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Structural Integrity Assessment of Turbine Driven Feed Pump Line due to Water Hammer

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ABSTRACT

While conducting mandatory tests towards preparation for start-up of one of the NPP unit, inadvertent opening of steam supply and control valves led to hammering of cold pipeline connected to steam supply header of Turbine Driven Feed water Pump (TDFP). Due to water hammer, the supports of the piping experienced high dynamic forces resulting in dislodging of few supports. First order analysis revealed stresses of high order, even though no visible damage was seen. Additional NDT examination also did not reveal any damage in pipe or bends. The water hammer scenario was analysed to assess stress levels and predict the extent of damage to the piping based on post-accident investigation details and numerical techniques considering as-built layout and supports of the TDFP pipeline subjected to water hammer loads. The portion of piping which had exceeded the acceptance criteria, has been replaced to ensure safe operation of the TDFP line.

INTRODUCTION

One of NPP in India is provided with two Turbine driven feed water pumps (TDFPs) at Feed water side of the Plant for supplying feed water to Steam Generators during normal operation. Source of steam supply to TDFP turbine is from auxiliary steam header when unit power is less than 80% Full Power (FP) and when unit power is more than 80%FP, steam is taken from Moisture Separator and Reheater (MSR) outlet. The general schematic diagram for steam supply sources to TDFP turbine during normal operation is given in Figure-1.

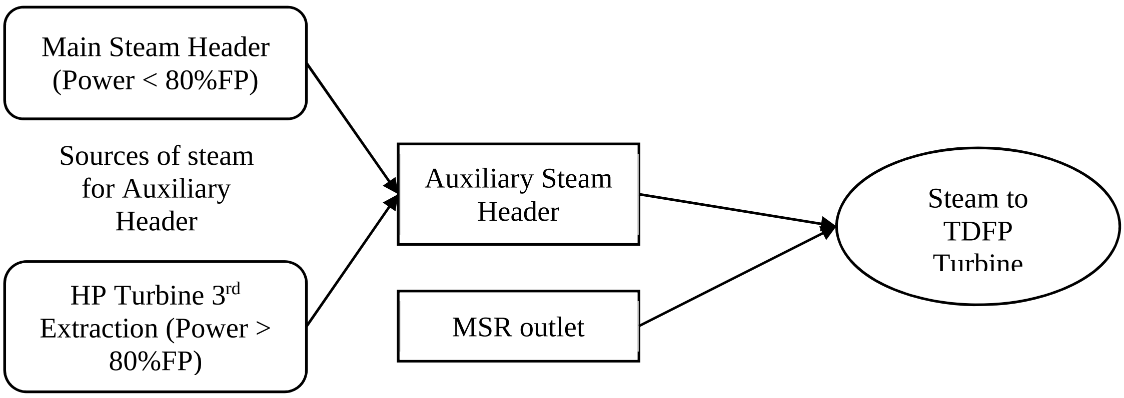

Figure 1: Layout of TDFP Pipeline experienced to water hammering

During mandatory tests for ensuring preparedness for plant start-up, an event of inadvertent opening of TDFP drive steam supply valve resulted in sudden supply of high temperature steam to the cold pipelines resulting in water hammer in the pipe lines connecting TDFP steam supply header and MSR outlet. Damage was noticed in supports of pipe line located between two anchors of Low Pressure Turbine steam header and TDFP steam header. Anchor supports (fixed) were observed to be healthy without any visual deformation, however sliding supports on straight portion of pipeline were found dislodged from the location and supporting members were observed in deformed condition. The straight portion of pipeline supported by sliding support was found displaced during visual inspection (around 225 mm) due to impact of water hammer and could not come to original position due to locking with support bottom base plate. However, after cutting the damaged support metal structure, it came to normal position indicating no plastic deformation of straight portion of pipeline, whereas, perhaps the piping elbows which absorbed the displacement loading had undergone plastic deformation.

AERB initiated a study to evaluate the extent of damage to the piping due to water hammer event based on the post-accident investigation details. A first order assessment about stress distribution in piping due to water hammer was carried out by Finite Element analysis. In order to verify the code qualification of said elbows, an additional exercise was carried out to analyse the TDFP steam supply piping, which was subjected to water hammer, for checking compliance to ASME Section-III NC stress limit requirements under Level-D loading condition. Though water hammer loading is not envisaged in piping design, the analysis was carried out to find out whether the elbows are meeting Level-D stress requirements. Based on the analysis, it was observed that stresses in the elbows exceeded the ASME Section-III NC Level-D stress limits.

This paper brings out the details of stress analysis results of TDFP piping, which was subjected to water hammer, for assessing integrity of the elbows and verification of compliance to ASME Section-III NC 3600 stress limit requirements for piping under service Level-D condition based on which Regulatory decision was taken for replacement of elbows. The paper further concludes the corrective actions taken by utility for avoiding recurrence of such events.

STRESS ANALYSIS OF PIPING

Geometric Details

The layout consists of 5 straight pipe portions and 4 elbows as shown in Figure-2. The span of straight pipe which experienced a displacement of 225mm was 27.5m. The salient geometric parameters of piping are provided in Table-1.

Figure 2: Layout of TDFP steam supply piping

The portion of pipeline between 2 fixed supports (anchor supports) was modelled for carrying out stress analysis. For the said displacement loading, the calculated percentage elongation was 0.87%, which is very much less than the % elongation observed for Carbon Steel materials at UTS i.e. 14-15%. The geometry of TDFP steam supply pipeline as per the layout was modelled in ANSYS with elastic straight pipe element (PIPE16) for pipeline and curved pipe element (PIPE18) for elbows. The length of pipe line, geometric details such as outer radius, wall thickness, radius of curvature of elbows, flexibility factor, and stress intensification factor etc. as mentioned in Table-1 are considered in the analysis.

Table 1: TDFP piping geometry data

Geometric Parameter	**Value**
Outer Diameter (OD) of Straight pipe and Elbow	368 mm
Mean radius of pipe (r_m)	179.5mm
Thickness (t) of Straight pipe and Elbow	9 mm
Elbow's radius of curvature (R_b)	600 mm
Bend characteristic of elbow ($h=(t^* R_b/ r_m^2)$)	0.1675
Flexibility factor of elbow (K=1.65/h)	9.845
Stress intensification factor of elbow ($i=0.9/h^{2/3}$)	2.96
Section modulus of pipe (Z)	889513.15 mm^3

Material Properties

The construction material for piping is Carbon Steel equivalent to SA 106 Grade B. The material properties considered in analysis are given in Table-2.

Table 2: Material properties

Material Property	**Value**
Young's Modulus (E)	202 GPa
Poisson's Ratio	0.3
Yield Stress (S_y)	240 MPa
Ultimate tensile Stress	430 MPa
Hot allowable Stress (S_h) at 50^0C	117.9 MPa
Density	7833 kg/m^3

Loading conditions

Condensation induced water hammer is associated with pressure pulsations in the piping due to sudden release of energy. The pressure magnitude was found to exceed the range of the detectors. Hence actual time history of pressure loading during the event could not be estimated. Therefore, a displacement-controlled loading equivalent to 225mm displacement of straight portion of pipeline was considered for assessing the piping integrity. The effect of dead weight due to structural mass and fluid mass were accounted by specifying equivalent density. Loading data considered in the analysis are shown in Table-3.

Table 3: Loading data

Loading	**Value**
Internal Pressure	1.1 MPa
Temperature	Ambient (~45^0C)
Displacement Loading	225 mm (in -Z direction)

Boundary Conditions

The Finite element mesh of geometric model is shown in Figure-3.

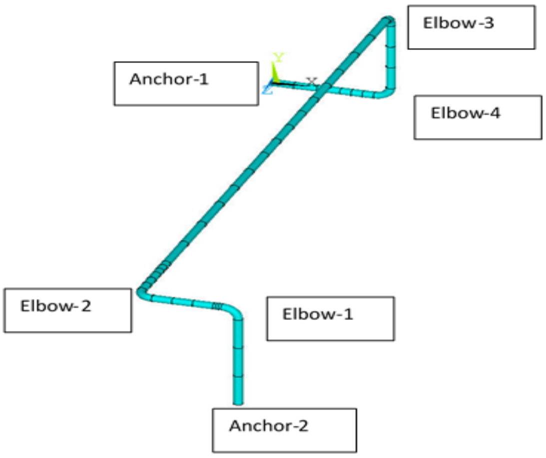

Figure 3: Finite Element Model of TDFP line

For the anchor supports (on both extreme ends of pipeline), all 6 degrees of freedom are constrained. For the sliding supports located on straight pipeline, the displacements are constrained in X & Y direction, while it is allowed to displace freely in axial (z) direction. Spring support located on straight pipe near to Anchor-2 was modelled by constraining in Y- direction (vertical). As per the observed displacement of straight pipeline portion, a displacement loading of 225mm in –Z direction was imposed on longer straight line to take into account the effect of water hammering impact.

Analysis Results

Due to the displacement induced loading, the maximum values of stress intensity were observed in the elbows shown in Table-4. The stress intensity has exceeded the yield stress in 3 out of 4 elbows and maximum stress intensity (354MPa) was observed in elbow-3. Stresses in the straight pipelines were less than yield stress indicating elastic behaviour of the straight piping. Based on the preliminary estimation of stresses, yielding has occurred in 3 out of 4 elbows.

Table 4: Stress intensity values at elbows

Elbow No	**Stress Intensity (MPa)**
Elbow-1	184.58
Elbow-2	322.38
Elbow-3	354.7
Elbow-4	275.91

ASME CODE CALCULATION

Preliminary estimation of stresses in the elbows due to water hammer event in terms of imposed displacement was done using FEM. Subsequently an exercise to check compliance with Section-III NC-

3600 (Class-2) Level-D stress limits was carried out. Though water hammer loading was not envisaged in any of the service conditions in design, it was prudent to check compliance with Service Level-D requirements. The piping was modelled in CAEPIPE (customized piping analysis software) for evaluating bending moments on pipe & elbows for the given loading. The piping layout, geometry and material properties were modelled in CAEPIPE as per details given in Tables-1 & 2. By introducing a minimum displacement as 225 mm through the feature of limit stops in CAEPIPE, a pre-loading in axial direction was imposed on piping. The CAEPIPE model of TDFP steam supply piping is shown in Figure-4.

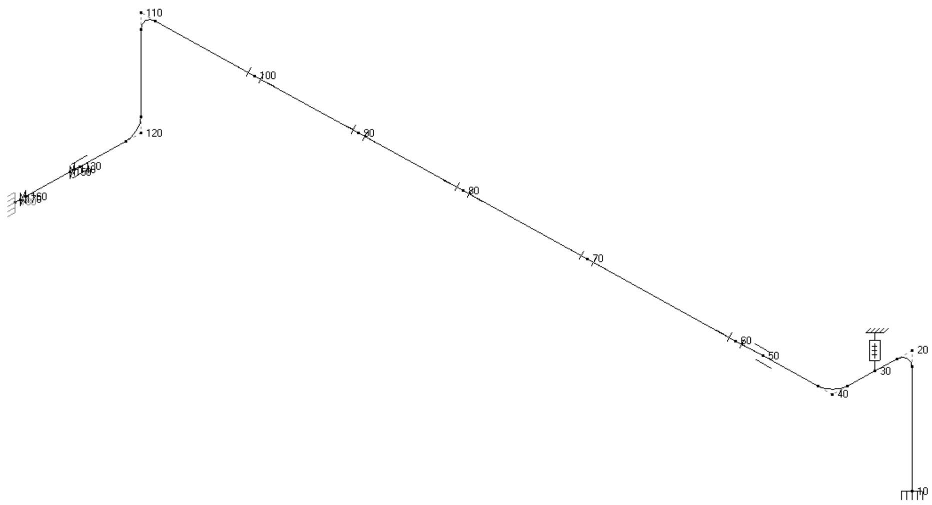

Figure 4: CAE Pipe model of TDFP piping

After introducing a pre loading on piping by imposing axial displacement, the bending moments along 3 axes (X, Y & Z) for both sustained and displacement induced (expansion loads) were evaluated. The resultant bending moment (M_i) is calculated as SRSS of bending moments in X, Y & Z directions i.e. $\sqrt{M_x^2 + M_y^2 + M_z^2}$. The maximum pressure observed during the time of event as per log data records was ~ 1.1 MPa, which was considered as P_{max}. The values of primary stress indices (B_1 & B_2) for straight pipe and elbows is given in Table-5.

Table 5: Stress indices for various piping elements

Type of Pipe	**B_1**	**B_2**
Straight pipe	0.5	1
Elbow	0	4.28

Since the term B_1 for elbows is zero (due to very high bend radius), it implies that the stress induced in elbows due to effect of pressure surge is zero and the only stress inducing load on elbows is the bending moment. Table-6 brings out compliance to Section-III NC, Level-D stress limits for elbows of piping. The value of stress ratios computed by ratio of stress evaluated from Equation (1) and the limiting stress $2S_y$ for elbows are presented in the Table-6 (for Elbows, A&B denotes two ends). For remaining portion of pipeline, the stress ratios were less than 1.

$$S_{OL} = B_1 \frac{P_{max} D_0}{2t_n} + B_2 \left(\frac{M_A + M_B}{Z}\right) \leq 3S_h, but\ not\ greater\ than\ 2S_y \quad (1)$$

where B_1 & B_2 are primary stress indices of pipe, P_{max} is peak internal pressure, M_A is resultant moment loading on cross section due to weight and other sustained loads, M_B is resultant moment loading on cross section due to occasional loads such as thrusts from relief and safety valve loads from pressure and flow transients, and reversing and non-reversing dynamic loads, Z is section modulus of pipe, t_n is nominal wall thickness, S_h is hot allowable stress of pipe material, S_y is yield strength of material.

Table 6: Compliance Check to ASME Section-III NC Level-D Condition

Elbow Number	**$S_{OL}/2S_y$**
Elbow 20A	1.45
Elbow 20B	1.25
Elbow 40A	1.16
Elbow 40B	1.37
Elbow 110A	1.24
Elbow 110B	1.04
Elbow 120A	1.08
Elbow 120B	1.37

Even though the stress ratio exceeded 1 in elbows as per analysis, no physical failure of elbows was observed (during post-event inspection) because the current analysis considers elbows material as elastic neglecting strain hardening behaviour and stress redistribution due to plastic deformation. From the results it can be concluded that the elbows might have undergone significant plastic deformation.

CORRECTIVE ACTIONS RECOMMENDED BY THE REGULATORY BODY

Based on the current study, AERB recommended utility to replace all 4 elbows of TDFP Piping. It was also recommended to ensure healthiness of all affected TDFP piping supports and weld joints by carrying out MPT and UT. As a part of NDT inspection, PT and MPT was carried out on fixed supports and no reportable indications were noticed. Embedded Parts of the supports, which were damaged, have been replaced.

CONCLUSIONS

First order independent analysis was carried out on TDFP piping system by simulating a water hammer loading as displacement type loading to find out the integrity of elbows. It was noted that elbows are of major concern than straight pipe because in straight pipes elastic behaviour was observed during inspection as their displacements were fully recovered after cutting the obstructed sliding support base plate.

Finite element analysis results indicated that in 3 out of 4 elbows there was plastic deformation because the stresses were found to exceed Yield strength of material. An exercise was carried out to assess the compliance to ASME Section III NC-3600 code stress limit requirements for TDFP steam supply pipeline in CAEPIPE for displacement induced loading. It was found from the results that all 4 elbows have exceeded the stress limit requirements of Service Level-D condition. In view of significant amount of plastic deformation noticed in elbows as per the analysis, it was recommended to replace all 4 elbows for ensuring safe operation of TDFP.

ACKNOWLEDGEMENT

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