There is Knowledge in Failure- If Followed by Root Cause Analysis

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Introduction

I obtained my B.Tech. degree in Mechanical Engineering from I.I.T. Mumbai in 1973 and joined the 17th batch of Bhabha Atomic Research Centre (BARC) Training School immediately thereafter. After completing the training, I joined Indira Gandhi Centre for Atomic Research (erstwhile Reactor Research Centre). After working for 15 years in the area of structural analysis and design of fast reactor components, I joined the Reactor Engineering Division of BARC in 1989. Subsequently I assumed the charge of Head, Reactor Safety Division and later Director, Reactor Design & Development Group. I retired in Sep 2014 after 40 years of service.

During my tenure at BARC I carried out extensive work in the areas of Nuclear Reactor Safety, Earthquake Engineering, Structural Integrity Assessment, Leak-before-break, Structural Analysis and Design, Fatigue, Fracture and Failure Analysis.

It so happened that around the time I joined BARC, there were quite a few failures in Indian Industry. For Root Cause Analysis as well as corrective actions, these were referred to BARC because of its eminence in structural analysis.

In this article I am going to talk about this single aspect of my work viz. Failure Analysis. This article is prompted by my reading of the book "The Mind of an Engineer" [1] in which many authors have pondered on the question whether the mind of engineer is different.

Dr. P.S. Goel in "Is an Engineer's Mind Different?" brings out that Engineer's mind ought to be different but most of our engineers do not possess that. Prof. Indranil Manna reflects on the dilemma "An Engineer or a Scientist?"

What better way than to learn from the Nobel Laureate Dr. Richard Feynman? After reading his memoirs *"Surely You're Joking, Mr. Feynman!": Adventures of a Curious Character"[2] and* "*What Do You Care What Other People Think? Further Adventures of a Curious Character"[3],* one comes to an inescapable conclusion that he was a Scientist with the mind of an engineer. One area where the mind of an engineer distinguishes itself is the aftermath of a failure. The question that bothers him is "What is the Root Cause of the failure?"

The two stories in the memoires "He fixes radios by *thinking!" and "*Mr. Feynman Goes To Washington: Investigating the Space Shuttle Challenger Disaster" are masterpieces of Failure Analysis.

Another aspect that assisted us in our Failure Analyses was our assimilation of the ASME Boiler and Pressure Vessel Code, Section III [4] "Rules for Construction of Nuclear Facility Components" where the guiding principles are "Design by Analysis" and "Failure Mode Orientation" as opposed to the conventional approach of "Design by Rule" which provides design formulas, curves, charts and design procedures, which set the minimum required thickness and once this major parameter is fixed, the designer simply follows the rules for detailing of components such as flanges, heads, nozzles etc.

The rational approach for design adopted in Sec. III consists of -

(i) Identifying various failure modes,

(ii) Identifying the parameter causing the failure mode and its critical value and

(iii) Separating the operating value of the parameter from its critical value by appropriate factor of safety

The key to the success in identifying the root causes in the case studies presented here lay in following the first two steps of this approach.

Case Study 1: Investigation of the Accident at a Gas Cracker Complex

Indian Petrochemicals Corporation Limited (IPCL) operated a gas based petrochemical complex at Nagothane near Mumbai, designed to produce 2.75 lakh tones of polymers. In Nov. 1990 there was an accident involving hydrocarbon leak followed by fire and explosion. A high powered Committee, headed by Dr. Mashelkar, constituted to investigate the accident, sought BARC's assistance in performing stress analysis of piping.

Process: A portion of the Ethane-Propane (C2-C3) feed to the cracker complex is diverted to Outside Battery limit (OSBL) plant where it is chilled and stored. Simultaneously the chilled liquid is sent back to main feed, exchanging heat with the incoming stream and getting preheated in the process. See Fig. 1 for Flow Sheet.

Incident: OSBL plant was being commissioned. First two stages of the four-stage chilling were commissioned successfully with chilling to -35 deg C. Ethylene refrigeration system was valved in for further chilling. Temperature dropped to -100 deg C. At that instant, massive leakage was observed forming a vapour cloud. There was an explosion followed by fire, extensive damage and loss of life. From the nature and spread of damage the source of initial leak could be pinpointed to one of the heat exchangers (HX 4 in Fig. 1).

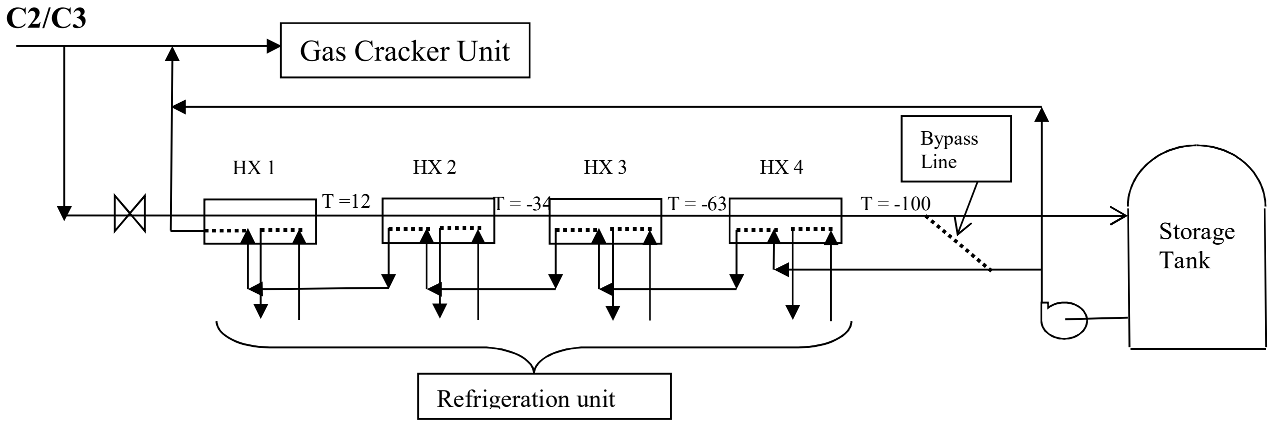

Fig. 1 Partial Flow Sheet

Investigation

While commissioning, a need was felt to isolate the Storage Tank and for this purpose a bypass line was provided across the tank. A doubt was raised about the effect of bypass line on the overall stress picture of the pipeline. However, a detailed stress analysis showed only a marginal change in the stresses.

Two probable causes were investigated.

Weld failure hypothesis

The weld joining the aluminium flange to the nozzle at the suspected leakage location was found to be ruptured and metallurgical examination showed poor quality weld with extensive interpass porosity. However stress and fracture analyses showed that even the poor quality weld should have survived the operating stress once it passed the hydrotest because the operating stress is lower.

Alternate hypothesis

The piping uses low alloy steel studs for joining an aluminium flange to a carbon steel flange. The studs were tightened at room temperature and temperature was then lowered. The differential contraction between the flanges and studs, caused by the large difference in thermal expansion coefficient of aluminium and carbon steel, led to reduction in the gasket compression which in turn caused leakage. In support for this hypothesis, the following extract from Appendix XII of ASME Code Sec. III [5] can be cited:

“DESIGN CONSIDERATIONS FOR BOLTED FLANGE CONNECTIONS

A decrease in bolt stress, below any that may be due to internal pressure, might occur in service during startup or other transient conditions, or perhaps even under normal operation. This can happen when there is an appreciable differential in temperature between the flanges and the bolts, or when the bolt material has a different coefficient of thermal expansion than the flange material. Any pronounced decrease due to such effects can result in such a loss of bolt load as to be a direct cause of leakage. In this case, retightening of the bolts may be necessary.”

The retightening or “Cold Bolting” was not followed in IPCL. In order to demonstrate that such a situation can indeed lead to leakage some tests were carried out in BARC.

Leakage Tests

Similar flange assembly containing air at pressure was immersed in methanol and leaktightness was demonstrated. Methanol was then cooled to -90 deg C by liquid nitrogen. Extensive bubbling of air observed demonstrating possibility of leakage.

Root Cause

In view of the two facts: i) The leakage quantity in the tests was not substantial and ii) Whether the failed weld was the cause of the accident or the effect could not be established; it was concluded that the root cause was probably a combination of both.

Corrective Actions

- Use studs made of stainless steel whose coefficient of thermal expansion is between those of aluminium and low alloy steel. This reduces the differential contraction.
- Follow ‘cold bolting’ practice strictly i.e. tighten the studs after temperature change
- Tighten the specifications for non-destructive examination of nozzle weld

With these modifications, the plant was rebuilt and has been operating satisfactorily.

Case Study 2: Failure Analysis of Methanol Converter Vessel

Deepak Fertilizers and Petro Chemicals Ltd is one of the largest producers of Methanol in India with an installed capacity of 1,00,000 MTPA at Taloja, near Mumbai.

Deepak’s low pressure methanol plant was built with know-how derived from ICI via one of ICI’s licensees, Davy. The plant was built between January 1988 and September 1991. It was commissioned in October 1991.

Process

- Synthesis gas ($CO + CO_2 + H_2$) enters the vessel through the bottom head (See Fig. 2)
- Rises through the tubes acting as a cooling medium and getting preheated in the process
- Descends through the catalyst bed with following reactions

$$CO + 2H_2 \Rightarrow CH_3OH + 91\ \text{kJ/mole}$$

$$CO_2 + 2H_2 \Rightarrow CH_3OH + H_2O + 50\ \text{kJ/mole}$$

- Other possible reactions

$CO + 3H_2 \Rightarrow CH_4 + H_2O +$ 209 kJ/mole

$2CO + 2H_2 \Rightarrow CH_4 + CO_2 +$ 252 kJ/mole

Design Data

• Diameter	2270 mm
• Thickness	39 mm
• Thickness of hemispherical ends	39 mm
• Design pressure	90 kg/sq.cm
• Operating Pressure	78 kg/sq.cm
• Design temperature	325 deg C
• Operating Temperature	325 deg C
• Material	2.25 Cr- 1 Mo steel

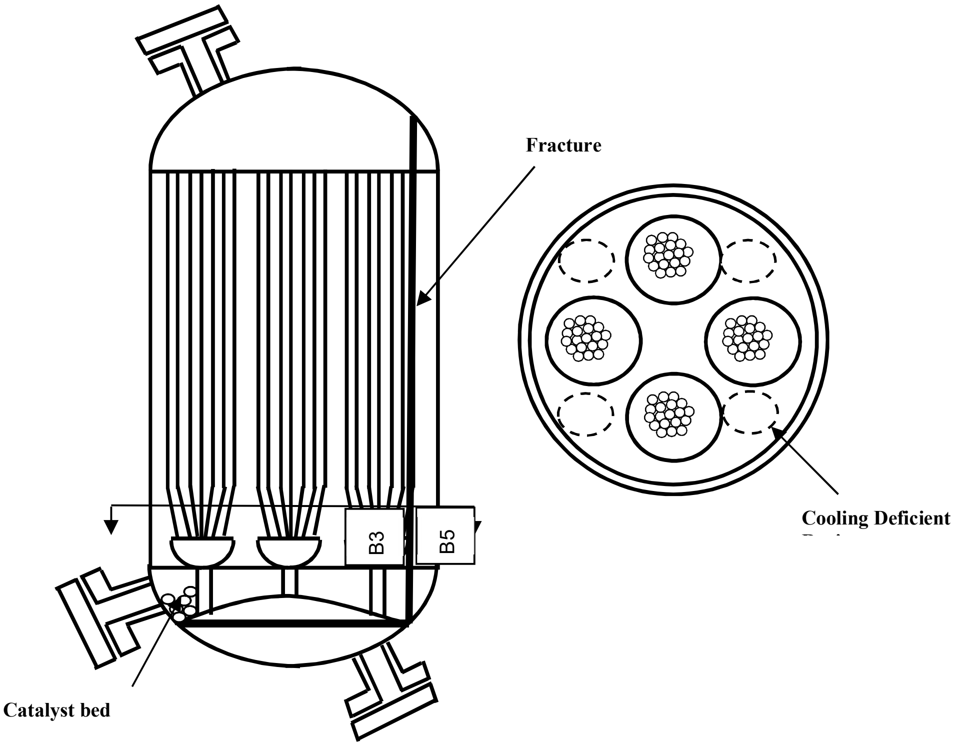

Fig. 2 – Schematic View of Methanol Converter Pressure Vessel

Incident

After about one year of operation, the 2.27 m diameter methanol converter vessel, designed for 90 Kg/sq.cm internal pressure and operating at 325 C, failed catastrophically. The vessel had split open and after flinging its contents, was catapulted to a distance of 80 meters.

Investigation

- The failure was investigated from the following angles:
  - Stress Analysis
  - Fracture Mechanics evaluation
  - Metallurgical studies
  - Process Analysis
- Various hypotheses were postulated and examined in detail

Different hypotheses examined

Postulate	Investigation	Result
Gross material error	Chemical analysis	Ruled out
Error in heat treatment	Tensile tests	Tests show low strength near B3, B5 (See Fig. 2) but not low enough to fail at op. pr.
Gross design error	Stress analysis	Ruled out as Codal limits were satisfied
Material defect	Fracture mechanics evaluation	Critical crack size depth = 19 mm, length = 130 mm, Too large to escape detection
Overpressure	Burst pressure calculation	Burst pressure = 259 kg/sq.cm against design pressure of 90 kg/sq.cm Pressure record does not show any increase
Internal explosion	Examination of fracture edges	Occurrence of bulge and extensive thinning suggests slow deformation
External overheating	Burst pressure vs. temp. calculation	Temp. required for burst at operating pr. is ~ 700 deg C. Requires sustained fire
Internal overheating	Burst pressure vs. temp. calculation	Temp. required for burst at operating pr. is ~ 700 deg C. Possibility of local temperature rise due to methanation reaction

Findings – Accident Progression

- Due to the degraded catalyst, a part of the vessel was operating at a higher temperature
- This portion of the vessel was supporting methanation
- Sustained high temperature resulted in lowering of strength
- The temperature reached the threshold for a runaway methanation reaction.
- Local temperature rose to a value at which the UTS of the material was exceeded.
- Bulging and thinning followed by rupture near B3, B5
- Unstable crack propagation through the length of the vessel

Root Cause

- The failure was due to a local temperature excursion due to methanation reaction.

Lessons learnt

- Consider worst case scenario i.e. runaway methanation reaction and guard against the same
- Detect onset of instability by measurement of temperature at proper locations
- Provide adequate margin between design and operating parameters

Corrective actions

- Avoid areas of cooling deficiency
- Temperature measurement at more locations
- Change the catalyst bed if it results in higher temp.

The plant has been rebuilt with these changes and has been operating satisfactorily.

Case Study 3: FAILURE ANALYSIS OF A NAPHTHA STORAGE TANK

Incident

In November 1988, a fire occurred on a naphtha storage tank (11 m dia x 8 m height, Fig. 3) of BPCL Refinery at Mumbai. The tank roof ruptured releasing a large amount of hydrocarbon vapour spread over an extended area and ignited; causing considerable damage and loss of life.

Design inadequacy was suspected to be the cause and in order to check this possibility, M/s BPCL had asked BARC to perform stress analysis of the tank and also carry out strain gauge instrumentation during a burst test they had planned to carry out.

Investigation

- Theoretical stress analysis was carried out using finite element method. [Fig. 4]

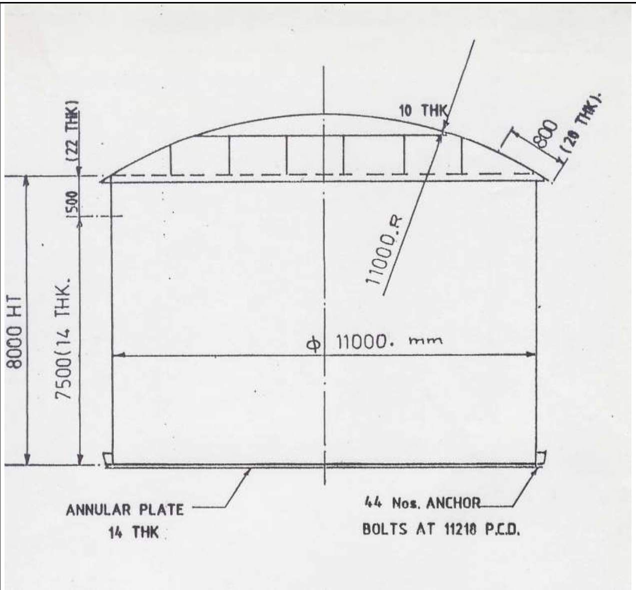

Fig. 3 – BPCL Tank Geometry

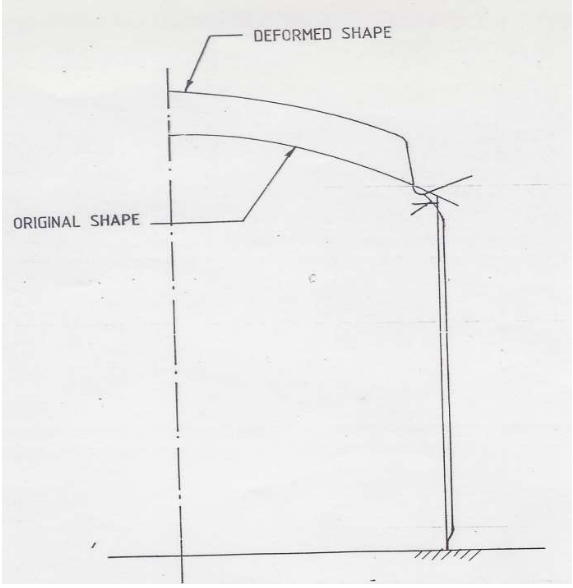

Fig. 4 - Deformed shape

The results showed significant deformation at the shell-roof junction and consequent localized yielding, which commenced at a pressure of 0.6 kg/sq.cm. However, this is permitted by the codes and the tank, as designed, was safe for the design pressure of 1.0 kg/sq.cm.

BPCL carried out a burst test on a similar tank. The tank and the roof were instrumented with strain gauges. The tank was gradually pressurized and the strain gauge readings were taken at regular intervals. The measured and the calculated strains compared very well. Strain Gauges showed non-linearity at 0.6 kg/sq.cm pressure indicating initiation of yielding.

The tank actually failed at a pressure of 3.2 kg/sq.cm, indicating a factor of safety of 3.2 over the design pressure.

Root Cause

- Failure was not due to any inadequacy in design
- Further investigation revealed that the tank was overfilled and consequentially over pressurized because of the faulty indication by tank level gauge.

Lessons Learnt and Corrective Action

- Follow code rules for pressure relief
- Avoid overpressurization during filling

Case Study 4: Damage to Internal Shells of Exchange Tower in Heavy Water Plant

Heavy Water Plant at Baroda is based on monothermal hydrogen ammonia exchange. The synthesis gas which contains about 115 PPM of Deuterium is passed through isotopic exchange tower 12T1, operating at 640 kg/sg.cm. pressure and -20 deg.C temperature In the presence of catalyst, potassium amide, deuterium from feed gas is transferred to liquid ammonia which is further enriched and processed for heavy water production. Exchange Tower-12T1 is a multiwall construction having outside dia 2660 mm and length 3122 mm and a thickness of 329 mm and weighing around 530 MT. Tower has 12 exchange stages

Incident

During the annual shut-down in April-May 1991, tower was opened for maintenance; after it was depressurised purged and made ready for opening as per the procedure laid down for the purpose. Accordingly, the cover of the tower was lifted, kept aside and cable stage removed. When tower stages were removed one by one, stages 6th, 7th and 8th were found to be damaged. The damage was in the form of a 75 mm deep dent in each of the three shells. [6] (Fig. 5)

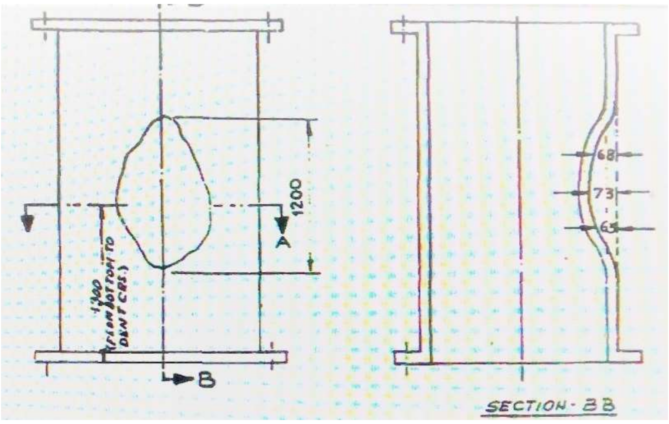	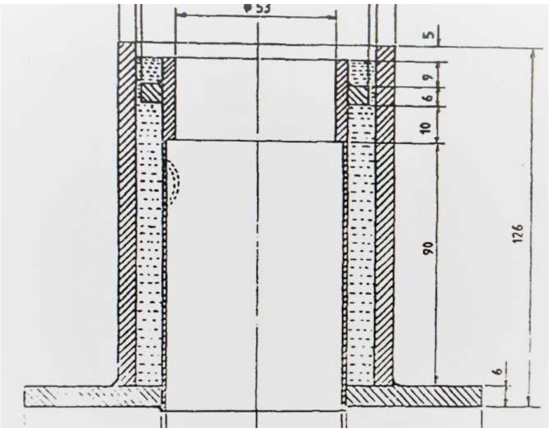
Fig. 5 - Dent on Stage No.6	**Fig. 6 - Model for Simulation of Denting**

Investigation

Causes such as explosion in the annular space, high differential pressure, mechanical damage due to impact during handling, explosion etc. were investigated but were found to be untenable.

During investigation it was discovered that a lot of water was sprayed inside the tower to wash residual ammonia. A postulate that the dents occurred because of freezing of water in the annular space was investigated analytically as well as experimentally. Although it could be verified that the quantity of water sprayed was sufficient to fill the annular space and had in fact frozen (the temperature was below zero deg C); it was difficult to believe that a 30 mm thick shell could be damaged by this mechanism. To verify this, a scaled model of the tower-shell assembly (Fig. 6) was filled with water and put in a refrigerator. Next day, when the water in the annular space had frozen, the same dent appeared in the model. Thus it was conclusively demonstrated that this was indeed the cause.

A fitness-for-purpose evaluation was also performed using finite element method. It was found that for the intended service, the shells could be used without repair. The tower has since been put back into service and has been operating satisfactorily.

Lessons learnt

This is a textbook case. We have read about bursting of water-carrying pipes during winter. The lesson has been relearnt.

Case Study 5: Collapse of Dome of Kaiga Atomic Power Station during Construction

The containment building of a nuclear reactor houses the reactor, primary coolant and moderator systems, and other systems related to steam generation. Its function is to contain the radioactivity release in the event of a postulated Design Basis Accident so that the radiation level in the environment is within acceptable limits.

The reactor building of the Kaiga Atomic Power Project, Unit-1 (Kaiga-1) has full double containment with an annular gap of 2.0m between inner (primary) and outer (secondary) containment structures (Fig. 7).

The inner containment (IC) structure was designed as a prestressed concrete cylindrical shell (42.56m diameter and 610mm thick) capped with a pre-stressed concrete dome having 340mm thickness.

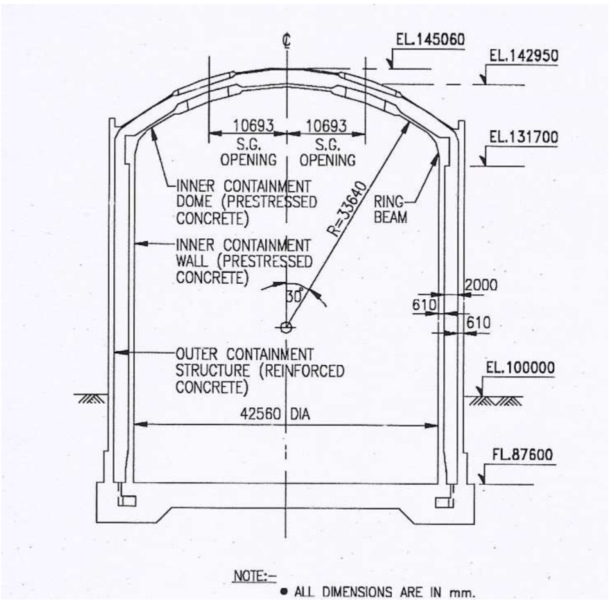

Fig. 7 – Cross Section of Containment Structure

Incident

On 13 May 1994, the inner containment dome of unit 1 of the Kaiga nuclear power plant collapsed during reactor construction. The dome itself had been completed but cabling and other tasks were being carried out. The failure was in the form of delamination. The under surface of the dome in the central portion delaminated and fell down completely. However, the upper portion had sufficient strength to hold itself in position under the action of its self-weight and whatever super-imposed load it had on it [7, 8].

Investigation

The nature of the delamination indicated that it occurred due to the action of radial tensile stress. For the normal operating condition involving dead weight and prestress, there is no external load which will cause net radial tensile stress; which is also the reason for not providing any radial reinforcement.

However, presence of local radial tensile stresses could not be ruled out; one of the sources being the stress concentration effect near an opening, Fig. 8.

Since these radial tensile stresses are localized in nature, there was hesitation in concluding that delamination was caused by them. In order to demonstrate that the radial stresses due to the stress concentration can indeed lead to delamination; an experiment was conducted using a Perspex sheet with two holes drilled into it (Fig. 9). The sheet can be visualized as a slice of the containment dome with the two holes simulating the sheath holes. The compressive load generated by the cables running transverse to the holes was simulated by clamping the sheet in a vice. On application of compressive load the ligaments between the holes and between the holes and the edges cracked, demonstrating the ability of the radial stress to cause cracking. The sheet however, remained as a single piece showing the secondary nature of the radial stress which disappeared on cracking.

Notwithstanding the difference between the two materials viz. concrete and Perspex, the experiment did show the possibility of delamination, in principle. The process of delamination is aided by short spacing between the two openings, which was the case at the location of delamination.

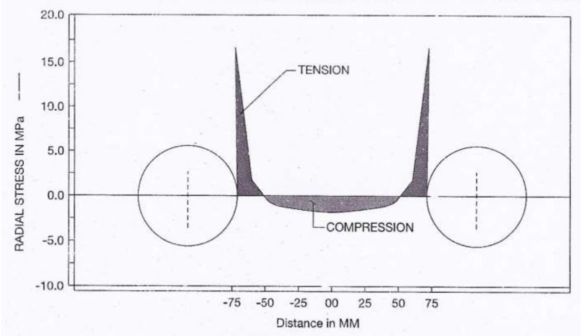

Fig. 8 – Radial Stress Distribution Near Penetrations

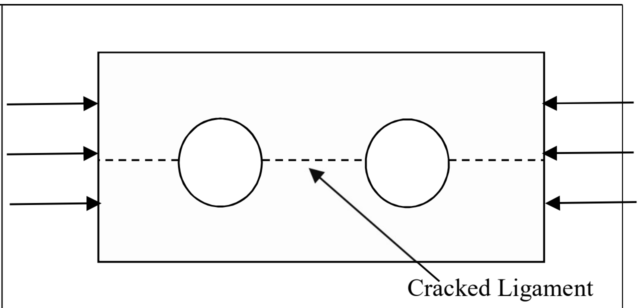

Fig. 9 – Simple Experiment to Demonstrate Delamination Phenomenon

The fact that the sheet remained as a single piece showed that delamination alone may not lead to falling of the delaminated portion. That requires application of external load which will cause radial stress. In case of Kaiga dome, the hooks embedded in the dome were being used to lower the shuttering members. This created the radial stress which tended to separate the delaminated layers.

Root Cause

A detailed stress analysis which included the local changes in thickness and the openings for prestressing cables indicated occurrence of local radial tensile stresses because of some additional phenomena:

1. The in-plane compressive membrane stresses also generate radial stress near the hollow sheath in the thickness of shell due to stress concentration effect, as brought out earlier
2. The curved prestressing cables exert pressure towards centre leading to development of radial stress
3. The radial stress is also generated where the shell thickness changes within a short distance

    These radial stresses coupled with congestion caused by large quantity of reinforcement and closely spaced prestressing cables were identified as root causes of the failure.

Follow up

As a result of the investigation, a number of recommendations had been made for re-engineering of the delaminated dome [7]. Some of the major recommendations were:

(1) The intact portion of the dome to be demolished; extent depending on detailed examination
(2) Measures to be taken in design:
    a) increase of general thickness of dome from 340 to 470 mm;
    b) to minimize the induced radial tension in the transition zones, the dome thickness to be increased gradually to the higher value of the thickened portion around the SG openings;
    c) introduce radial reinforcement;
    d) increase in minimum cable spacing from 108 to 225 mm to avoid congestion

After incorporating the above, the dome was reconstructed and the inner containment structure was accepted after successful pre-commissioning proof test for structural integrity and leakage rate tests.

Epilogue

At this point, I revisit “Mind of an Engineer” [1] and refer to Dr. P. Ghosh who has aptly said “Engineers have a mind of a polymath: someone who knows something about everything and everything about something". The failure analyses described herein required exactly that kind of mind with *some* knowledge about many things and *expertise* in the core domain of structural analysis.

I hope I have been able to provide a glimpse into the mind of an engineer. The journey, though prompted by some unfortunate incidents, has been fruitful in the sense of providing answers. To borrow from Dr. Ghosh [1] again, "Mistakes strengthen engineers' self-confidence". It is hoped that the Root Cause Analyses and follow up recommendations did achieve that purpose.

There are many quotations on failure, especially ones pointing out how it is the path to success. But that hinges on Root Cause Analysis and the follow up. That is why I have named this article "There is Knowledge in Failure – If Followed by Root Cause Analysis"

In a Root Cause Analysis one can ponder over the question "How far should one go in finding the Root Cause"?

In engineering terms, it would suffice to identify "use of improper material" as root cause. But one can go deeper and identify "Lack of Quality Control in Design" or "Inadequate Knowledge" or "Improper Education/training" as the root cause.

That reminds me of a lecture on Failure Investigation which I attended. The excellent lecture was followed by a Question & Answer session. When I asked this question about where to stop in Root Cause Analysis, the lecturer admitted that the chain may indeed become too long to be meaningful. He cited the example of Challenger Disaster where the chain led to White House because of the instructions to fly the shuttle by certain date!

Acknowledgment

In all of these failure investigations the investigating team was necessarily a multi-disciplinary one and consisted of: K.K. Vaze, V. Bhasin, K.M. Prabhakaran, D. Munshi, L.M. Gantayet, H.S. Kushwaha, A.R. Biswas, B.K. Shah, P.R. Vaidya, P.G. Kulkarni, S.C. Mahajan and Dr. A. Kakodkar

As a postscript, I would also like to acknowledge the role played by the BARC work culture in my career. The complete absence of adherence to hierarchy was exemplified by the panel on the door of our boss Dr. Kakodkar, which proclaimed "Disturb". One could walk in with your problems and be sure to get a patient hearing or walk in with suggestions and be sure to get an enthusiastic audience. The willingness of others to share the knowledge/expertise was also contagious and if I were to summarize my innings in one sentence, it would be a quotation: "Choose a job you love, and you will never have to work a day in your life." I loved everything I did during those 40 years, it was done in the most congenial atmosphere and I did not have to *work* for even a day.

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