Izlaganje na seminaru "Integritet građevinskih konstrukcija" održanom u okviru
Druge godišnje konferencije Društva za integritet i vek konstrukcija, Beograd, 27-28. oktobar 2005.

Presented at the seminar "Integrity of Civil Engineering Structures" held in the scope of
The Second Annual Conference of the Society for Structural Integrity and Life, Belgrade, 27-28 October 2005

Stojan Sedmak [1], Aleksandar Sedmak [2]

INTEGRITET CEVOVODA HIDROELEKTRANE

INTEGRITY OF PENSTOCK OF HYDROELECTRIC POWERPLANT

Originalni naučni rad / Original scientific paper
UDK /UDC: 621.643.2-112.81 669.15-462-112.81
Rad primljen / Paper received: 10.09.2005.

Author's address:
[1] Društvo za integritet i vek konstrukcija, Beograd
[2] Mašinski fakultet, Beograd

Ključne reči
- Cevovod
- Čelik visoke čvrstoće
- Zavarena konstrukcija
- Krti lom
- Otpornost prema prslinama

Izvod

Iskustvo iz eksploatacije cevovoda hidroelektrana ukazuje na moguće procurivanje posle stabilnog rasta prsline ili raspucavanje u slučaju krtog loma. Uvođenje zavarljivih čelika visoke čvrstoće za izradu cevovoda donosi značajne uštede, ali se zahteva otpornost prema prslinama, naročito prema krtom lomu, osnovnog metala, metala šava i zone uticaja toplote. Za cevovod hidroelektrane "Bajina Bašta" je korišćen zavarljiv čelik visoke čvrstoće (do 700 MPa nazivnog napona tečenja), pa je investitor tražio dokaze o njegovoj otpornosti prema prslinama i krtom lomu. Prikazani su rezultati ispitivanja modela cevovoda i zavarenih spojeva, kojima je dokazana zadovoljavajuća zavarljivost čelika sa metalom šava niže čvrstoće (andermečing) i otpornost prema prslinama i krtom lomu.

UVOD

Reverzibilna hidroelektana "Bajina Bašta", velikog kapaciteta, je u vreme projektovanja, pre oko 30 godina, predstavljala rešenje sa najvišim padom i brzinom vode u svetu /1/. Projekt je izvela firma „Tošiba", Japana. Osnova projekta je jednostepena Fransis reverzibilna pumpa-turbina sa dve jedinice, maksimalne snage 315 MW pri najvišem padu, i brzine od 428,6 o/min. Visina pumpanja je 621,3 m, protok 50,8 m^3/s, maksimalna snaga pumpe 310 MW, brzina obrtanja 428,6 o/min. Broj obrta rotora je 650 o/min. Maksimalni pritisak u cevovodu je 900 m.

Na sl. 1. je prikazan dovodno-odvodni sistem dužine 9750 m /2/, koji povezuje akumulaciju „Beli Rzav" sa turbinsko-pumpnim postrojenjem. Od kote 800 m (sl. 2) spušta se dovodno-odvodni tunel sa čeličnom oblogom do vodostana i zatvaračnice na koti 770 m, na dužini 8000 m. On se nastavlja gornjim cevovodom, u kosom delu dužine 738 m, pod nagibom 45° do kote 248 m i u horizontalnom delu dužine 700 m, do kote 216 m (sl. 2). Projektant se odlučio za izradu cevovoda od čelika visoke čvrstoće, pa je za najopterećeniji segment izabran čelik napona tečenja 700 MPa, do tada primenjen na samo na nekoliko cevovoda.

Keywords
- Penstock
- High strength steel
- Welded structure
- Brittle fracture
- Crack resistance

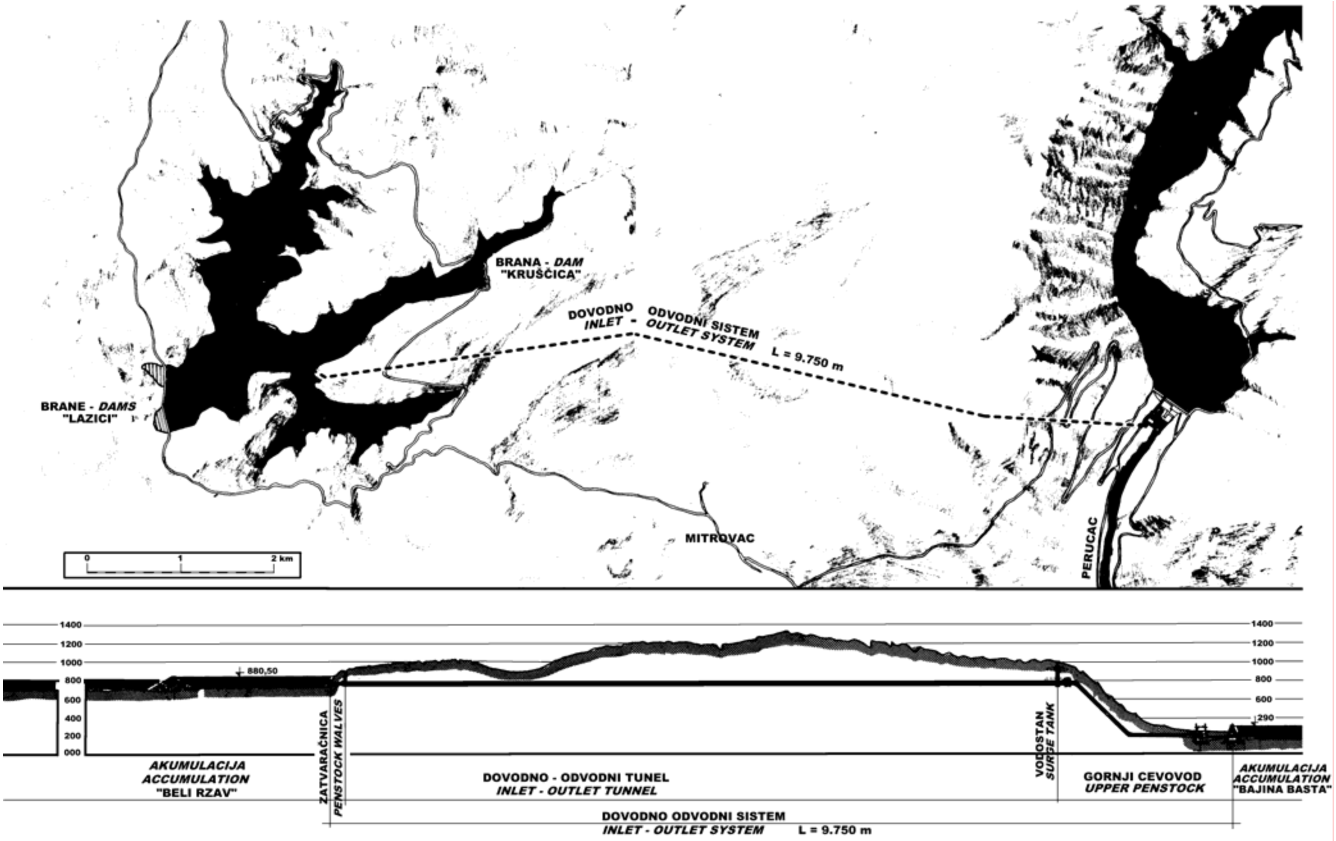
Abstract

Experience from service of hydroelectrical power plant indicates the possible leakage after stable crack growth or bursting in the case of brittle fracture. Introduction of weldable high strength steels for production of penstock brings important savings, but crack resistance, especially to brittle fracture, of parent metal, weld metal and the heat-affected-zone is required. For the penstock of "Bajina Bašta" hydroelectrical power plant weldable high strength steel is applied (up to 700 MPa nominal yield strength) and investor requested the proof for its resistance to cracks and brittle fracture. The results of testing of penstock model and welded joints are presented, which confirmed acceptable weldability of undermatched weld metal (undermatched effect) and resistance to cracks and brittle fracture.

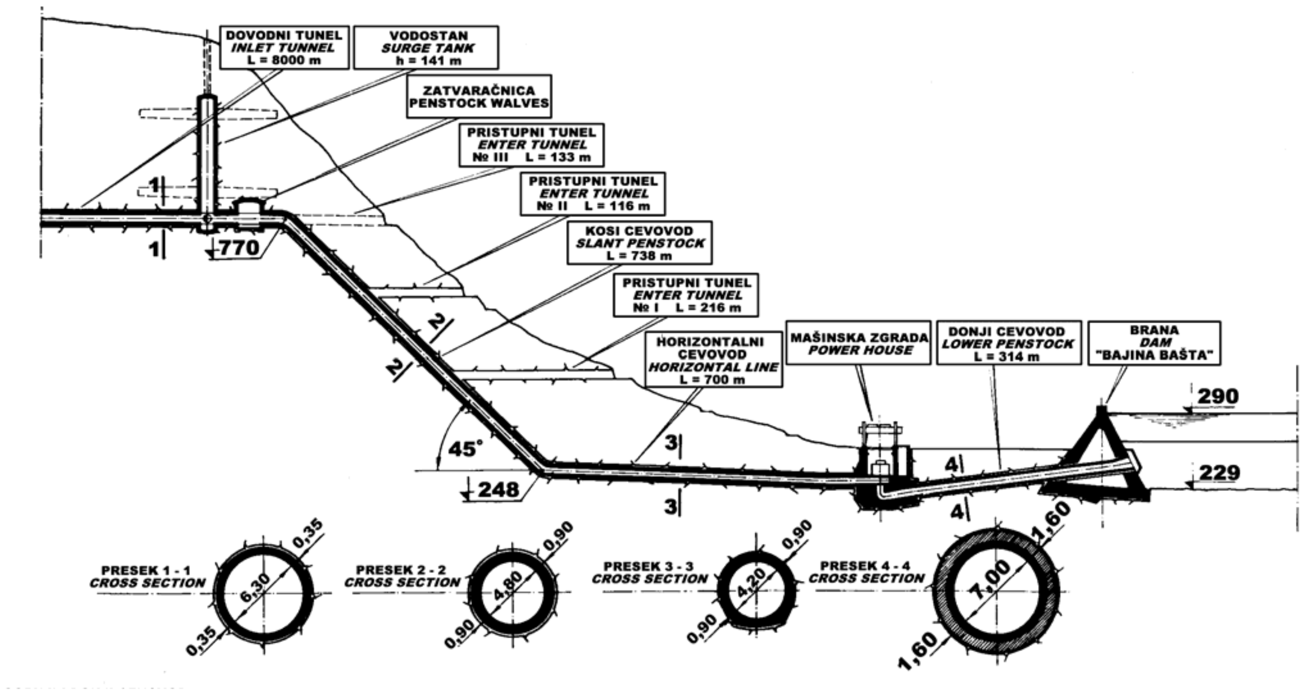
INTRODUCTION

Pumped storage power station "Bajina Bašta" of large capacity, in design period about 30 years ago, represented the solution of world's highest head and water speed /1/. Design is performed by „Toshiba" from Japan. Design is basically 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, revolving speed 428.6 rpm. Rotor runaway speed is 650 rpm. Maximum pressure in penstock is 900 m.

Figure 1 presents water pipeline sistem 9750 m long /2/, which connects acummulation „Beli Rzav" and turbine-pump equipment. From water level (w.l.) 800 m (Fig. 2) inlet-outlet tunel is directed downstars with steel pipe to the surge tank and penstock valve at w.l. 770 m, 8000 m long, continued by slant penstock under 45°, 738 m long at w.l. 248 m (upper pipeline) and horizontal part 700 m long to w.l. 216 m. Designer decided to apply high strength steel for penstock manufacturing, and consequently for most stressed segment the steel of 700 MPa yield strength was selected, before that used only for several penstocks.



Slika 1. Gornja i donja akumlacija i dovodno-odvodni sistem hidroelektrane “Bajina Bašta”
Figure 1. Upper and lower accummulation and inlet-outlet system of hydroelectrical power plant “Bajina Bašta”.



Slika 2. Dispozicija gornjeg i donjeg cevovoda “Bajina Bašta”
Figure 2. Disposition of penstock (upper and lower pipeline) “Bajina Bašta”.

OTKAZI CEVOVODA

Otkazi cevovoda se ne javljaju često, pa o njima nema mnogo podataka u literaturi. Kao glavni razlozi /3/ navode se mehanička oštećenja uočena pre puštanja i u toku eksploatacije, greške u materijalu, zamorne prsline, greške unete zavarivanjem i uticaj radne sredine. Plastični kolaps i krti lom se ne navode kao razlozi otkaza, što je jasno jer su čelici za izradu cevovoda duktilni, a cevovodi se koristi iznad prelazne temperature krtosti.

U okviru priprema za izgradnju reverziblne elektrane “Bajina Bašta“ je 1976. godine održano je savetovanje o cevovodima pod pritiskom hidroelektrana /4/. Nekoliko primera otkaza u eksploataciji je prikazano je u radu J. Raztresena /4/, str. 229-236.

Tipičan primer je havarija na cevovodu pod pritiskom (dužina 2640 m, hidrostatički pritisak 864 m), koji se dogodio 1973. godine prilikom probe na pritisak na jednoj krivini u blizini mašinske hale na hidroelektrani „Santa Izabel“ u Boliviji. Do havarije je došlo na pritisku 735 m, tj. na 84% projektnog pritiska. Mlaz vode je istekao kroz otvor dužine 1 m i širine 0,7 m i uništio je tropsku vegetaciju na dužini 130 m i širini 10 m. Isteklo je oko 6000 m^3 vode za sat, dok je spušten zatvarač u vodostanu. Cevovod je saniran novim segmentima za koleno.

Cevi su izrađene od austrijskog poboljšanog (kaljenog i otpuštenog) čelika Aldur 50/65D. Ovaj čelik je razvijen za cevovode pod pritiskom. U oštećenoj krivini je pečnik cevi 1,15 m, debljina lima 22 mm. Mehaničke osobine, utvrđene posle havarije su odgovarale specifikaciji. Metalografsko ispitivanje je pokazalo da je uzrok havarije krti lom, iniciran u sredini krivine u zoni uticaja toplote uzdužnog automatski izvedenog šava. Prslina je rasla od mesta inicijacije u oba smera paralelno šavu i zaustavila se kod poprečnog ručno izvedenog šava, gde je skrenula pod pravim uglom. Ocenjeno je da je moguć uzrok loma na mestu popravke šava zbog nekorektnog predgrevanja pri zavarivanju. Kako je ugrađeni čelik vrlo duktilan, žilav i otporan prema prslinama, pretpostavljeno je prisustvo visokih zaostalih napona od zavarivanja u fazi probe pod pritiskom. Pri ponovnoj probi posle sanacije cevovod je izdržao pritisak od 1170 m, 30% viši od projektnog pritiska.

I drugi interesantan slučaj krtog loma je zabeležen pri ispitivanju probnim pritiskom /5/. Cevovod prečnika 2 m je imao dve grane dužine 553 m do zatvaračnice i 1000 m dalje do turbine. Vlasnik cevovoda, izgrađenog 1912. do 1914, imao je nameru da ga aktivira posle dugotrajne pauze. Kako su prve probe pokazale nisku udarnu žilavost od oko 5,7 J/cm^2, vlasnik je ugovorio ispitivanja da bi se odredio pritisak raspucavanja. Ispitivanja su prvo izvedena na isečenom segmentu cevovoda kvazistatičkim pritiskom i eksplozijom.

Na sl. 3. je prikazan prototip, isečen iz cevovoda i zatvoren kao posuda, u trenutku procurivanja pri pritisku od 29,8 bara, i ukupnoj deformaciji između 0,001 i 0,0001, zavisno od mernog mesta. Tome je odgovarao obimni napon od 240 MPa.

Na sl. 4. je prikazan prototip u trenutku eksplozije pri pritisku od 42 bara. Na osnovu izvedenih ispitivanja prototipova bilo je moguće napraviti dijagram sigurnosti od

FAILURES OF PENSTOCKS

The failures of pipelines don’t occurr frequently, so there are not to many data about them in references. As most important causes /3/ mechanical damages observed before and during service, defects in material, fatigue cracks, welding defects and environment effect are cited. Plastic collaps and brittle fracture are not cited as failure cause, what is clear because steels for pipelines are ductile, and pipelines are used above nil-ductility transition temperature.

In the scope of preparing for constructiton of reversible plant “Bajina Bašta“ in 1976 year a symposium about penstocks in hydroelectrical power plant was held /4/. Several examples of in-service failures are presented in the paper of J. Raztresen /4/, pp. 229-236.

Typical example is catastrophic failure of penstock (length 2640 m, hydrostatic pressure 864 m), occurred in 1973 year during pressure proof test in one knee close to machine house in hydrelectrical power plant „Santa Isabel“ in Bolivia. Failure occurred at pressure 735m, e.g. at 84% of design pressure. Water jet passed through hole 1 m long and 0.7 m wide, and distroyed tropical vegetation along 130 m and 10 m in width. About 6000 m^3 leaked for one four, before the closing the valve in surge tank. The penstock was repaired by new segments for the knee.

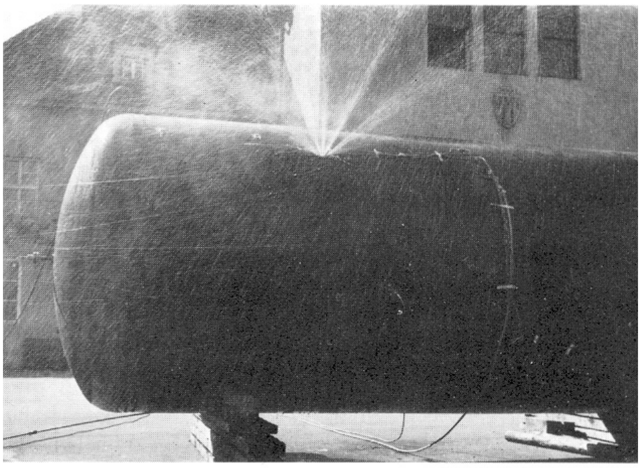
The tubes were produced of Austrian quenched and tempered steel Aldur 50/65D. This steel is developed for penstocks. In damaged knee pipe diameter was 1.15 m, plate thickness 22 mm. Mechanical properties, determined after failure, corresponded to specification. Metallographic examination revealed that failure cause is brittle fracture, initiated in curvature middle in the heat-affected-zone of longitudinal automatically welded joint. Crack developed from initiation point in both directions parallel to weld, and arrested at transversal manual arc welded joint, where continued in normal direction. It is evaluated that the possible failure cause is position of weld repairing due to improper preheating for welding. Since involved steel is ductile, tough and crack resistant, the presence of high welding residual stress level was assumed during proof pressure test. In repeated test after repair penstock passed pressure of 1170 m, 30% higher that design pressure.

Second interesting example of brittle fracture was also noted during proof pressure test /5/. Penstock of 2 m in diameter consisted of two lines 533 m long to the closing gate and next 1000 m to turbine. The owner of penstock, constructed between 1912 and 1914, intended to activate it after long term inactivity. Since the first tests had shown low impact toughness of about 5.7 J/cm^2, the owner contracted testing in order to determine burst pressure. Tests were performed first on derived penstock segment by quazi-static pressurizing and explosion.

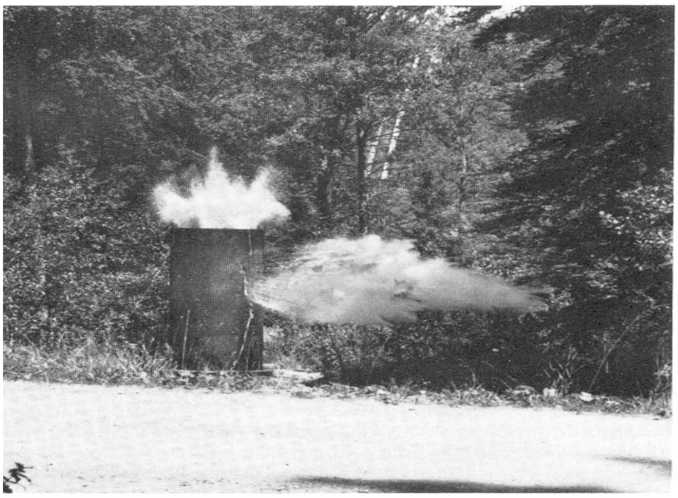
Figure 3 presents the prototype, cut from the penstock and closed to form a pressure vessel, in an instant of leak at pressure 29.8 bar, and total strain between 0.001 and 0.0001, depending on measuring point. Corresponding hoop stress was 240 MPa.

Figure 4 presents the prototype in an instant of explosion at the pressure of 42 bar. Based on performed testings it was possible to design a diagram of safety against burst as raspucanja u zavisnosti od opterećenja (sl. 5). Taj dijagram je omogućio izradu programa ispitivanja cevovoda probnim pritiskom, koje je izvedeno pri spoljnjoj temperaturi 1 do 4°C. Do krtog loma je došlo pri pritisku od 15,2 bara, što odgovara obimnom naponu od samo 120 bara, znatno ispod napona tečenja čelika (190 MPa). Izgled cevovoda posle ispitivanja prikazan je na sl. 6. Posle ovih ispitivanja vlasnik je odustao od namere da koristi cevovod.

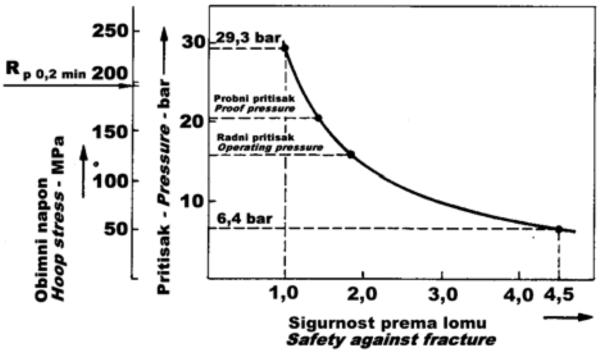
depended on loading (Fig. 5). This diagram enabled to define program for penstock proof pressure testing, which was performed at an outer temperature between 1 and 4°C. Brittle fracture occurred at the pressure of 15.2 bar, which corresponded to hoop stress of only 120 MPa, well bellow steel yield stress (190 MPa). The view of penstock after this test is presented in Fig. 6. After these tests the owner decided to leave the intention to use the penstock.



Slika 3. Procurivanje prototipa cevovoda pri hidrostatičkoj probi
Figure 3. Leakage of penstock prototype during proof pressure.



Slika 4. Eksplozivna proba prototipa
Figure 4. Explosion test of prototype.



Slika 5. Promena sigurnosti prema lomu sa opterećenjem
Figure 5. Safety against fracture with load.

Slika 6. Krti lom cevovoda pri ispitivanju vodenim pritiskom
Figure 6. Brittle fracture of penstock during water proof pressure test.

Sledeći primer, otkaz cevovoda hidroelektrane „Perućica" je ukazao na značaj obezbeđenja kvaliteta u zavarivanju /6/. Iako nije došlo ni do krtog loma ni do procurivanja, pojava prslina u zavarenom spoju je zahtevala preduzimanje mera radi sprečavanja eventualnog isključivanja elektrane iz pogona.

The next example„failure of penstock of hydroelectrical power plant „Peručica" showed the significance of quality assurance in welding /6/. Neither brittle fracture nor leakage occurred, but the occurrence of cracks in welded joints required measures for preventing of the break of power plant service.

Prsline su se pojavile u zavarenom spoju prstena širine 100 mm, sastavljenom od 6 segmenata po obimu (poz. 104 na sl. 7). Prečnik dovodnog cevovoda (poz. 103 levo) se sa 4000 mm smanjuje na 3400 mm na uvodu (poz. 103 desno) u turbinu. Kako su ta dva cevovoda izradili različiti proizvođači, došlo je do veće nesaosnosti i većeg razmaka krajeva, što je rešeno obujmicom, koja se zavaruje pre prstena i prima opterećenje preko ugaonih spojeva (poz. 105), dok prsten služi kao ispuna. Posle zavarivanja je tunel oko cevovoda ispunjen betonom, a cevovod iznutra zaštićen premazom. Za obujmicu i prsten je izabran čelik napona tečenja 450 MPa, mikrolegiran sa vanadijumom. Posle 10 godina eksploatacije uočene su brojne prsline, dužine i nekoliko stotina milimetara, na oba zavarena spoja prstena „A" i „B" (sl. 8), od kojih su neke probile šav i doprle do ugaonog šava poz. 105, odnosno u prostor između obujmice i prstena. Pri pregledu ispražnjenog cevovoda je nađena je voda u prslinama, što je potvrdilo da je dubina prslina dostigla debljinu prstena, odnosno cevi. Praćenje prslina je pokazalo da one ne rastu ili da rastu sporo.

Ispitivanja su pokazala da su u pitanju hladne prsline, koje su se pojavile zbog nedovoljnog predgrevanja i zbog krutosti cevovoda pri zavarivanju prstena, a jednom inicirane rasle su dalje pod uticajem korozije. Od značaja za njihovu pojavu je i preopterećenje koje je cevovod pretrpeo u početnoj fazi rada, praćeno vibracijama. Prsline nisu direktno ugrožavale integritet konstrukcije, ali su dovele do kontakta unutrašnjeg zavarenog spoja obujmice sa vodom, što u sadejstvu sa delujućom koncentracijom napona može da inicira prsline i u nosećem spoju obujmice. Zbog toga je izvedena sanacija zamenom svih segmenata prstena.

CEVOVOD REVERZIBLINE HIDROELEKTRANE „BAJINA BAŠTA"

Ispitivanja modela u punoj veličini daju važne podatke kada se razmatra sigurnost cevovoda. U nekim slučajevima, među koje spada i ovde prikazan (sl. 6), ona su neizbežna uprkos visokoj ceni, jer mogu dati pravi odgovor o ponašanju opterećene zavarene konstrukcije. Tri uticaja se ne mogu u potpunosti kontrolisati pri zavarivanju: koncentracija napona zbog oblika zavarenog spoja, zaostali naponi i mogućnost postojanja grešaka tipa prslina veličine manje od praga osetljivosti oprema za ispitivanje bez razaranja. Njihov značaj se može oceniti ispitivanjem probnim hidrostatičkim pritiskom modela u vidu posude pod pritiskom i samog cevovoda.

Potreba da se izvedu ispitivanja modela u punoj veličini je prihvaćena i u slučaju zavarenog cevovoda reverziblne hidroelektrane „Bajina Bašta", koji je u naopterećenijem delu izrađen od niskolegiranog čelika visoke čvrstoće (nazivni napon tečenja 700 MPa) /7/. Zbog ograničenog iskustva u zavarivanju čelika ove klase čvrstoće, atestiranje zavarivača, specifikacija postupka zavarivanja i njegova kvalifikacija su striktno zahtevani, slično današnjem pristupu prihvaćenom u standardima EN287 i EN288. Sem toga, neka vrsta ocene „podobnosti za upotrebu" je takođe zahtevana, da bi se bolje razumeo značaj prslina. Sledeće činjenice su dodatno doprinele da se donese odluka o izradi dva prototipa u punoj razmeri ovog cevovoda da bi se prikupili podaci o njegovom integritetu /8, 9/:

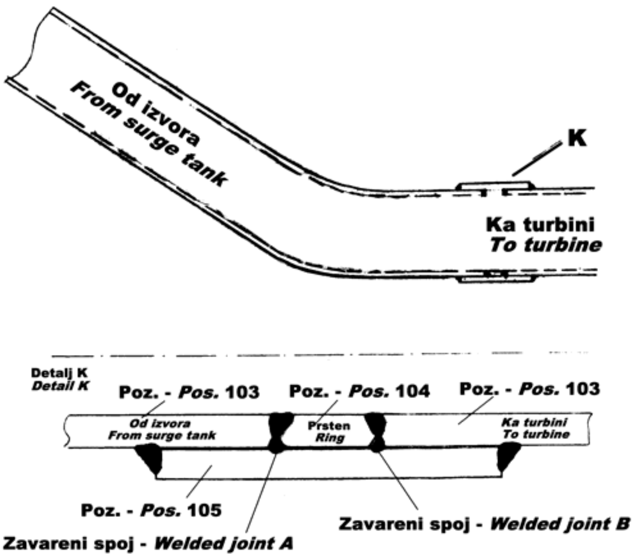
Cracks occurred in welded joint of a ring, 100 mm wide, consisting of 6 circumferential segments (pos. 104 in Fig. 7). The diameter of penstock (pos. 103 left) is reduced from 4000 mm to 3400 mm in inlet line for turbine (pos. 103 right). Since two pipelines were produced by different manufacturers, significant misalignment and end distance occurred, what was solved by wrist, welded before the ring and accepting the loading by fillet welds (pos. 105), while the ring served to fill the gap. After welding the tunnel was filled with the concrete outside penstock, and penstock protected inside by lacquer. Steel of 450 MPa yield stress microalloyed by vanadium, was selected for wrist and ring. After 10 years of service numerous cracks were revealed, several hundreds millimeters long, in both ring welded joints „A" and „B" (Fig. 8), some of them passing through the weld and reaching fillet weld of pos. 105, i.e. the space between wrist 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.

The examination had shown that cold cracks are in question, occurred due to improper preheating and the rigidity of penstock at ring welding, and once initiated developed further under effect of 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 wrist with the water, what in addition to acting stress concentration could initiate cracks also in loaded welded joint of wrist. For this reason the repair is performed by change of all segments of a ring.

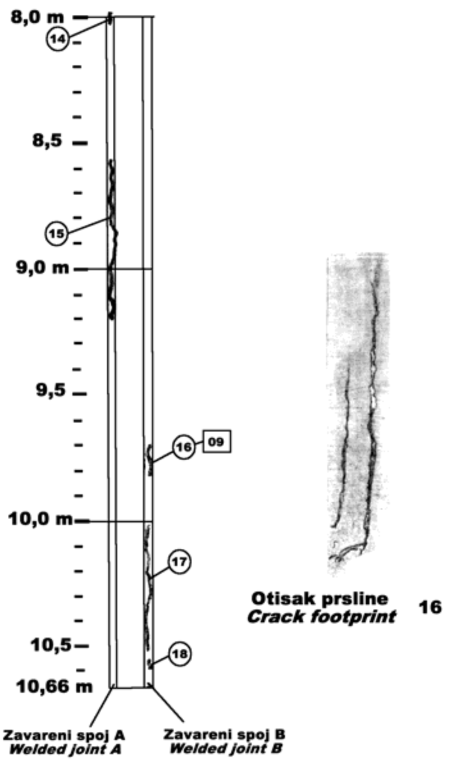
PENSTOCK OF REVERSIBLE HYDROELECTRICAL POWER PLANT „BAJINA BAŠTA"

The test of prototype model in full scale gives important data when penstock safety was considered. In some cases, among them is here presented (sl. 6), they are inevitable in spite of high costs, because they can deliver proper answer about the behaviour of loaded welded structures. Three effects can not be completely controlled during welding: stress concentration due to welded joint form, residual stresses and possibility of existence cracks lower in size than the sensitivity of non-destructive test equipment. Their significance can be evaluated by proof water pressure test of model in the form of pressure vessel and penstock itself.

The necessity to perform testing of prototype in full scale was accepted also in the case of penstock of reversible hydroelectrical power plant „Bajina Bašta", which is in the most stressed part produced of high strength low alloy steel (nominal yield strength 700 MPa) /7/. Due to limited experience in welding of steel of this strength class, certification of welders, welding procedure specification and its qualification were strictly required, similarly to nowadays approach accepted in standards EN287 and EN288. In addition, a kind of "fitness for purpose" was required, in order to understand better crack significance. Following facts additionally contributed to make a decision to produce two full scale prototypes of this penstock in order to gather the data about its integrity /8, 9/:



Slika 7. Konstrukcijsko rešenje obujmice (poy. 105) i prstena (poz. 104) za spajanje krajeva cevovoda
Figure 7. Design solution of obzjmica (pos. 105) and ring (pos. 104) for joining of penstock ends.



Slika 8. Delimični prikaz rasporeda prslina na kružnim spojevima prstena
Figure 8. Part presentation of cracks didstribution on circumferencial welded joints of the ring.

1. Izbor mekog konstrukcijskog čelika, napona tečenja do 350 MPa za cevovod bi za zahtevani kapacitet uslovio izgradnju dva cevovoda i dva tunela, što je izuzetno skupo rešenje.

2. Za samo jedan cevovod je primena konstrukcijskog čelika napona tečenja nivoa 700 MPa bila neizbežna. Ovaj zahtev može da ispuni čelik klase HT80, zavarljiv, poboljšan (kaljen i otpušten), nisko legirani čelik visoke čvrstoće (HSLA), zatezne čvrstoće iznad 800 MPa..

1. The selection of mild structural steel of yield strength up to 350 MPa for penstock for requested capacity required the structure with two penstocks and two tunnels, what was extremely expensive solution.

2. For only one penstock the application of structural steel of yield strength level 700 MPa was inevitable. This requirement can be fulfilled by HT80 steel class, weldable, quenched and tempered, low alloy high strength steel (HSLA), ultimate tensile strength above 800 MPa.

3. Izborom HSLA čelika su se pojavila dva nova problema. Debljina lima na najopterećenijem delu cevovoda je 47 mm, i to je smatrano gornjom granicom u proizvodnji limova od čelika te klase. Maksimalna debljina u prethodno izgrađenom cevovodu od takvog čelika je samo 32 mm /1/. Drugi problem je mali usvojeni stepen sigurnosti, od samo 1,7 u odnosu na napon tečenja.prema nemačkim propisima za HSLA čelike /10/. Prema drugim propisima, potrebno je usvojiti veći stepen sigurnosti, npr. prema japanskom iskustvu u primeni tih čelika se preporučuje stepen sigurnosti najmanje 2,07 /11/.

4. Cevovod je delom trebalo zavarivati u terenskim uslovima, tj. u tunelu, i strogi uslovi su mogli biti ispunjeni samo sa obučenim, obrazovanim i kvalifikovanim osobljem. Deo praktične obuke je morao biti izveden pre izrade cevovoda. Odabrani proizvođači su bili prvi put u situaciji da zavaruju cevovod od kaljenog i otpuštenog čelika tipa HSLA, napona tečenja 700 MPa i debljine 47 mm.

Dve posude pod pritiskom, modelovane u obliku prototipa najopterećenijeg dela cevovoda (sl. 9), izrađene su od HSLA čelika SUMITEN 80P (SM 80P), debljine lima 47 mm, proizvodnje "Sumitomo", Japan. Ispitivanje rasprskavanjem je izvedeno na modelu sa prslinom radi ispitivanja otpornosti prema brzom lomu i sposobnosti zaustavljanja prslina /9/. Ispitivanje hidrostatičkim pritiskom modela bez prsline omogućilo je eksperimentalnu analizu zavarenih spojeva kada nije došlo do pojave prslina /8/.

Ukupno ponašanje zavarenog cevovoda pod opterećenjem je analizirano na osnovu rezultata tri pristupa (inicijacija prsline, rast i zaustavljanje prsline, stabilni rast prsline), što je omogućilo ocenu značaja prsline /12, 13/ i ocenu "podobnosti za upotrebu". Utvrđeno je da je opšte ponašanje prototipa i cevovoda prihvatljivo i da se eksploatacijska sigurnost može oceniti kao zadovoljavajuća.

Konstrukcija modela cevovoda

Model, koji predstavlja najopterećeniji deo cevovoda, prikazana je na sl. 9, odgovara preseku 3-3 (sl. 2). Cilindrični omotač, prečnika 4200 mm, konstruisan sa kolenom od 5° koje odgovara prelaznom komadu u cevovodu, zatvoren je sa dva oblikovana danca. Korišćeni su postupci ručnog elektrolučnog zavarivanja (E) i zavarivanja pod praškom (EPP).

Ispitivanje prvog modela rasprskavanjem – otpornost prema brzom rastu prsline

Ispitivanje rasprskavanjem je izvedeno na modelu "Metalna" /9/. Tri dodatna uzdužna EPP zavarena spoja su izvedena na donjoj ljuski cilindričnog omotača, čime su dobijena još tri ukrsna mesta sa kružnim E metalom šava.

Slika 10. prikazuje raspored merne opreme, veštačke površinske prsline CS2 i CS3, započete u ukrsnom mestu šava, koje se pružaju duž uzdužnih spojeva, i prslinu CS1, izvedenu kao skrivenu u trećem uzdužnom spoju. Merna oprema za ispitivanje se sastoji od dva merača otvaranja prsline (COD) (koji su postavljeni na CS2 i CS3), 22 merne trake, 9 moare mreža, 3 senzora akustične emisije, davača pritiska i sistema za merenje izduženja obima.

3. Selection of HSLA steel two new problems arose. The plate thickness in the penstock most stressed part is 47 mm, and this was regarded as the upper limit in plate fabrication for this steel class. The maximum thickness in previously constructed penstocks with this steel is only 32 mm /1/. The second problem was low safety margin adopted of only 1.7 regarding steel yield strength according to German specification for the HSLA steel /10/. According to other specifications, a higher safety margin is required, e.g. Japanese experience with this grade of steel recommended a minimum safety margin 2.07 /11/.

4. Penstock welding was to be partly performed in the field. i.e. tunnel conditions and strict requirements could be satisfied only with educated, skilled and approved personnel. Practical training had to be done prior fabrication of penstock. The selected manufacturers were for the first time in situation to weld a penstock of a quenched and tempered HSLA steel of 700 MPa yield strength and 47 mm thick.

Two full-scale pressure vessels, modeled in a prototype form of the most stressed part of penstock (Fig. 9), were produced of SUMITEN 80P (SM 80P) HSLA steel, 47 mm thick plates, produced by "Sumitomo", Japan. The burst test was performed on pre-cracked model for testing of resistance to fast fracture and of crack arrest properties /9/. The hydro-pressure test on a model with no crack enabled the post-yield experimental analysis of weldments, when cracks did not initiate /8/.

The overall behaviour 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 /12, 13/ and "fitness-for-purpose" assessment. It was found that overall behaviour of prototype and penstock is acceptable and service safety can be evaluated as satisfactory.

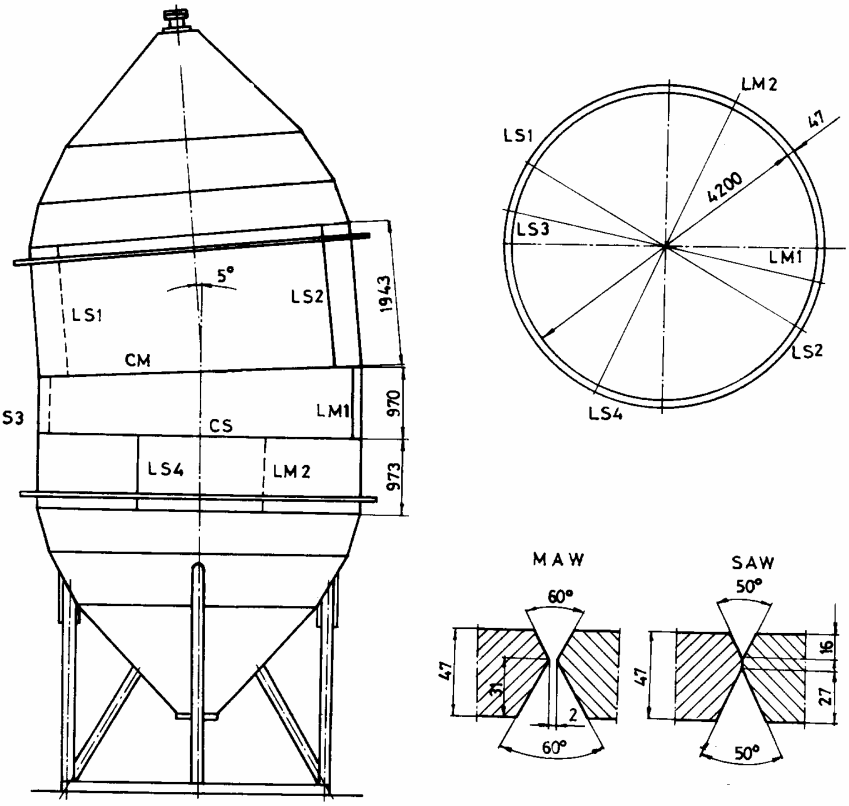
Penstock models design

The full-scale model, which presents the most stressed penstock segment, is given in Fig. 9, corresponds to Section 3-3 (Fig. 2). Cylindrical mantle, 420 mm in diameter, designed with 5° knee corresponding to the penstock transition segment, was covered with two shaped lids. Manual arc welding (MAW) and submerged arc welding (SAW) were used.

First full-scale model burst test – resistance to fast crack propagation

The burst test was performed on the model "Metalna" /9/. Three additional longitudinal SAW welds were made on cylindrical mantle bottom shell, providing next three crossings with circular MAW weld metal.

Figure 10 shows the disposition of instrumentation, the artificial surface cracks CS2 and CS3, starting in weld crossings and spreading along longitudinal welds, and crack CS1 embedded in the third longitudinal weld. The instrumentation consisted of two crack opening displacement (COD) gauges (over CS2 and CS3), 22 strain gauges, 9 moiré grids, 3 acoustic emission sensors, pressure transducer and a measuring system of outer periphery elongation.



Slika 9. Konstrukcija i dimenzije dela cevovoda na modelu pune razmere. LS1-LS4 - uzdužni EPP zavareni spojevi, LM1-LM2 - uzdužni E zavareni spojevi, CS - kružni EPP zavareni spoj, CM - kružni E zavareni spoj

Figure 9. Design and dimensions of pipeline segment full-scale models. LS1-LS4 - Longitudinal SAW welds, LM1-LM2 - Longitudinal MAW welds, CS - Circular SAW weld, CM - Circular MAW weld.

Površinske prsline CS2 i CS3 u zavarenom spoju su zaoštrene kontrolisanom eksplozijom iz mašinskog zareza do konačne veličine (CS2:180 × 4,3 mm; CS3:50 × 6 mm), da bi se postigla sličnost sa zamornom prslinom, kakva se traži u ispitivanjima mehanike loma. Skrivena prslina (veličine 40 × 3 mm) je napravljena u procesu zavarivanja.

Model u punoj veličini je prvo bio statički opterećen ravnomerno rastućim pritiskom vode u dve faze, pri čemu je dostignut nivo od 117 bar, što odgovara obimnom naponu idealnog cilindričnog oblika $\sigma_t = 518$ MPa. Sledeće ispitivanje je bilo dinamičko, sa dve eksplozije kontrolisane brzine, polazeći od statičkog predopterećenja 60 bar ($\sigma_t = 265$ MPa). Na taj način je simuliran uticaj vodenog čekića, koji se javlja pri brzom zatvaranju protoka vode. Eksperiment je završen trećim statičkim opterećenjem, pri pritisku od 151 bar (σ_t=668 MPa), uz zadržavanje tokom dva časa na pritisku 140 bar. Nestabilnost za prslinu CS3 je mogla da se dostigne na ovom pritisku, jer je predviđen pritisak za nju 137 bar ($\sigma_t = 606$ MPa) /14/. U preliminarnom ispitivanju prototipa je došlo do krtog loma pri pritisku od 101 bar, što je bilo važno iskustvo za dalja ispitivanja. Analiza površine preloma iz tog ispitivanja je pokazala da je početna prslina premašila kritičnu veličinu, zbog čega je i zahtevana analiza izneta u dokumentu /14/.

Surface cracks CS2 and CS3 in weldment were sharpened by controlled explosion from machined notches to final size (CS2:180 × 4.3 mm; CS3:50 × 6 mm) in order to obtain similarity to fatigue crack, required by fracture mechanics tests. The embedded crack CS1 (sized 40 × 3 mm) was made during welding process.

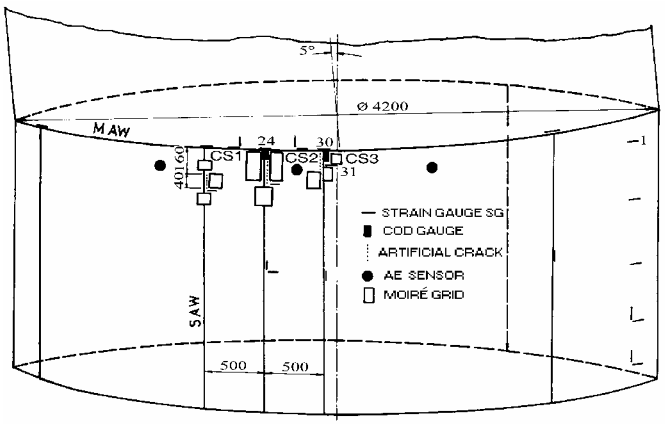
The full-scale model was first statically pressurized by uniformly raising water pressure in two steps, achieving maximum level of 117 bar, which corresponded to the hoop stress in an ideally shaped cylindrical vessel $\sigma_t = 518$ MPa. Next test was dynamic, performed by two successive explosions of controlled rate, starting from the static pre-loading of 60 bar ($\sigma_t = 265$ MPa). In this way the water hammer effect in the penstock caused by quick gate closing was simulated. The experiment was ended by the third static pressurizing, at the pressure of 151 bar ($\sigma_t = 668$ MPa), with two hours holding at the pressure of 140 bar. The instability for crack CS3 could be reached at this pressure, since predicted pressure of it was 137 bar ($\sigma_t = 606$ MPa) /14/. In prototype preliminary test brittle fracture occurred at the pressure of 101 bar, what was important experience for next testings. The analysis of fracture surface from this testing revealed that initial crack overpasses critical value, and due to this the analysis presented in document /14/ was required.

Interesantno je uočiti da plastična deformacija prati brzinu eksplozivnog opterećenja, što ukazuje na stabilni rast prsline, kako je i naknadno utvrđeno akustičnom emisijom, za pritisak 117 bar (drugo statičko opterećenje) i 140 bar (treće statičko opterećenje, uz zadržavanje dva časa). Tek kada se pritisak približavao nivou od 151 bar u trećem statičkom opterećenju akustična emisija je počela naglo da raste, ukazujući na nestabilni razvoj prsline /9/. Eksperiment je zaustavljen, jer je opasnost od brzog loma postala očigledna. Ispitivanje bez razaranja područja sa prslinama je pokazalo da je prslina CS3 napredovala za 28 mm u dužinu (10 mm i 18 mm na stranama, sl. 11), dok prslina CS2 nije napredovanla u dužinu. Dve nove prsline, nastale u ispitivanju, označene su sa A i B na sl. 11.

Detaljna analiza je pokazala da se lom razvijao kroz krto područje ZUT, blizu linije stapanja. Kako krto područje može biti vrlo usko, jasno je da vrh prsline ne može biti precizno postavljen u njemu i da izvesna energija mora biti utrošena pre nego što započne brzi, krti lom.

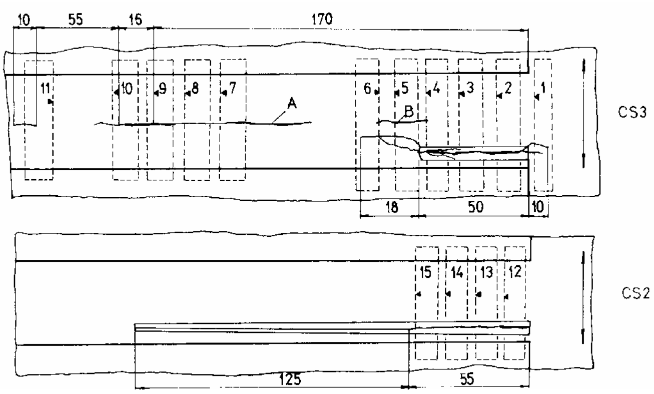
It is interesting to note that the plastic deformation could follow the explosion loading rate, indicating stable crack growth, as additionally confirmed by acoustic emission, for the pressure of 117 bar (second static loading) and 140 bar (third static loading for 2 hours holding). Only when approaching the pressure of 151 bar in the third static loading, acoustic emission started to grow significantly, indicating unstable crack propagation /9/. The experiment was stopped, since the danger of fast fracture became obvious. The non-destructive examination of pre-cracked region showed that CS3 crack propagated for 28 mm in length (10 mm and 18 mm on sides, Fig. 11), while CS2 crack did not propagate in length. Two new cracks, initiated during testing, denoted by A and B in Fig. 11.

Detailed analysis revealed that fracture developed through brittle region in HAZ, close to fusion line. Since the brittle region can be very narrow it is clear that pre-crack tip can not be positioned precisely in it and some energy must be spent before fast, brittle fracture initiated.



Strain gauge SG - Merne trake SG COD gauge - Merač otvaranja prsline
AE senzor - Senzor akustične emisije Moiré grid - Moare mreža
Artifical crack - Veštački izvedena prslina

Slika 10. Priprema omotača prototipa za ispitivanje raspucavanjem
Figure 10. Preparation of prototype mantle for burst test.



Slika 11. Izgled razvoja prsline posle ispitivanja eksplozijom
Figure 11. View of crack development after explosion test.

Najvažniji zaključak je bio da model u punoj veličini i cevovod mogu sa sigurnošću da izdrže radni pritisak (90 bar) i dodatni pritisak vodenog čekića (dinamičko opterećenje do120 bar), čak i u prisustvu velike prsline (6 mm duboke, 50 mm dugačke) i pri utvrđenom značajnom odstupanju delova zavarenog spoja od ose. Treba napomenuti da se i mnogo manje prsline mogu otkriti ispitivanjima bez razaranja. Iako su se plastične deformacije pojavile u metalu šava već u ranoj fazi ispitivanja (posle rasterećenja sa pritiska 117 bar), njihova veličina (u globalnom smislu) je bila značajna tek posle rasterećenja sa 151 bar, što je utvr|eno promenom ukupne dužine obima. Raspodela plastičnih deformacija nije poznata. Ekstremno velike plastične deformacije u metalu šava su praćene razvojem prsline u dubinu i u dužinu (prslina CS3).

Ispitivanje rasprskavanjem je dalo samo približno rešenje za kritičnu veličinu prsline i njeno ponašanje tokom opterećenja, sličnog radnom opterećenju. Međutim, vrh prsline nije mogao pouzdano da se postavi u kritičnu mikrostrukturu. Sa druge strane, izrada tog modela je omogućila kvalifikaciju tehnologije zavarivanja i obuku zavarivača, što je bilo od posebnog značaja za izgradnju cevovoda.

The most important conclusion was that full-scale model and penstock can safely withstand the working pressure (90 bar) and an additional water hammer pressure (dynamic loading up to 120 bar) even in the presence of large flaw (6 mm deep, 50 mm long) and a significant misalignment of weldment. It should be mentioned that much smaller flaws can be easily detected by non-destructive testing. Although plastic strains occurred in weld metal in the early loading stage (after unloading from 117 bar), they were of significant value (in global sense) only after unloading from 151 bar, as indicated by the change in periphery overall length. The distribution of plastic strain was not known. Extremely high plastic strains in the weld metal were followed by crack propagation in depth and in length (crack CS3).

Burst test offered only the approximate solution for critical crack size and crack behaviour during loading, similar to working loading. Anyhow, crack tip could not be reliably positioned in the most critical microstructure. At the same time manufacturing of that model enabled qualification of welding procedure and welders training, that was of special importance for penstock construction.

Ispitivanje vodenim pritiskom modela u punoj razmeri - otpornost prema inicijaciji prsline

Cilj ovog ispitivanja je bio da se analizira ponašanje cevovoda bez prslina pri projektnom opterećenju i očekivanom preopterećenju i uticaj plastične deformacije na žilavost zavarenog spoja. To je postignuto poređenjem rezultata mehaničkih ispitivanja i ispitivanja brzog loma (udarno ispitivanje, ispitivanje padajućim tegom i eksplozijom), epruveta uzetih sa modela posle lokalne plastične deformacije zavarenog spoja i istovremeno zavarenih nedeformisanih pridruženih proba.

Model (sl. 9) je ispitivan na temperaturi okoline (+6°C do -3°C). Deformacije su praćene mernim trakama i dodatno kontrolisane moare mrama. Senzori akustične emisije, postavljeni na kritičnim mestima, omogućili su kontrolu velikih plastičnih deformacija i inicijacije prslina, da bi se ispitivanje zaustavilo ako se dostigne kritična tačka i da se spreči katastrofalni lom tokom ispitivanja pritiskom.

Model je ispitivan pritiskom u dve faze. U prvoj fazi je pritisak dostigao 90,2 bar (σ_t=399 MPa), što odgovara radnom pritisku, a model je držan na pritisku 73,5 bar tokom dva časa. Posle rasterećenja, model je u drugoj fazi ispitan pritiskom od 120,6 bar (σ_t=533 MPa), što približno odgovara ukupnom opterećenju od radnog pritiska i vodenog čekića. Posle ispitivanja hidrostatičkim pritiskom su isečene epruvete za mehanička ispitivanja sa omotača. Mehaničke osobine su ispitane za E i EPP uzdužne i kružne zavarene spojeve, zajedno sa odgovarajućim uzorcima pridruženih zavarenih spojeva. Sem toga, izvedena su udarna ispitivanja po Šarpiju, ispitivanja padajućim tegom i eksplozijom.

Neki tipični dijagrami pritisak - deformacija (sl. 12) treba detaljnije da se analiziranju. Razvoj deformacija je ravnomeran u osnovnom metalu (merna traka 53), kružnom EPP metalu šava, i EPP uzdužnom metalu šava (merne trake 2 i 34), kao i na E kružnom metalu šava (merna traka 59). Korišćena merna oprema je omogućila da se odredi veličina zaostalih plastičnih deformacija, koje su se pojavile u metalu šava posle prve i druge faze ispitivanja (sl. 12). Maksimalna plastična deformacija je izmerena na metalu šava EPP zavarenog spoja, na mestima mernih traka 2 i 34 za koje je u drugom opterečivanju dobijen dijagram zavisnosti pritisak-deformacija u obliku petlje (sl. 13). Najveće deformacije na tom mestu su posledica koncentracije napona, globalne, zbog kolena od 5°, i lokalne, zbog geometrijskog oblika i uzdužnog položaja zavarenog spoja, i nivoa andermečing efekta. Moguće objašnjenje za pojavu petlje je kombinovani uticaj andermečing efekta, ojačavanja metala šava i preraspodele napona tokom rasterećenja i ponovnog opterećenja.

Rezultati udarne žilavosti su zadovoljavajući, a nije uočen uticaj plastične deformacije na žilavost. Dobri rezultati, dobijeni u oštrim uslovima ispitivanja, kao što je ispitivanje padajućim tegom i eksplozijom, su dokaz zadovoljavajuće otpornosti prema prslinama metala šava. I ovde EPP metal šava ima najslabije osobine.

Na osnovu ovih rezultata zaključeno je da početna plastična deformacija nije bitno uticala na sigurnost cevovoda, zbog velike duktilnosti čelika SM80P i njegovih zavarenih spojeva.

Full-scale model hydro-pressure test – resistance to crack initiation

The aim of this experiment was to analyze the behaviour of crack free penstock under design loading and expected overloading, and the effect of plastic strains on weldment toughness. This was achieved by comparing the results of mechanical and fast fracture tests (impact, drop weight and explosion bulge tests) of specimens, taken from the model after local plastic deformation in weldments and undeformed trial samples, welded simultaneously.

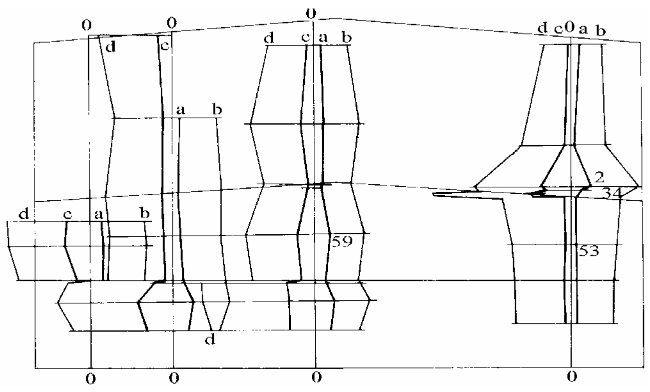
The model (Fig. 9) was tested at an ambient temperature (+6°C to -3°C). Strains were monitored by strain gauges, and controlled by moiré grids. Acoustic emission sensors, positioned in the critical areas, enabled the control of large plastic strains or crack initiation, in order to stop the test if the critical point was reached and to prevent a catastrophic failure during pressurizing.

Pressurizing of the model was performed in two stages. In the first stage the pressure reached 90.2 bar (σ_t =399 MPa), corresponding to working pressure, and model was held pressured at 73.5 bar for two hours. After unloading, in the second stage model was tested by the pressure 120.6 bar (σ_t =533 MPa), that is close to the total working and water hammer load. After hydro pressure testing the specimens for mechanical tests were cut out of the mantle. The mechanical properties were tested for MAW and SAW welded joints, longitudinal and circular, simultaneously with the corresponding trial sample. In addition, Charpy V impact, drop weight and explosion bulge tests were performed.

Some typical plots pressure-strain (Fig. 12) should be analyzed. Strain developed uniformly in the base metal (strain gauge 53), circular SAW weld metal, and SAW longitudinal weld metal (strain gauges 2 and 34), as well as on MAW circular weld metal (strain gauge 59). Applied instrumentation allowed quantifying local residual plastic strains that occurred in weld metals after first and second pressurizing stage (Fig. 12). Maximum plastic strain was measured on SAW longitudinal weld metal, in position of strain gauges 2 and 34 for which is an odd form of pressure-strain dependence in the second loading stage is obtained, in the form of a loop in the diagram (Fig. 13). The highest strains in this position are the consequence of acting stress concentration, global, due to 5° knee, and local, due to weldment geometry, and of longitudinal position of the welded joint and its undermatching level. Possible explanation for loop occurrence is the combined effect of undermatching, weld metal strain hardening and strain redistribution during unloading and reloading.

The results of toughness testing were satisfactory, and no clear effect of plastic strain on toughness could be recognized. Good results, obtained in very severe testing condition, as drop weight and explosion bulge test, can serve as a proof of satisfactory crack resistance of weld metals. Again, SAW welded joints exhibited the lowest properties.

Based on these the results it was concluded that initial plastic deformation did not affect significantly penstock safety, because of high toughness of the SM 80P steel and its weldments.



Slika 12. Raspodela deformacija u zavarenim spojevima posle ispitivanja pritiskom
Figure 12. Distribution of strains in weldments after pressurizing.

Ocena preostale čvrstoće posude pod pritiskom - otpornost prema stabilnom rastu prsline

Sledeći korak je ocena preostale čvrstoće posude pod pritiskom sa prslinom i otpornosti prema stabilnom rastu prsline. Konturni J integral, nezavisan od putanje integracije, je usvojen za ovu ocenu, kao najpogodniji parametar mehanike loma zbog njegove teorijske osnove, primene i u plastičnom području, prikladnosti za eksperimentalno određivanje i mogućnosti direktnog merenja, metodom koju je razvio Rid /15/.

Ocena preostale čvrstoće pomoću J-R krive se može primeniti na posudu pod pritiskom kao prikladan primer kvazistatičkog opterećenja. Kod tankozidne posude pod pritiskom pri ravnom stanju napona treba očekivati da prslina posle inicijacije stabilno raste sa porastom pritiska /16, 17/. Poređenje sile rasta prsline, izražene preko J integrala, i J-R krive materijala daje kritični rast prsline. Predloženi postupak je primenjen za ocenu preostale čvrstoće modela /12/, prikazanog na sl. 9 /18/.

Sila rasta prsline u cilindričnoj ljuski može da se izračuna primenom modela koji su predložili Ratvani, Erdogan i Irvin (REI) /19/. Oni su uveli J^*, J integral normiran modulom elastičnosti E, naponom tečenja $R_{p0,2}$ i dužinom prsline $2c$ za površinsku prslinu dubine a u obliku:

$$J^* = J \cdot \frac{E}{2c \cdot R_{p0,2}^2} = \frac{2}{\sqrt{3}}\left[\frac{\delta_o}{d_1} + \frac{\theta_2}{d_2}\left(0{,}5 - \frac{a}{W}\right)\right]$$

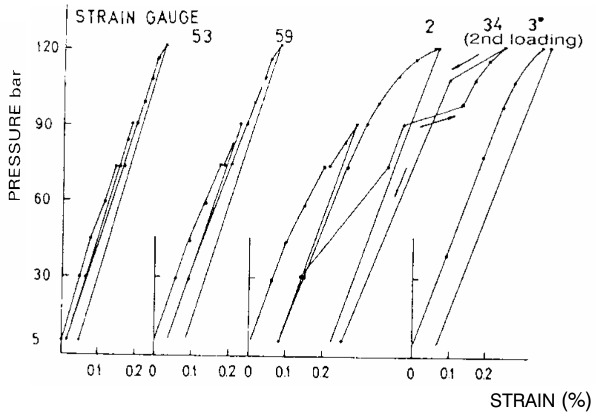
$$d_1 = \frac{4c \cdot R_{p0,2}}{E} \qquad d_2 = \frac{4c \cdot R_{p0,2}}{E \cdot W}$$

Količnici δ_o/d_1 i θ_2/d_2 mogu da se nađu u literaturi /17/, za otvaranje prsline u srednjoj ravni, δ_o, i ugao zakretanja ravni prsline, θ_2, različite debljine zida W, različite pritiske p, i parametre ljuske

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{\frac{1}{4}} \frac{C}{\sqrt{RW}}$$

gde je R je poluprečnik srednjeg preseka ljuske, a ν koeficijent Poasona.

Familija sila rasta prsline, izračunatih za model sa sl. 9, prikazana je na sl. 14. za različite pritiske, definisane odnosom $pR/WR_{p0,2}$. Sila rasta prsline zavisi od napona tečenja materijala $R_{p0,2}$.



Slika 13. Tipične zavisnosti pritiska i deformacija
Figure 13. Typical relationships between pressure and strain.

Pressure vessel residual strength prediction – resistance to stable crack growth

Next step was the assessment of residual strength of cracked pressure vessel and resistance to stable crack growth. Path-independent contour J integral is selected for this assessment, as the most promising fracture mechanics parameter due to its theoretical background, application in plastic range, convenience for experimental determination and direct measurement method, developed by Read /15/.

Residual strength prediction by J-R curve can be applied on pressure vessel as a convenient example for quasi-static loading. In the case of thin-walled pressure vessel under plane stress condition one can expect crack to grow after initiation in a stable manner with increasing pressure /16, 17/. The comparison of crack driving force, expressed by J integral, and material J-R curve provides the critical crack extension. The proposed method is applied for residual strength evaluation of the model /12/, presented in Fig. 9 /18/.

Crack driving force in cylindrical shell can be calculated using model, proposed by Ratwani, Erdogan and Irwin (REI) /17/. They have introduced J^*, J integral normalized by elasticity modulus E, yield strength $R_{p0.2}$ and crack length $2c$ for a surface part-through crack of depth a in the form:

$$J^* = J \cdot \frac{E}{2c \cdot R_{p0.2}^2} = \frac{2}{\sqrt{3}}\left[\frac{\delta_o}{d_1} + \frac{\theta_2}{d_2}\left(0.5 - \frac{a}{W}\right)\right]$$

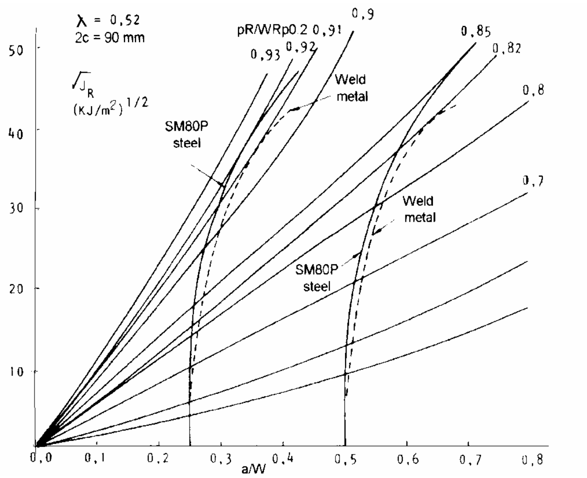
$$d_1 = \frac{4c \cdot R_{p0.2}}{E} \qquad d_2 = \frac{4c \cdot R_{p0.2}}{E \cdot W}$$

The ratios δ_o/d_1 and θ_2/d_2, can be found elsewhere /17/, with crack opening displacement in the center of crack plane, δ_o, and rotation angle of crack plane, θ_2, for wall thickness W, different pressure levels p, and shell parameters

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{\frac{1}{4}} \frac{C}{\sqrt{RW}}$$

where R is the mid-thickness shell radius and ν is Poisson's ratio.

Set of crack driving forces, calculated for the prototype, shown in Fig. 1, is given in Fig. 8 for different pressures, defined by the ratio $pR/WR_{p0.2}$. Crack driving force depends on material yield strength $R_{p0.2}$.



Slika 14. Postupak za predviđanje preostale čvrstoće posude pod pritiskom sa prslinom, sa silom rasvoja prsline i J-R krivama
Figure 14. Procedure for residual strength assessment of cracked pressure vessel, with crack driving force and J-R curves.

Krive otpornosti za osnovni metal - čelik SM80P i EPP metal šava su dobijene na epruvetama za savijanje u tri tačke (SENB) 22,5×45×180 mm prema standardu ASTM E1152. One su prenete u isti dijagram sa silama razvoja prsline na sl. 14. Za pretpostavljeni odnos *a/W* = 0,25 (dubina prsline *a* = 11,75 mm) prslina će rasti stabilno 3,75 mm u metalu šava i 4,25 mm u osnovnom metalu, sa kritičnom vrednosti pritiska za brzi lom 155 bar i 144 bar, respektivno. Za *a/W* = 0,5 (*a*=23,5 mm) te vrednosti su 8,5 mm i 140 bar za osnovni metal, a 6,1 mm i 104 bar za metal šava.

Dobijeni rezultati su pokazali visok nivo otpornosti prema prslinama čelika SM80P i njegovog EPP metala šava. Iako ZUT nije ispitivana, ispitivanje rasprskavanjem je pokazalo njeno zadovoljavajuće ponašanje.

Resistance curves for base metal (steel SM80P) and SAW weld metal were obtained by three point bend specimens (SENB) 22.5x45x180 mm, standard ASTM E1152. They are transferred to the same plot with crack driving forces in Fig. 14. For assumed ratio a/W=0.25 (crack depth a=11.75 mm) crack will grow in a stable manner 3.75 mm in weld metal and 4.25 mm in base metal, with critical pressure for fast fracture 155 bar and 144 bar, respectively. For a/W=0.5 (a=23.5 mm) the values are 8.5 mm and 140 bar for base metal and 6.1 mm and 104 bar for weld metal.

Obtained results demonstrated high level of crack resistance of SM8OP and its SAW weld metal. Although HAZ was not examined, the burst test demonstrated its satisfactory behaviour.

LITERATURA – REFERENCES

1. Reverzibilna hidroelektrana Bajina Bašta, „Vesti“, Titovo Užice, 1981.
2. Hidroelektrane „Bajina Bašta“, „Vesti“, Titovo Užice, HE „Bajina Bašta“, Perućac, 1982.
3. R.J.Elber, J.F.Kiefner: „Failure of Pipelines”, Metals Handbook, Ninth Edition, Volume 11 “Failure Analysis and Prevention”, ASM, Metals Park, Ohio, 1986.
4. „Cevovodi pod pritiskom hidroelektrana“, Referati i diskusije sa konsultacije održane 1976. godine, Zajednica jugoslovenske elektroprivrede, Beograd, 1979.
5. H. Joas:„Berst und Sprengversuche an Rohrleitungsabschnitten eines Pumpspreicher-Wasserkraftwerks“, „Messtechnische Briefe“, MTB 16 (1980), Heft 3, str. 49-55.
6. Izveštaj komisije eksperata za utvrđivanje pojave širenja prskotina sučeono zavafrenih spojeva za cjevovod, 1995.
7. S. Sedmak, A. Sedmak:”The experimental analysis of crack behaviour in welded pressure vessels”, IIW X-1447, 1998
8. S. Sedmak. A. Radović, Lj. Nedeljković:„The strength of welds in HSLA steel after initial plastic deformation”, in Mechanical Behaviour of Materials (Edited by K. J. Miller and R. F. Smith). Vol. 3. Perganion Press, Oxford & New York, 435-446, 1979.
9. I. Rak. V. Gliha and J. Kuder: „The testing of penstock model, welded of quenched and tempered structural steel for pumping-ap hydroelectric power plant Bajina Bašta”, Metalna Strokovni bil. '84/1, 15-23, 1984, (in Slovene)
10. Dast Richilinie 011 „The application of high strength weldable fine-grained structural steels StE47 and StE70”, Deutscher Ausschuss fur Stahlbau, 1974 (in German)
11. Technical standards for gates and penstocks (1971), Water Cate and Penstock Association, Tokyo, 1971.
12. 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, Beograd, 21-24, 1989
13. US-Yugoslav joint project "Fracture mechanics of weldments" Annual reports, Faculty of Technology and Metallurgy, Universily of Beograd, Principal investicator S. Sedmak, 1982-1991
14. „Recommendation for notch size of the prototype penstock burst test” Sumitomo Metals lndustry Ltd, (private communication), 1977
15. D.T. Read: „Experimental method for direct evaluation of the J contour integral”, ASTM STP 791, 199-213,1983
16. F. Erdogan and M.M. Ratwani:„Plasticity and the crack opening displacement in shells”, Int. J. Fract. Mech. 8(4), 413-426, 1972
17. M.M. Ratwani, F. Erdogan, G.R. Irwin: „Fracture propagation in cylindrical shell containing an initial flaw”, Lehigh University, Bethlehem, 1974
18. M.M. Ratwani, S. Sedmak, B. Petrovski: „The assessment of residual strength ol pressure vesseI with surface crack by resistance curve”, the monograph Fracture Mechanics of Weldments, ed. S Sedmak), GOŠA, TMF, Beograd, 131-162, (in Serbian), 1985