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Steel Liners for Pressure Shafts – Hydrostatic Pressure Testing and Other Quality Control Aspects

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ABSTRACT

Support requirements for underground excavation are governed by the nature and use of the structure apart from the basic requirement concerning the geological conditions. Pressure shaft is an important part of the water conveyance system designed to bear the high internal water pressures. Further, pressure shaft manifolds or the penstocks have to be designed to bear the gross head of water. The fabrication and erection of these steel liners is a challenging task. The thickness of the steel liners has to be varied in accordance with the variation in internal water pressure. Since, the liners are subjected to abrasion under high velocity and silt laden water; the inner surfaces need to be painted with abrasion resistant epoxy paint. Apart from the fabrication and erection, testing of these liners also require utmost attention. Quality of liners has to be maintained starting with the materials, fabricated pieces in the workshop and field testing of all the welds including joints and grout plugs. Hydrostatic testing of fabricated pipes is mandatory. Manifolds or the Y-pieces need special attention as these are subjected to maximum pressure and cumbersome field weld joints. This paper discusses various tests and measures adopted for assuring the quality of the steel liners for pressure shafts of a hydroelectric project.

***Keywords*:** Pressure shaft; Ferrule; Dye penetration test (DPT); Dry film thickness (DFT); Hydrostatic pressure testing; Pressure shaft manifolds

1. INTRODUCTION

Water conveyance system in case of hydroelectric projects consists of intake tunnels, desilting arrangements, head race tunnel, surge shaft, pressure shaft, penstocks/manifolds, tail race tunnel etc. The pressure shaft in hydro power projects is a major appurtenant as it works under high hydrostatic and hydrodynamic heads. Concrete lining can serve the purpose to cater the low heads. Use of steel liners becomes essential due to high velocity of water of the order of 6 m/sec. The fabrication and erection of these liners require highly experienced and specialised manpower. Quality of weld material has to match with the parent steel. The high quality of steel is also not easily available everywhere. It requires a huge setup for setting up of the workshop called ferrule workshop. Steel plates of rectangular shape are bent to the desired shape to suit the design requirements. These steel plates have to pass physical, mechanical and chemical tests. Two pipes can be joined together by welding. Field welding is difficult compared to shop welds. Even repairing of the defected joints is not an easy job due to the difficult working environment inside the shafts.

Not only the fabrication and erection of these steel liners need utmost care, the testing of steel plates and the fabricated pipes also require special attention. Fabricated units require precise testing in the workshop as well as in the field. While shop joints can be tested with much better accuracy because of the testing facilities and the convenience; testing of field welds is a cumbersome process due to the site conditions. The accuracy of the testing equipment is also important. Testing of steel liners requires highly qualified staff; starting with the tests on raw materials to fabricated units in the shop and erected/welded pipes in the field.

The present paper discusses the testing requirements of steel liners used in the pressure shafts of a hydroelectric project in the Himalayas. Steel liners are used to provide stability and safety to the structure under high internal hydrostatic pressures. Various shop and field tests on the steel plates and fabricated pipes have been discussed in this paper. Special emphasis has been given to hydrostatic testing of penstock bifurcations being the crucial part due to its complexity.

2. PRESSURE SHAFTS

Two pressure shafts each of 4 m finished diameter and 1.1 km long inclined at about 52^0 and 55^0 with horizontal have been provided at Tala hydroelectric project in Bhutan to function under 860.5 m gross head of water. Pressure shafts and manifolds are lined with steel liners of 30 to 45 mm thickness. The minimum excavation diameter varied between 5.0 to 5.3 m. Specification and properties of steel plates for fabrication of steel liners of pressure shafts are given in Table 1. Figure 1 shows layout plan of the pressure shaft along with surge shaft and power house complex whereas layout plan of penstock manifolds is shown in Fig. 2.

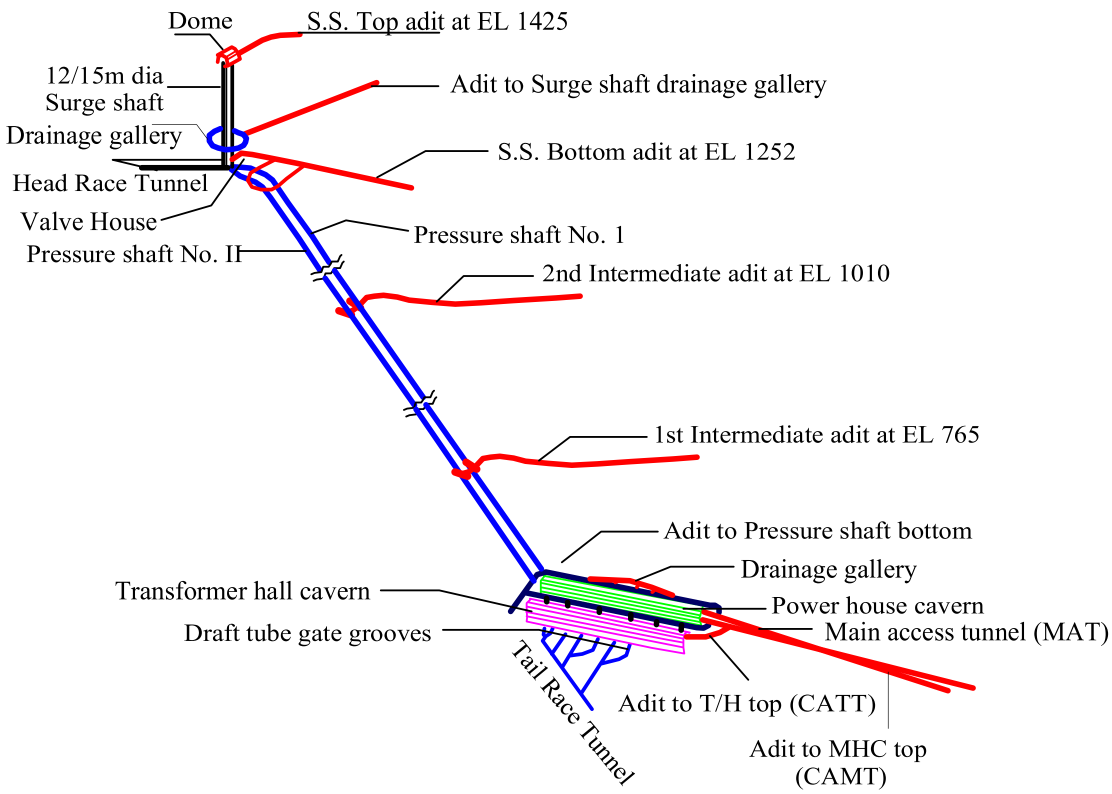


Fig. 1- Layout of surge shaft, pressure shafts and power house complex

Table 1 - Specification and properties of steel plates

Type of steel	Properties of steel			
	Tensile strength MPa	Yield strength MPa (Minimum)	Elongation in 50 mm (% Minimum)	Impact value Joules at -20^{0}C (Minimum)
ASTM - A - 537 Cl - II	550-690	415	22	40
ASTM - A – 517 – Grade F	795-930	690	16	41

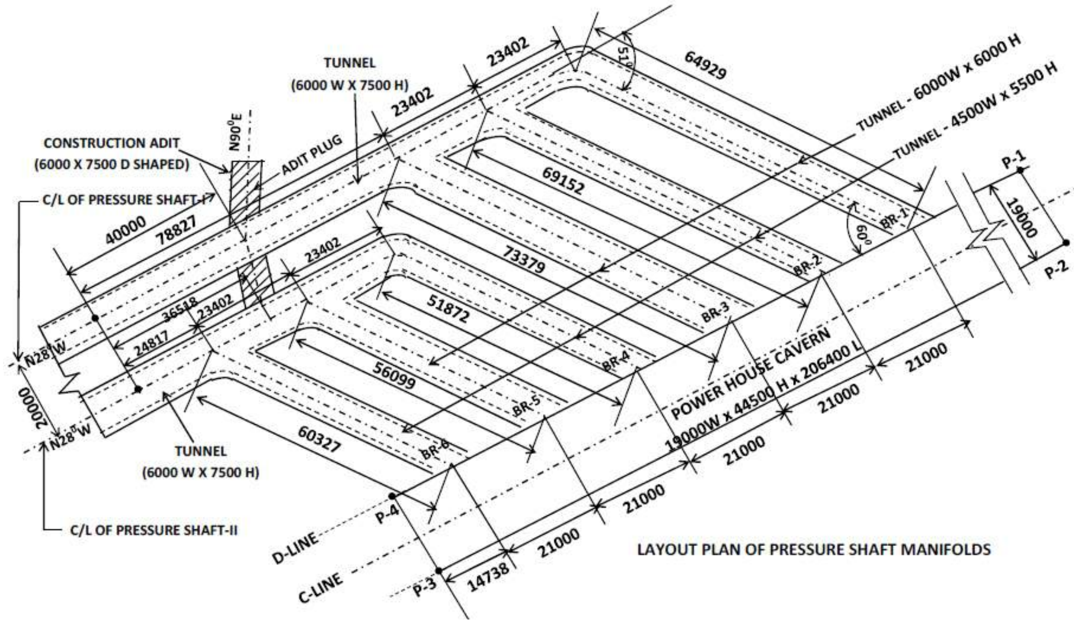


Fig. 2 - Layout plan of penstock manifolds

Fabrication of steel liners was done in the ferrule workshop set up at the project site. Steel plates were bent into required diameter of 4.0 m, 3.25 m and 2.3 m. For 4 m and 3.25 m diameter pipes, 2 bent plates were assembled to give 2.5 m long cylindrical shell. However, 2.3 m diameter plates were fabricated from a single plate. Two shells were then welded in the workshop to make 5 m long pipe. In specific reaches of poor rock mass conditions, stiffeners were also provided around on these liners. These fabricated pieces are then subjected to various quality tests. Application of heat before, during and after welding was done because of the following reasons to:

- avoid cold cracking, minimize shrinkage and distortion,
- increase toughness of weld joint, and
- reduce residual stresses in welded steel.

These fabricated pieces of 5.0 m length were then transported to respected sites, erected, aligned and welded. Field welds were also tested for any defects. The ferrules were aligned first and then M20A20 grade concrete was poured between rock and ferrule with the help of concrete placement pump. There was no reinforcement in the backfill. Due to difficulty in using the vibrators for compaction of backfill concrete, it was proposed to use self-compacting concrete

(SCC). Steel liner with stiffeners installed at horizontal section of pressure shafts is shown in Fig. 3.

Fig. 3 - Steel liners in position

3. QUALITY CONTROL TESTS FOR STEEL LINERS

Weld tests are necessary to confirm the choice of filler material and welding process for defined base material (steel plate) and to make sure that final features of the welded joint have achieved the required standards. Production weld test plate of size 900 mm x 400 mm consisting of two strips, welded edge to edge in longitudinal direction was prepared similar to actual welding of fabricated pieces. These test plates were tested at regular specified intervals.

Various tests such as radiographic examination, tensile tests, bending test, impact test, hardness test, chemical analysis, microscopic/ macroscopic examination, X-groove restraint cracking test, diffusible hydrogen test etc. were conducted to monitor the soundness and properties of welds on routine basis.

Robert et al. (2002) illustrated the application of state of the art in-line inspections tools and analysis of data with case studies. The case studies document how in-line inspection tools have been used to detect a number of common pipeline defects including: Longitudinal Seam Cracks, Stress Corrosion Cracking, Internal Corrosion, External Corrosion, Top-Side Anomalies, Dents, and Gouges.

The steel liner was designed to bear 60% of the internal loads whereas the rest 40% was supposed to be borne by the adjacent rock. This means 40% rock participation was assumed in design.

3.1 Dye Penetration Test (DPT)

After completion of welding from one side of V-groove, the weld at the root was grounded and dye penetration test was conducted to check for defects, if any. The same was rectified by grinding and re-welding.

3.2 Radiographic Examination

All the longitudinal as well as circumferential joints were subjected to 100% radiographic examination. The following defects were judged unacceptable:

- Any type of crack, or zone of complete fusion or penetration.
- Any elongated slag inclusion, which has length greater than 1/3t, where t is the thickness of the weld.
- Any group of slag inclusion in line that have an aggregate length greater than ‘t’ in a length of 12t except when the distance between the successive imperfections exceeds ‘6L’ where ‘L’ is the length of largest imperfection in the group.

3.3 Hydrostatic Pressure Testing

After radiographic examination, the pipes were subjected to hydrostatic pressure varying from 25 kg/cm^2 to 139 kg/cm^2 (2.5 to 1.39 MPa) depending upon the thickness of steel plate. The test pressure was applied for a sufficient time for detection of leakage or other defects.

3.4 Magnetic Particle and Ultrasonic Test for Welding of Stiffeners

Stiffeners and backing plate for grout plugs were welded on pipes as specified in the drawings. Same grade of steel for respective pipe was used. The circumferential welding joints of stiffeners with the pipe were checked by ‘Magnetic Particle Inspection’ test and specified number of joints between two stiffeners by ultrasonic testing.

3.5 Testing of Field Welds

All the field circumferential joints were subjected to ultrasonic tests. Any defect was taken due care. After completion of skin, contact and consolidation grouting, the grout holes were plugged with steel plugs of the same material. These grout plug welds were then subjected to dye penetration tests for detection of pinholes/cracks.

All the grout holes in PS liners were plugged after completion of grouting operations. These welded plugs were subjected to DPT for detection of pinholes/cracks. Each plug was tested in the presence of quality control representatives. The defects noticed in the plugs were attended by the executing agency and DPT was conducted again till it was found defect free. The results of DPT conducted on grout plug welds are given in Table 2. Out of 3830 number of total plugs, defects were noticed in 584 plugs which were subsequently rectified.

4. HYDROSTATIC PRESSURE TESTING OF PENSTOCK BIFURCATIONS

Hydrostatic testing has long been used to determine and verify pipeline integrity. Several types of information can be obtained through this verification process. However, it is essential to identify the limits of the test process and obtainable results. ASME B 31.8 specifies the test pressure factors for pipelines operating at hoop stress of ≥ 30% of specified minimum yield strength (SMYS). Test pressures need not exceed a value that would produce a stress higher than yield stress at test temperature (ASME B 31.3 section 345.4.2 (c)). The allowed stress in the pipe material is limited to 72% of SMYS. In some cases it is extended to 80% of SMYS.

Table 2 - Results of DPT on grout plugs

Pressure shaft	Location	Total plugs	DPT conducted	Defects noticed and rectified
PS-I	Horizontal, bends and inclined reach	1688	1688	303
	Manifolds 1, 2 and 3	314	314	22
PS-II	Horizontal, bends and inclined reach	1604	1604	250
	Manifolds 4, 5 and 6	224	224	9
Total		3830	3830	584

Each pressure shaft feeds three generating units. Therefore, each pressure shaft was bifurcated twice at the horizontal section for feeding each Pelton turbine. The erection of penstock bifurcations also called as Y-pieces was a complex job requiring utmost care in welding due to stress concentrations. After completion of bifurcation 3 and 4 of PS - II, the hydrostatic testing was taken up.

Technical specification criteria were applied for deciding the maximum hydrostatic pressure for testing of bifurcations. Maximum pressure was applied equivalent to minimum of the following three conditions:

- 1.5 times the gross head of water,
- 90% of the yield strength of steel plates, or
- 50% of ultimate tensile strength (UTS) of steel plates.

The steel liner has been designed to bear 60% of the internal water pressure whereas the rest 40% will be borne by the adjacent rock. This means 40% rock participation was assumed in the design. However, the bifurcations were tested for maximum pressure satisfying the above criteria. Therefore, based upon this criteria, hydrostatic pressure of 89 kg/cm^2 (8.9MPa) was applied which was guided by the 50% UTS of steel i.e. 7900 kg/cm^2 (790MPa).

4.1 Bifurcations 3 and 4

After erection of 4.0 m diameter steel liners, 45 mm thick hemispherical bulkhead at reducer end, entire horizontal reach of steel liner upto main inlet valves (MIV) of units 4, 5 and 6, water was filled in the entire shell. Testing was commenced after filling of the shell with water and removal of air through the air vent provided on the top of the shell. These bifurcations were tested on 28.2.2006 to 01.3.2006 upto a maximum pressure of 89 kg/cm^2 (8.9MPa).

The hydrostatic pressure was applied in stages of 25, 50, 75 and 89 kg/cm^2 (2.5, 5.0, 7.5 and 8.9 MPa). At each stage, load was maintained for 10-15 minutes. All the exposed circumferential and longitudinal joints of bifurcations were physically inspected for leakage or defects at each stage. The pressure was then reduced to 66 kg/cm^2 and again increased to 89 kg/cm^2 (8.9MPa). This process was repeated twice. No leakage from any joint was observed in bifurcations 3 and 4.

4.2 Bifurcation 1 and 2

After erection of 4.0 m diameter steel liners, 45 mm thick hemispherical bulkhead (Figure 4) at reducer end, entire horizontal reach of steel liner upto MIV of units 1, 2 and bulkhead at MIV end for manifolds 3; hydrostatic testing of bifurcations 1 and 2 was taken up.

Fig. 4 - Hemispherical bulkhead

Unlike bifurcations 3 and 4, it was decided to monitor the strains while pressurizing the manifolds. For this, strain gauges were installed for measuring the actual strains. Critical locations along the bifurcations were selected for installation of strain gauges in consultation with the designers and based on numerical modelling results. Bondable/spot weldable type water proof strain gauges of 87 x 22 x 18 mm overall size and maximum strain range of 3000 µ e with an accuracy of ±1 µ e were fixed on the steel pipes (Figs. 5 and 6).

Fig. 5 - Bondable/spot weldable strain gauge

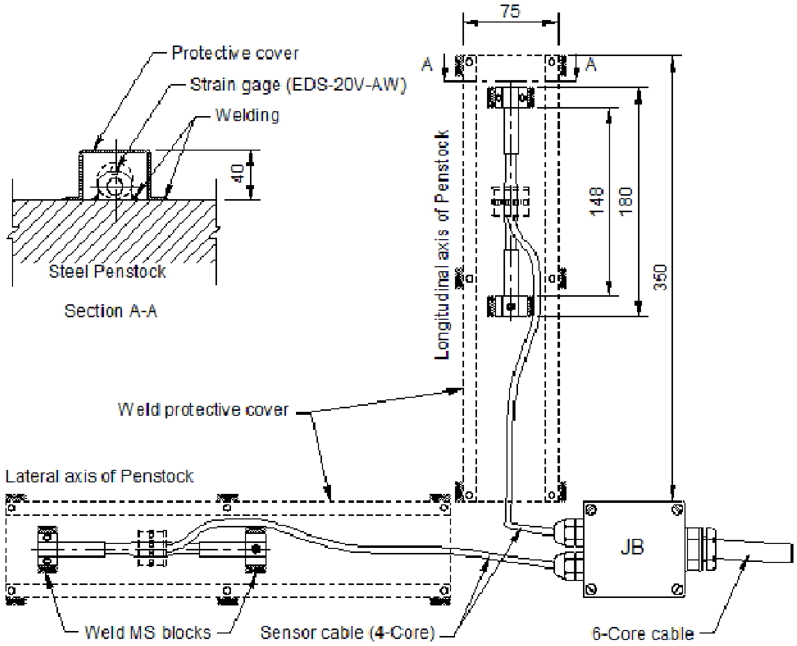
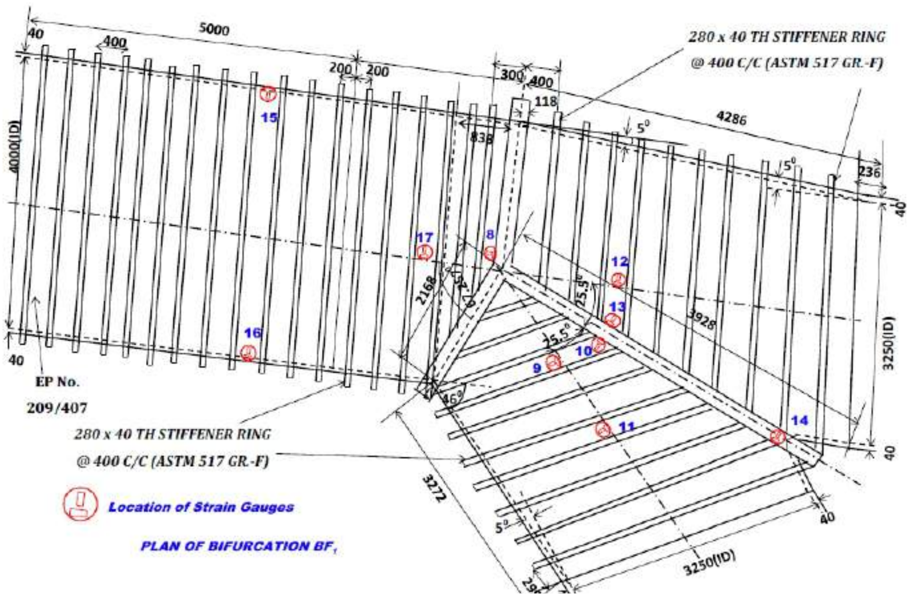


Fig. 6 - Arrangement of strain gauges and junction box

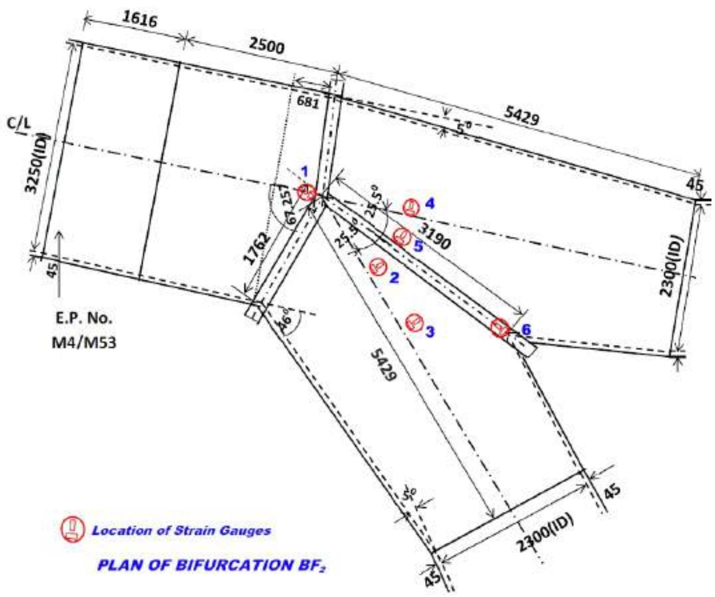
4.2.1 Testing Procedure

After installation of strain gauges, the entire horizontal reach of steel liner was filled with water. As per consultant's advice, bifurcation and adjoining straight ferrules reach were required to be tested to 100 kg/cm^2 (10.0MPa), but this was restricted to 89 kg/cm^2 (8.9MPa) as in 4 m diameter section of reducer, the stress in liner corresponding to 100 kg/cm^2 (10.0MPa) was exceeding 50% of UTS value, which was not conforming to stipulation of technical specifications. Hydrostatic testing of this reach was started on 28.07.2006. After attaining a hydrostatic pressure of 75 kg/cm^2 (7.5MPa), minor leakage was observed through a small pinhole/crack in a weld joint of bifurcation 1. Test was stopped and the penstock was depleted. Repair was carried out after gauging of joint at the defected location and test was repeated on 01.08.2006 strictly adhering to the provisions contained in technical specifications. Pressure in steel liner assembly being tested was increased slowly and uniformly to 89 kg/cm^2 (8.9MPa). This test pressure was applied in three cycles successively increasing and decreasing at uniform rate (lowering the pressure to 66 kg/cm^2 (6.6MPa)and then increasing to 89 kg/cm^2 (8.9MPa)). Test pressure of 89 kg/cm^2 (8.9MPa) was maintained for minimum 10 minutes in each cycle and during this period, inspection of steel liner plates and all exposed welded joints of BF1, BF2, 3250 mm ø straight ferrules, reducers (4000 mm ø to 3250 mm ø, 3250 mm to 2300 mm ø and 2300 mm ø to 1650 mm ø) were carried out. No leakage was observed from any joint throughout the test.

Strain gauges were installed on the steel shell to measure the hoop as well as longitudinal strains. Location of all the strain gauges is shown in Figs. 7a and 7b. Strain measurements of strain on steel liner were also monitored at various points for assessment of actual stresses at varying internal hydrostatic pressure of 0 to 89 kg/cm^2 (0 to 8.9MPa).



a) Bifurcation BF_1



b) Bifurcation BF_2

Fig. 7 - Location of strain gauges

As the complete Y-pieces along with the straight section constitute a complex geometry, two locations were chosen in the straight section so as to measure the hoop strain for assessing the hoop stresses on the cylindrical section. Since, reinforcement steel was fixed on the liners for placing the R.C.C. around the annulus space between the liners and surrounding rock, it was difficult to install the strain gauges. A total of 17 locations including two locations on the horizontal section were selected to measure the strains resulting from hydrostatic stress. Cables of all these strain gauges were extended upto a monitoring point with the help of junction boxes. Digital readout unit was employed to measure the strains.

Induced strains on the steel liner as a result of applied hydrostatic pressure were monitored using the digital readout unit at various stages of pressurisation. During installation, strain gauges at two locations got damaged. At each increment of hydrostatic pressure, strains at all the locations were recorded. Strains measured at 15 locations are presented in Table 3.

Table 3 - Measured strains at various sections of the bifurcations

Hydrostatic pressure, kg/cm^2 →	Empty shell	Full Shell	25	50	75	89	66	75	89	66	80	89	50	Full shell
Gauge No.	Strain (micro strain)													
S1H	0	-61	160	334	467	525	365	466	532	372	481	511	250	-64
S1L	0	-2	166	339	461	521	368	466	531	372	481	511	250	0
S2H	0	46	369	562	689	740	602	653	720	599	650	687	424	46
S2L	0	36	128	195	248	273	211	249	274	213	255	265	160	36
S3H	0	44	357	474	639	675	616	641	670	504	653	698	348	32
S3L	0	52	59	85	108	130	109	116	130	120	116	129	104	35
S4H	0	17	364	634	838	931	715	842	935	724	890	903	573	24
S4L	0	7	60	100	134	166	123	137	151	124	140	114	93	18
S5H	0	-30	304	550	731	812	598	783	809	604	778	819	420	-16
S5L	0	34	151	170	189	201	138	171	204	140	173	205	87	7
S6H	0	34	160	256	329	361	296	330	362	301	342	355	222	36
S6L	0	34	160	256	328	361	295	331	362	301	343	354	222	35
S8H	0	18	118	215	291	329	253	295	332	260	309	323	181	1
S8L	0	10	114	209	287	325	248	290	328	255	305	318	172	-4
S9H	0	30	370	679	918	1025	785	926	1042	874	978	1023	578	25
S9L	0	-3	41	92	131	147	90	123	145	91	129	139	41	-6
S10H	0	21	230	440	605	682	517	603	683	529	632	664	358	26
S10L	0	21	230	439	604	680	515	605	683	527	634	662	345	25
S11H	0	9	253	495	688	779	588	696	790	611	736	774	425	12
S11L	0	9	253	494	687	777	588	700	790	607	740	772	408	11
S12H	0	0	47	114	171	197	157	175	199	162	185	193	113	-9
S12L	0	0	47	114	170	197	156	176	198	160	185	192	107	-10
S13H	0	8	217	426	591	671	501	595	680	517	629	665	356	6
S13L	0	31	17	24	35	54	48	51	54	48	52	55	46	32
S14H	Gauge damaged during installation													
S14L	Gauge damaged during installation													
S15H	**0**	**38**	**497**	**785**	**988**	**1068**	**859**	**988**	**1068**	**879**	**996**	**1026**	**601**	**48**
S15L	0	2	24	42	51	58	24	50	58	24	50	58	39	3
S16H	**0**	**37**	**498**	**786**	**989**	**1067**	**860**	**987**	**1067**	**860**	**998**	**1028**	**605**	**43**
S16L	0	-5	7	19	29	34	30	32	34	30	33	34	26	3
S17H	Gauge damaged during installation													
S17L	Gauge damaged during installation													

Figures 8, 9 and 10 show the plot between hydrostatic stress and strains for bifurcations 1, 2 and straight section of liner, respectively. Maximum strains were recorded by strain gauges S-15 and S-16 located at the straight section. These hoops strains were used to determine the hoop stress on the liners. Strains measured at critical locations around Y-pieces were lower as compared to the straight section.

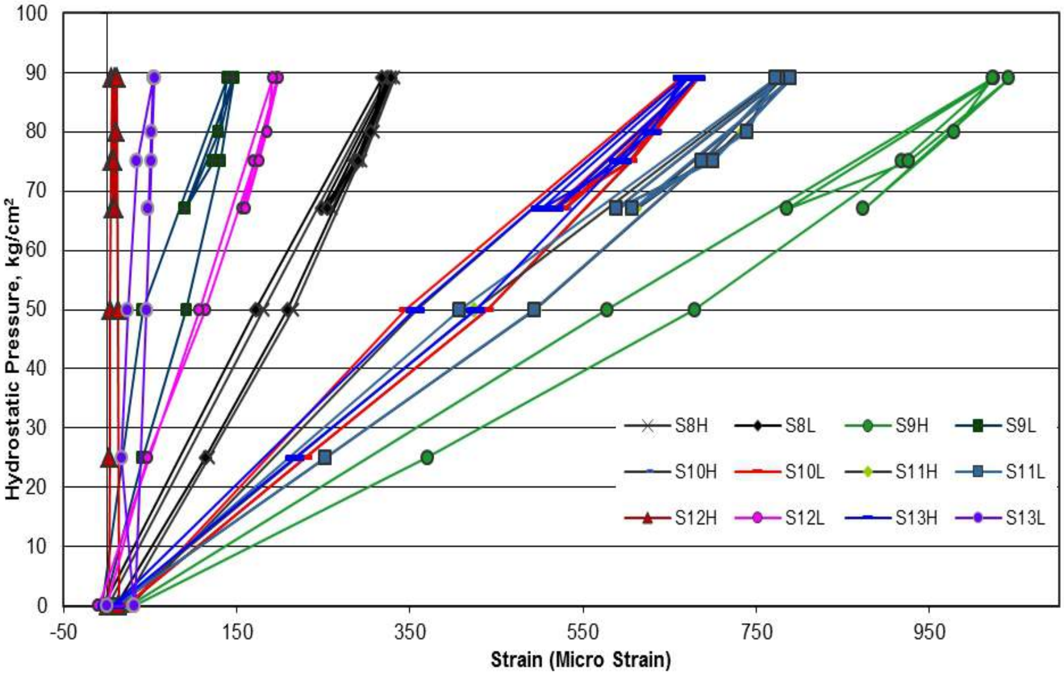


Fig. 8 - Stress-strain plot for bifurcation 1

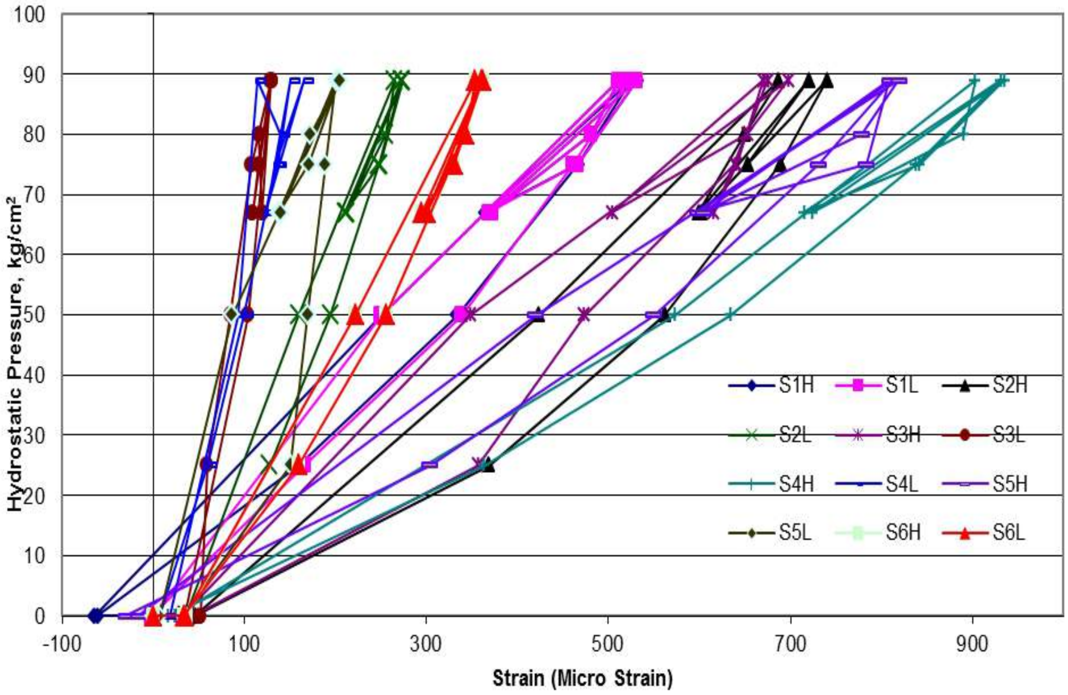


Fig. 9 - Stress-strain plot for bifurcation 2

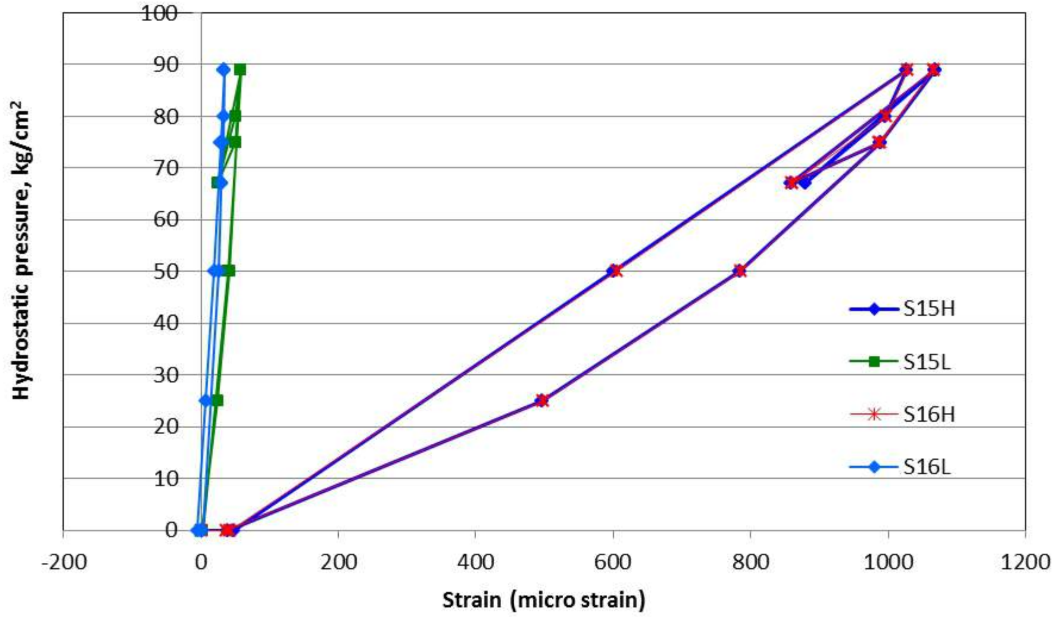


Fig. 10 - Stress-strain plot for straight section (S-15H and S-16H strain gauges)

4.2.2 Theoretical and Actual Stresses

Locations 15 and 16 were assumed to be sufficiently straight such that strains recorded by S15H and S16H were hoop strains. Further, Table 3 indicates that the strains measured by these strain gauges were same. Measured strains from S-15H and S-16H were almost same at various hydrostatic pressures. Hence, average values have been used for calculation of stresses using Equation 1:

$$E = \frac{\sigma}{\varepsilon} \tag{1}$$

Where
E = Young's modulus of elasticity of steel,
= 2.1×10^6 kg/cm^2 (2.1×10^5 MPa),
σ = stress, kg/cm^2, and
ε = strain.

Also, thin cylinder theory was applied to calculate theoretical stresses using Equation 2:

$$\sigma = \frac{Pd}{2t} \tag{2}$$

Where
σ = Hoop Stress,
P = Applied internal water pressure,
D = diameter of the shell, and
T = thickness of the shell.

Comparison of theoretical and actual hoop stresses obtained from the hydrostatic pressure tests has been given in the Table 4 and the same has been shown in Fig. 11.

Table 4 - Hoop stresses on liners – measured and theoretical

Hydrostatic pressure (kg/cm^2)	0	25	50	75	89	66	75	89	66	80	89	50
Strain (micro strain)	0	497.5	785.5	988.5	1067.5	859.5	987.5	1067.5	869.5	997	1027	603
Measured stress (kg/cm^2)	0	1043.7	1648.5	2074.8	2242.8	1803.9	2074.8	2242.8	1845.9	2091.6	2154.6	1262.1
Theoretical stress (kg/cm^2)	0	902.8	1805.6	2708.3	3213.9	2383.3	2708.3	3213.9	2383.3	2888.9	3213.9	1805.6

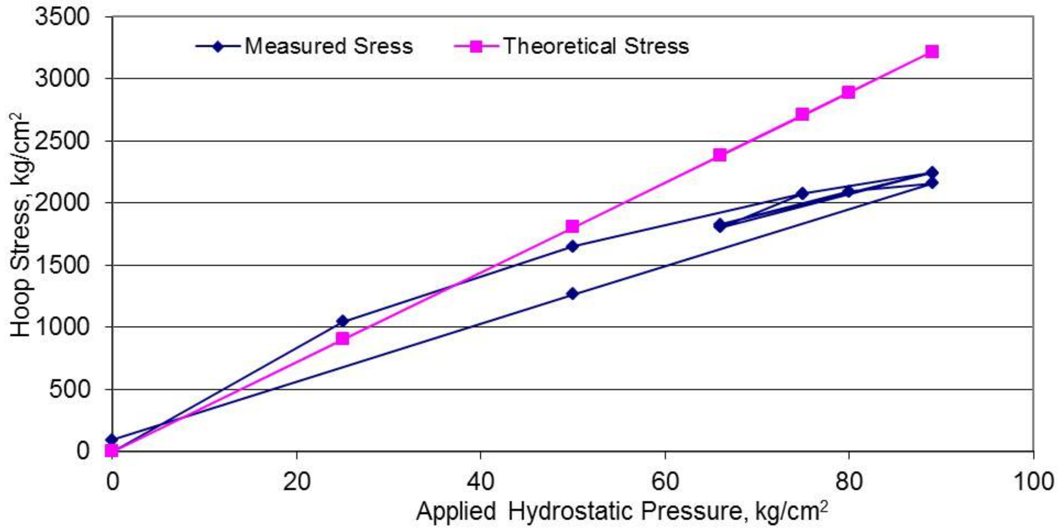


Fig. 11 - Theoretical and measured hoop stresses under cyclic hydrostatic pressure

At low hydrostatic pressure, the actual stresses seem to be slightly higher than the theoretical stress. However, at higher hydrostatic pressure, the actual stresses were found to be significantly lower than the theoretical values. Actual stresses acting on the liner were of the order of 70 - 75 % of the theoretical stresses. Therefore, the steel liners were found to safe against the applied internal hydrostatic pressure of the order of 89 kg/cm^2 (8.9MPa), thus satisfying the technical specifications criteria.

5. PAINTING OF DAMAGED SURFACE, CIRCUMFERENTIAL FIELD JOINTS AND GROUT PLUG/CLEAT AREAS

As the liners are to be subjected to abrasion under high velocity and silt laden water, the inner surfaces of the steel liners were painted with abrasion resistant epoxy paint. Apart from engineering standards, it should also pass the health hazard tests. Painting of inner surface with anti-abrasion paint was carried out for all the pipes in the Ferrule workshop. In accordance with technical specifications, methodology for painting of ferrules had been specified as per the practices adopted earlier. In workshop, ferrules were sand blasted and 2 coats of zinc rich primer was applied with 50 micron dry film thickness (DFT) each. Thereafter, 3 coats of coal tar epoxy were applied with 150 micron DFT each, thus giving a total paint thickness of 550 micron. The circumferential field weld joints approximately 30 cm wide and grout plug weld joints approximately 30 cm x 30 cm were cleaned by grinding/buffing. After ensuring proper cleaning, primer and paint were applied (in 5 coats) as per procedure adopted in the workshop.

While applying primer and painting on the field circumferential joints and grout plugs, it was noticed that due to natural air draft in view of elevation difference of the order of 750 m, high fumes were formed. These fumes were causing eye irritation, vomiting and severe headaches to the workers engaged in painting and even to the workers engaged for the other works at far distances inside the shafts due to high natural draft and in confined site conditions. This was not only causing serious environmental conditions and health hazard but also affected the quality and speed of work.

The site was inspected jointly by the officials of Engineer-in-Charge, Quality Control Division and contracting agency and it was considered important to review the painting scheme for the field circumferential joints and grout plugs by consulting relevant literature and technical experts of various paint manufacturers. Experts form paint manufacturing firms were invited to visit the site to understand the actual working environment and difficulties being faced in achieving the required thickness and quality of paint on the joints inside the ferrules. All the technical points related to paint system for joints were deliberated in a meeting. It was well appreciated by all that primer to be chosen for ferrule joints and grout plugs inside the pressure shafts has to be such that it is durable for surface cleaned by grinding/buffing only as surface preparation for joints inside the shaft was not possible by sand blasting. Further, it should have the required consistency to achieve higher thickness in one coat, produce less fumes and have life long durability against water passing in the inclined shafts with velocity as high as 6m/sec with silt content less than 0.2 mm in size. It was indicated by experts that zinc rich primer, presently being specified is an excellent primer provided the surface is sand blasted. However, for non-sand blasted surface there are other recently produced products, which are much more durable and can achieve higher thickness in one coat and are more environmental friendly.

Keeping in view the above, paint system most suitable for ferrule joints and grout plug joints in inclined shafts was recommended in consultation with experts. Total thickness achieved was 550 micron in 3 coats.

6. INSPECTIONS

After completion of consolidation grouting, the grout plugs were fixed and welded to the steel liner. DPT was conducted on each plug for detection of any defect. The rollers and all other rods meant for movement of trolley were removed and grinded to match with the inner surface of steel liner. The areas around grout plugs and the cleats were painted with anti abrasion paint. Damaged areas were also repainted with primer and epoxy paint to get the desired thickness.

After completion of all the above works, the shafts were finally inspected by a team comprising of quality control unit, representatives of Engineer-in-charge and the executing agency. The general observations included the following points:

- Thick layers of leaching which needed to be removed,
- Grinding of surfaces from where cleats were removed,
- Repainting of the circumferential field joints and other areas of paint thickness less than specified,
- Painting of grout plugs area, and
- Area beneath the movement of wheels of the trolley needed to be repainted.

The observations were again complied by the executing agency before fixing of final make up pieces of steel liners at intermediate adit locations and at the bottom of pressure shafts.

7. CONCLUSIONS

Based on quality control measures adopted during construction of pressure shafts, following conclusions are drawn:

- Tests on steel plates/welds in the shop as well as in the field are necessary to detect the defects and to ensure the quality. Each lot of the material need to be subject to quality tests.
- Joints in liners and grout plugs being the weakest area in the liners require special attention while welding and testing. Hence, these should pass through 100% quality checks.
- Penstock bifurcations and manifolds are critical area due to its complexity and these have to bear maximum hydrostatic pressure. Hence, hydrostatic pressure testing of this section becomes imminent.
- Penstock bifurcations of pressure shafts (PS-I and PS-II) passed the hydrostatic pressure test upto 89 kg/cm^2 (8.9MPa) internal hydrostatic pressure. Measured strains do not indicate any overstress at any point. Actual stresses acting on the liner were of the order of 70 -75 % of the theoretical stresses. However, water leakage through a pinhole from a weld joint in bifurcation 1 was observed at hydrostatic pressure of 75 kg/cm^2 (7.5MPa). After rectification of defect, the bifurcation was subjected to a hydrostatic pressure testing of 89 kg/cm^2 (8.9MPa) and it passed the test.
- Selection and application of the anti-abrasion paint needs special attention for use in shafts to function under high velocity and silt laden water. Surface preparation for application of anti-abrasion paint is an important aspect. The thickness of paint should be ensured and checked extensively.
- Finally, a joint inspection of these liners along with representatives from construction, quality control and executing agency should be carried out. It is necessary to identify the minute defects and carryout the necessary repairs.

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