. For assumed ratio a/W = 0.25 (crack depth a = 11.75 mm) crack will grow in a stable manner for 3.75 mm in PM and 4.25 mm in WM, and critical pressure reached 155 bar and 144 bar, respectively. For a/W = 0.5 (a=23.5 mm) corresponding values are 8.5 mm and 140 bar for PM, and 6.1 mm and 104 bar for WM. The results have shown high crack resistance of SM80P and its SAW weld metal.

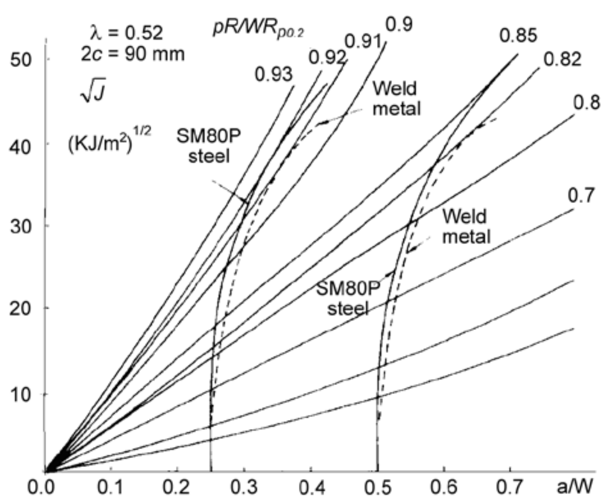

Figure 4. Procedure for residual strength assessment of cracked pressure vessel, with crack driving force and J-R curves, applied for preliminary prediction

5. DISCUSSION

The risk of failure by brittle fracture or leakage, which could endanger in-service safety, had been well recognized in the case of HEPP "Bajina Bašta" penstock. In order to assess the level and significance of possible risk, experimental investigation of fast fracture and stable crack growth were performed with two full scale prototypes according to specified program. The motivation for this investigation was to gain sufficient data for risk level assessment, based on experience and available knowledge in that time, about thirty years ago. Most important results, presented here, allowed to made qualitative assessment regarding brittle fracture, strain distribution in loaded penstock (Fig. 3), and crack resistance (Fig. 4). Obtained results have shown that applying proper measures in design and manufacturing, including welding; it is possible to assure safe operation of the penstock, based on qualitative assessment of the risk. However, much valuable information gained in this investigation has not been used and still are interesting for additional consideration on how to quantify risk levels of probability and consequence in meanwhile developed approach for inspection and maintenance /7, 9,10/. In that sense this paper, aimed to analyze applicability of new developed principle based on risk, can be considered as a continuation of performed investigation.

Large amount of stored water in HEPP, which might be released in the case of failure, indicates possible severe consequences, of level E (Table 1). This level can be accompanied by probability category 2 for medium risk and by category 1 for low risk, according to accepted approach. In both cases confident data are required, experimentally checked for determination quantitative level for the assessment of critical values for selected parameter.

As it is already mentioned, detrimental events which can cause the failure occurrence in penstock are fast fracture, leakage after stable crack growth and corrosion. All three failure modes are related to crack, its existence or initiation. Fracture mechanics introduced convenient parameters for each of them. For fast fracture it is plane strain fracture toughness K_{Ic}, as critical value of applied stress intensity factor K_I. For stable crack growth most convenient is J integral in the forms presented in Fig. 4 for curves of crack driving force CDF and J crack resistance: the tangent point of corresponding curves indicates the end of stable crack growth and beginning of fast fracture after plastic deformation. Time dependent rate of crack advancement is relevant for corrosion, and in the case of stress corrosion it is sub-critical value of the stress intensity, designated as K_{Iscc}. In previous chapters only general procedure is presented, but in fact several other aspects had been also considered in investigation, like heterogeneous microstructure of welded joint /15/, especially in HAZ /20/, and undermatching effect /16/, which could help for quantification of selected parameters. Based on experience and available data from literature, corrosion and stress corrosion are not critical in this penstock. Consequently, they were not requested by HEPP investor for the analysis. Requirements for penstock quality and safe service have been considered and proved in this investigation, at least at an empirical and indirect level. In the time of performed experiments it was sufficient to evaluate the risk just qualitatively. Namely, actual risk based approach has been introduced many years after the construction of the penstock. The examples like pop-in occurrence in HAZ, J integral direct measurement, the effect of undermatching are explained in Ref. /13, 15/ and can be used for quantification of critical relevant parameters.

From risk aspect of view following four steps can cover the activities in inspection and maintenance:

1. Non-destructive testing (NDT) for cracks detection, if they are present in a structure, including their location and size.
2. Assessment of crack significance using specified parameters and their determined measurable values.
3. Decision about repair actions for detected cracks.
4. Repair performance.

Let us consider actual situation first. Penstock is accepted for use thirty years ago after strict testing according standards and executed proof pressure test. So, this is sufficient to assume that penstock was defect free initially. Having in mind penstock construction and operation data it is accepted that the regular inspection should take place when HEPP operation would be stopped for general inspection of the system, after every ten years in service. According to available data this was performed twice till now. Only step 1 had been performed. It is to mention that, according to valid rules, educated and skilled personnel, certified for applied NDT methods, has to be engaged by independent testing institution. The results have shown that there is no need for next step.

Meanwhile an intensive development in inspection methods and devices took place, followed by extension of modeling and numerical programming. As a result, continuous monitoring could be applied for different objects, like that presented in Ref. /21, 22/. It might be expected that continuous monitoring will be developed also for penstock. This will be beneficial for risk based inspection (RBI).

For proper maintenance and safe operation, step 2, assessment of relevant parameters, is important. For penstock they can be defined and quantified based on presented results of performed experimental investigation of prototypes, after an additional theoretical and numerical analysis. The relevant data for risk based approach of considered penstock are:

- Characteristics of used material;
- Characteristics of welded joints and their constituent (PM, WM, HAZ);
- Effect of matching and heterogeneity of microstructure;

- Crack resistance and material behavior in the region ahead the crack tip;.

This is a complex task. It requires a series of standard testing, but this is not sufficient for undermatched welded joint, applied in considered case.

6. CONCLUSSION

Risk significance regarding brittle fracture and stable crack advancement preceding the leakage had been evaluated thirty years ago, after the experimental analysis at the level sufficient to accept the penstock of HEEP “Bajina Bašta”. Development regarding inspection and maintenance, which took place from that time, opened the possibility to assess risk consequence and probability at more accurate level. Considering this new development and performed experimental analysis it is found that new principles are applicable to the penstock. The experimentally obtained results also contain many valuable data, which can be additionally used for risk evaluation. For that further investigation in this field is necessary and welcome.

7. REFERENCES

[1]T. Sedmak, E. Veg, *Failure prevention of rotating equipment by vibrodiagnostics*, to be published in Structural integrity and life (IVK) 2/2012.

[2]J. Rastresen, *Failures of penstocks*, in „Penstocks in hydroelectrical power plants“, (in Serbian), Yugoslav Electricity, Belgrade, pp. 229-236, 1979.

[3]T. Sedmak, “Appliance of vibrodiagnostics in a tero technological risk management” master thesis, (in Serbian), Faculty of Mechanical Engineering, Belgrade, 2011.

[4]J. Bareißa, P. Buckb, B. Matscheckob, A. Jovanovicc, D. Balosc, M. Perunicic, *RIMAP demonstration project. Risk-based life management of piping system in power plant Heilbronn;* International Journal of Pressure Vessels and Piping 81 (2004) 807–813

[5]L. Krishnasamy, F. Khan, M. Haddara, *Development of a risk-based maintenance (RBM) strategy for a power-generating plant;* Journal of Loss Prevention in the Process Industries 18 (2005) 69–81

[6]N.S. Arunraj, J. Maiti; *Risk-based maintenance—Techniques and applications*; Journal of Hazardous Materials 142 (2007) 653–661

[7]R. Kauer, A. Jovanovic, S. Angelsen - Gjermund Vage ; Plant asset management RIMAP (risk-based inspection and maintenance for European industries)† the European approach; ASME PVP-Vol. 488, Risk and Reliability and Evaluation of Components and Machinery July 25-29, 2004, San Diego, California, US PVP2004-3020

[8]Fracture mechanics of weldments”, US-Yu joint project, Principal investigator S. Sedmak, Annual reports, University of Belgrade, Faculty of Technology and Metallurgy (TMF), University of Belgrade, 1982-1991.

[9]RBI-PETROL: RBI Risk Baed Inspection – Petrol; ESPRIT Course #4a; Stuttgart, june 2009

[10]Project: RiskNIS: Risk management and use of risk-based approaches in inspection, maintenance and HSE analyses of NIS a. d. plants; TECHNICAL REPORT RBI STUDY Gas Refinery Elemir (RGE) 2009

[11]A. Bređan, J. Kurai, *European Pressure Equipment Directive (PED) and structure (integrity*, (in Serbian), Structural Integrity and Life (IVK), 3(1), 31-42, 2003.

[12]Dast Richilinie 011 „*The application of high strength weldable fine-grained structural steels StE47 and StE70*" (in German), Deutscher Ausschuss fur StahIbau, 1974.

[13]B. Božić, S. Sedmak, B. Petrovski, A. Sedmak, *Crack gowth resistance of weldment constituents in a real structure*, Bulletin T. Cl de I'Academie serbe des Sciences at des Arts, Classe des Sciences techniques, No 25, Belgrade, 21-42, 1989.

[14]S. Sedmak, A. Sedmak, *The experimental analysis of crack behavior in welded pressure vessels*, IIW Doc. X-1447, 1998.

[15] S. Sedmak, A. Sedmak, *Welded penstock produced of high-strength steel and application of fracture mechanics parameters to structural integrity assessment*, in "Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines", Eds. G. Pluvinage, M. H. Elwany, Springer, 271-286, 2008.

[16]N. Gubeljak, J. Predan, I. Rak, D. Kozak, *Integrity assessment of HSLA steel welded joint with mis-matched strength*, Structural Integrity and Life (IVK), 9(3), 157-164, 2009.

[17]I. Rak, V. Gliha, J. Kuder, *The testing of penstock model, welded of quenched and tempered structural steel for pumping-ap hydroelectric power plant Bajina Bašta* (in Slovenian), Metalna Strokovni bil. 84(1), 15-23, 1984.

[18]S. Sedmak, A. Radović, Lj. Nedeljković, *The strength of welds in HSLA steel after initial plastic deformation*, in Mechanical Behavior of Materials Vol. III, Eds. K. J. Miller, R. F. Smith, Perganion Press, Oxford and New York, 1979, p. 435-446.

[19]M. M. Ratwani, S. Sedmak, B. Petrovski, *The assessment of residual strength of pressure vessel with surface crack by resistance curve*, in Fracture Mechanics of Weldments (in Serbian), Ed. S. Sedmak, GOŠA, TMF, Belgrade, 1985, p. 131-162.

[20] A. Sedmak, S. Sedmak, Lj. Milović, Monograph „Pressure equipment integrity assessment by elastic-plastic fracture mechanics methods", Society for Structural Integrity and Life (DIVK), Belgrade, 2011,

[21]N. Gubeljak, *Application of stereometric measurement on structural integrity*, Structural Integrity and Life (IVK), 6(1-2), 65-74, 2006.

[22] N. Gubeljak, J. Predan, T. Valh, D. Valh, *Continuous monitoring and structure integrity assessment*, in Fundamentals of Fracture Mechanics and Structural Integrity Assessment Methods, Ed. S. Sedmak, MF, TMF, DIVK, IMS, Belgrade, 2009, p. 261-284.