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# Fracture Testing and Analyses of Piping Components at Elevated Temperature under Bending Moment

**M. K. Sahu[1], J. Chattopadhyay, B.K. Dutta, K. K. Vaze**

Scientific Officer, Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai, India
[1](mksahu@barc.gov.in)

## ABSTRACT

In order to study the effect of high temperature on the fracture behaviour of the piping components used in PHT (Primary Heat Transport) piping of Indian PHWRs, fracture test were conducted on two pipes of carbon steel, SA333Gr6. Two pipes of nominal diameters of 219 mm and 406mm, having circumferential part through notch, have been tested under monotonic bending and at elevated temperature of $300^{o}$C. Different experimental results have been recorded during experiment relevant to test. Any crack growth has not been detected till last loading point. Hence the governing failure criterion for these pipes is the NSCL (Net Section Collapse Load Criterion) not the fracture mechanism. Subsequently, three dimensional finite element analyses (FEA) have been performed for both the pipes. The experimental and FEA results have been compared. The present difference in the experimental and FEA results have been discussed in the light of prevalent temperature distribution, during the testing.

## INTRODUCTION

The piping components are an integral part of all types of power plants. These pipes are used for extracting the heat from heat generation unit by coolants. These coolants are then transferred through these piping components to steam generators for steam production. These are exposed to different type of operational loading like thermal stresses, internal pressure and self weight, etc. During earth quake, these pipes are primary subjected to bending moment and its integrity assessment under bending moment has been important criterion for smooth running of power plants. For ensuring integrity of pressurized piping components, Leak Before Break (LBB) criterion is a well established criterion. For LBB qualification, credible test data is required. To address these issues, a Component Integrity Test Program was planned by Bhabha Atomic Research Centre (BARC), India in 1998. Under this program large numbers of straight pipes and elbows with and without cracks, had been tested under pure bending moment in Structure Engineering Research Centre (SERC), CSIR (Council of Scientific and Industrial Research), Chennai [ Chattopadhyay et al.]. The material of PHT (Primary Heat Transport) piping of Indian PHWRs is carbon steel, SA333Gr6. Since the pipes are subjected to internal pressure of reactor pressure (≈10MPa) and reactor temperature (≈$300^{o}$C) under plant operation condition. Hence to address the reactor operating conditions on the integrity of piping components, an Advanced Component Integrity Test Program was initiated by BARC in 2004. Under this program, few straight pipes and many elbows have been tested. In this program, two straight pipes have been tested under bending moment at elevated temperature of $300^{o}$C. Different experimental results like total load, Load Line Displacement (LLD), Crack Mouth Opening Displacement (CMOD), etc were monitored and recorded during test. The three dimensional Finite Element Analysis (FEA) have been performed to simulate those tests and different experimental and FEA results have been compared.

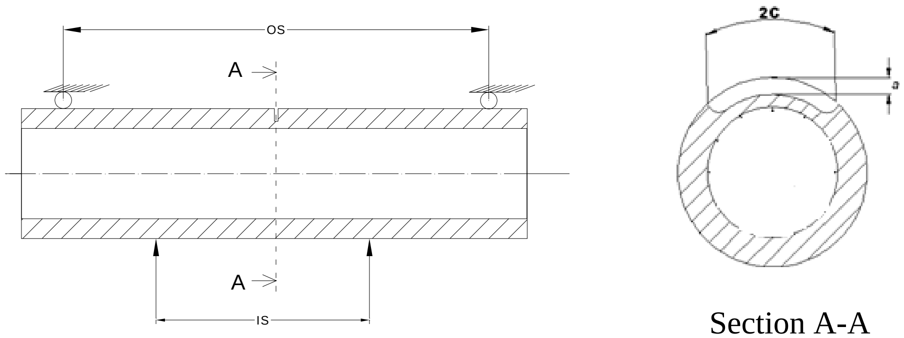
## FRACTURE TESTING OF PIPES

### *Test Specimens*

Both straight pipes have been fabricated with outside part throughwall circumferential cracks. Nominal diameters of these pipes are 8 inch and 16 inch. Relevant dimensions of pipes are shown in Table 1. The loading configuration is shown in schematic diagram in Figure 1 (a). Crack configurations are shown in Figure 1(b). Both pipes have been fatigue cracked to produce very sharp crack from machined crack. The maximum cyclic load was 20% of the predicted collapse load while minimum cyclic load corresponds to 10% of the maximum cyclic load. The cyclic load was applied using computer controlled servo-hydraulic actuator. The cyclic load was applied till the crack growth was approximately 2-3mm.

Table 1: Dimensions of Pipes.

| Test | Outer Diameter (mm) | Thickness (mm) | Outer span (mm) | Inner span (mm) | Crack length(2C) (mm) | Crack Depth (After fatigue pre cracking) (a) (mm) |
|---|---|---|---|---|---|---|
| TSPPTC8-1 | 219 | 18.8 | 4000 | 880 | 65 | 8.5 |
| TSPPTC16-1 | 406 | 26.9 | 5000 | 1620 | 134.5 | 16.14 |
| Test | Outer Diameter (mm) | Thickness (mm) | Outer span (mm) | Inner span (mm) | Crack length(2C) (mm) | Crack Depth (After fatigue pre cracking) (a) (mm) |



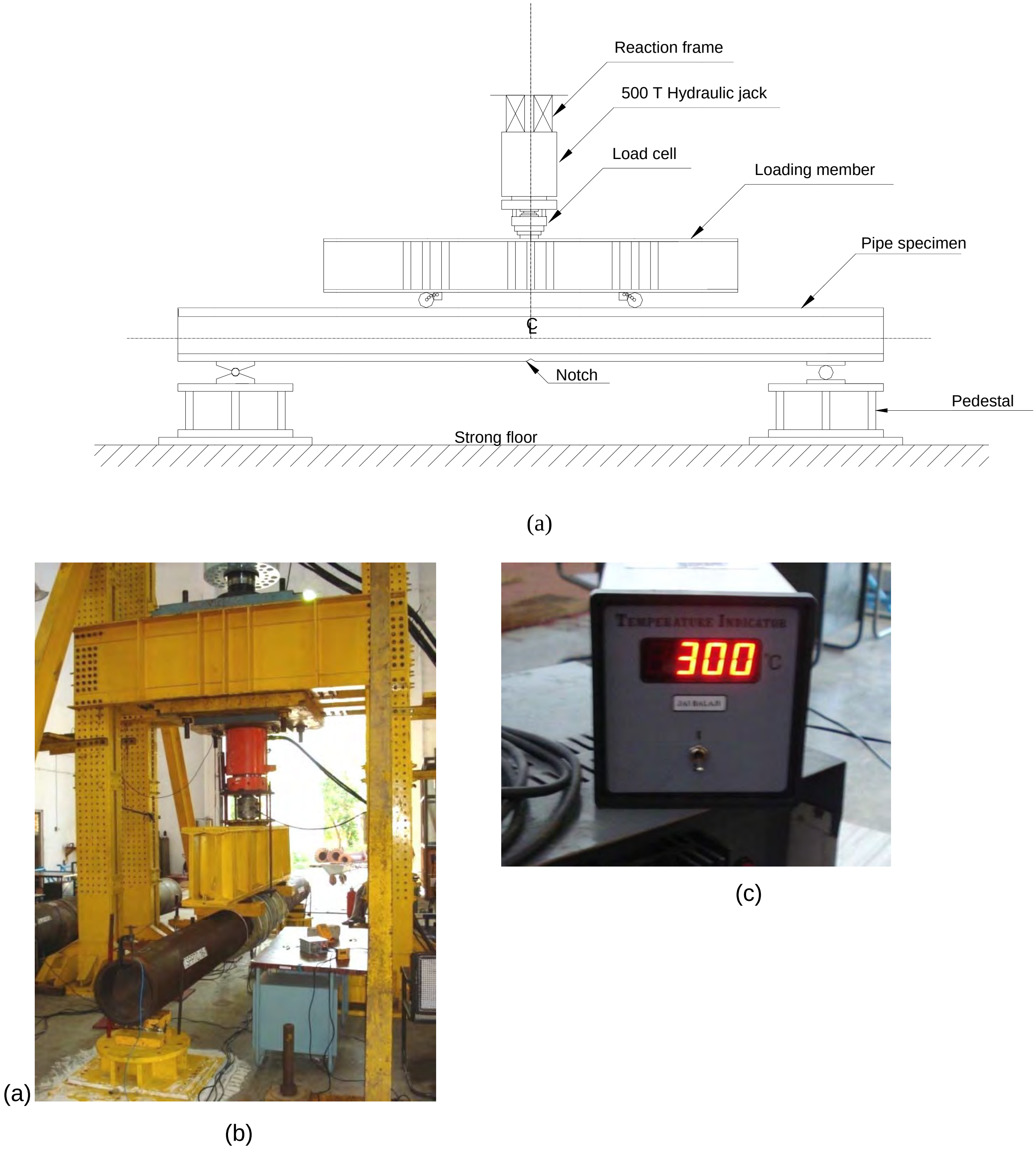
Section A-A

(a) (b)

Figure 1: (a) Schematic diagram of pipe showing IS (Inner Span) and OS (outer span). (b) Schematic diagram of surface crack for pipes.

***Test arrangement***

Fracture test have been performed under four point bending; TSPPTC8-1 and TSPPTC16-1 pipes, were conducted using a 5000kN capacity PROCEQ hydraulic jack. Figures 2(a) and 2(b) show schematic diagram and real image respectively, of the typical test set up for fracture test of pipes. Figure 2 (c)



(a)

(a)

(b)

(c)

Figure 2: (a) Schematic diagram of test set up. (b) TSPPTC16-1 subjected to combined loading of four point bending and constant internal pressure. (c) Test temperature is shown.

depicts that the test temperature is maintained at 300°C during entire testing. A hinge support was provided at one end and roller support at other end. Steel pedestals were used for supporting the pipe. A distribution beam with roller was used for applying two concentrated loads on the pipes over a distance i.e. inner span. The hydraulic jack/actuator was connected to the distribution beam by the suitable plates and tie rods. Details are available in [Saravanan et al.]. The hydraulic jack system consisted of an external Linear Variable Displacement transducer (LVDT) for measuring load-line displacement and a load cell for measuring the applied load. The actuator system consisted of an in-built LVDT for measuring load line displacement and a load cell for measuring the applied load.

### *Heating Arrangement*

For heating the pipe at the notch location, the notch portion of the pipe was wrapped with heating elements covered with ceramic cloth. Above this insulation material was provided to prevent heat loss. This arrangement can be seen in Figure 2 (b). Temperature regulators were used for setting the required temperature and maintaining the same throughout the test. The temperature was measured with regular intervals with a non contact type laser based temperature measuring instrument. In addition, thermocouples were also used to measure the temperature

### *Loading*

A static and monotonic load is applied on the pipe specimens under displacement control. The rate of displacement was fixed at 0.05mm/sec. Since the actuator has the maximum displacement of 130mm, the test is stopped manually after the maximum displacement of 130mm. The test is again continued after adjusting the displacement of the actuator using manual control and by providing packing plates at the loading points.

### *Instrumentation and data acquisition*

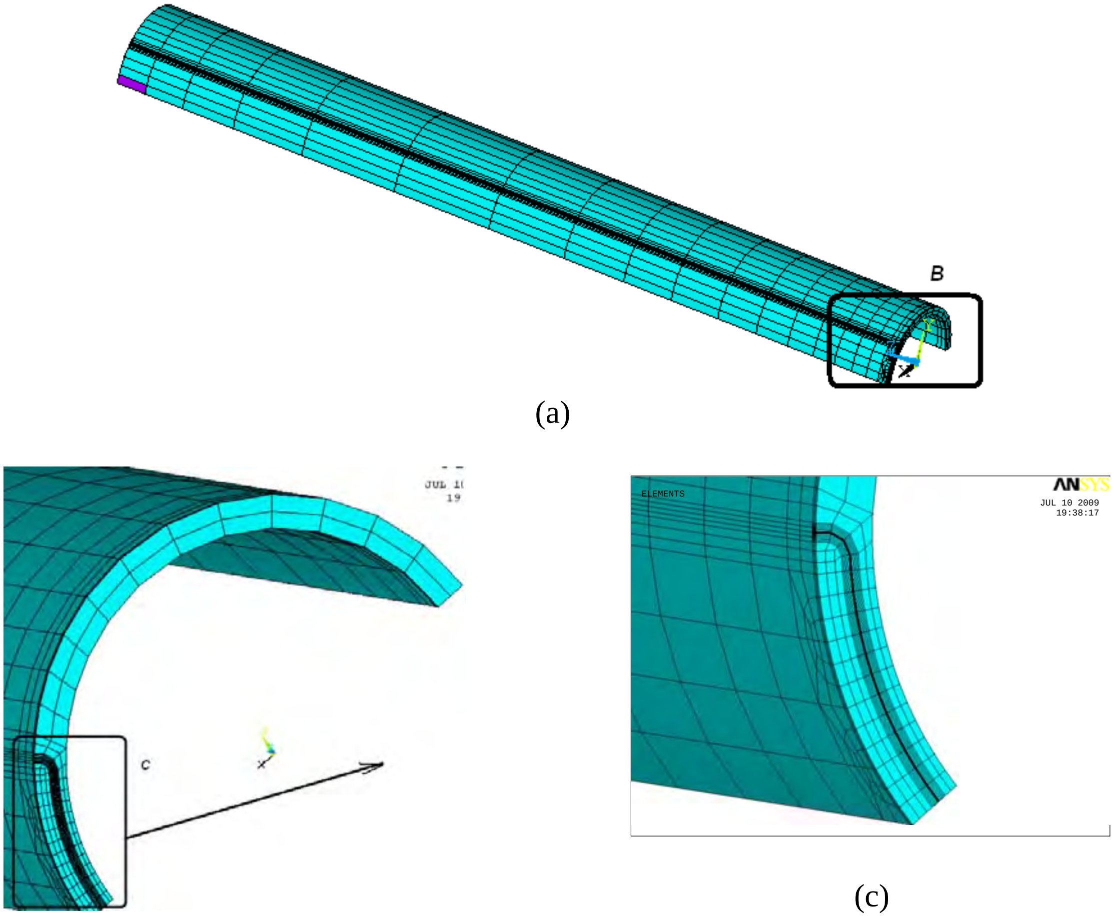
Different instrumentations are mounted on test configurations for monitoring and recording different experimental results like total applied load, CMOD, LLD, crack growth, strains, etc. The inbuilt strain gauge based load cell in the actuator is used for knowing total applied load while inbuilt LVDT is used to know total displacement of actuator. CMOD is measured by specially fabricated clip gauge that is fitted to the centre of crack. Deflection of pipe at different typical location is measured by installed LVDT. Crack growth in the fracture test of piping components is measured by the Alternate Current Potential Difference (ACPD technique. Steel pins of 1 mm diameter were spot welded at regular intervals of 10mm along the notch length. These pines were connected to the crack micro-gauge. During the fracture test, the readings were taken of ACPD at regular intervals of loading which is post processed later for crack growth data.

## THREE DIMENSIONAL FINITE ELEMENT ANALYSES:

### *Finite Element (FE) Model*

The 3D- elastic-plastic FEA were performed for both test cases. Due to symmitricity in the geometry and material only one fourth of pipe is needed to be modelled. At symmetric planes, appropriate constraints are applied to fix the planes. Very fine mesh is adopted near crack front to capture the steep gradient of stress and strain near crack front.

Figure 3 depicts the typical detail mesh of crack front. The isoparametric 20-noded brick element is adopted in the models. Reduced order of integration ($2\times2\times2$) is used to eliminate artificial locking under incompressibility condition imposed by plastic deformation. The finite element analyses are done under displacement control to simulate the actual testing. Non-linear material behaviour is modeled using incremental plasticity with Von Mises yield function associated flow rule and isotropic hardening. The true stress vs. strain data obtained from the testing of standard tensile specimen at elevated temperature of 300oC from same piping material is incorporated in the FE model.



(a)

(b)

(c)

Figure 3: (a) Finite element mesh used for pipe having part throughwall crack (b) zoomed on region B. (c) Detailed crack front meshing in the region C.

### *Material Parameters:*

Tensile specimens have been machined from the 16 inch piping material (SA333Gr6 Carbon Steel) is shown in Figure 4. Table 2summarizes the material properties [Singh et al.]. The true stress-strain data derived from the uni-axial test is fitted in the Ramberg Osgood equation (1) and the constants are given in Figure 4.

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left(\frac{\sigma}{\sigma_0}\right)^n \qquad (1)$$

Where, $\sigma_0$ and $\varepsilon_0$ are the value of true stress and strain at the yield point. $E=\sigma_0/\varepsilon_0$, $\alpha$ is a constant and n is the strain hardening exponent.

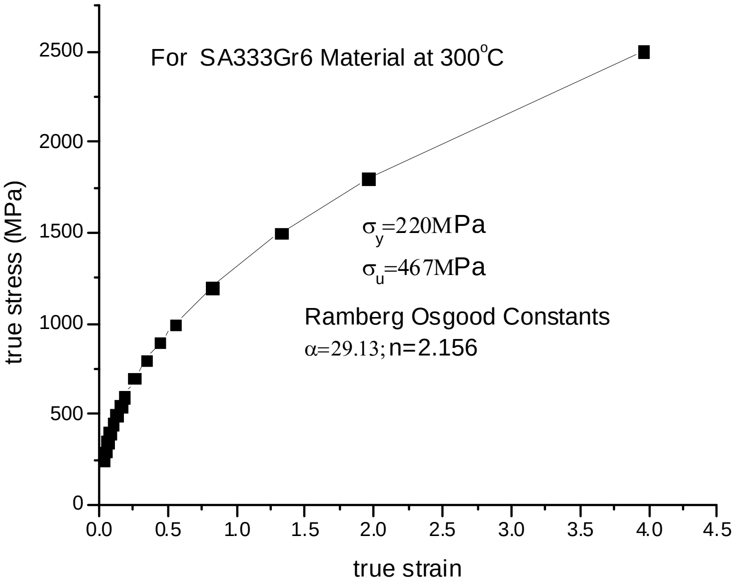


Figure 4. True stress-strain curve obtained from tensile specimen machined from the pipe

Table 2: mechanical properties of piping material (SA333Gr6 steel) at 300°C

| | |
|---|---|
| Yield Strength, $\sigma_0$ | 220MPa |
| Ultimate Tensile Strength, $\sigma_u$ | 464MPa |
| Young's modulus of elasticity, $E$ | 183GPa |
| Poisson's Ratio, $\nu$ | 0.3 |

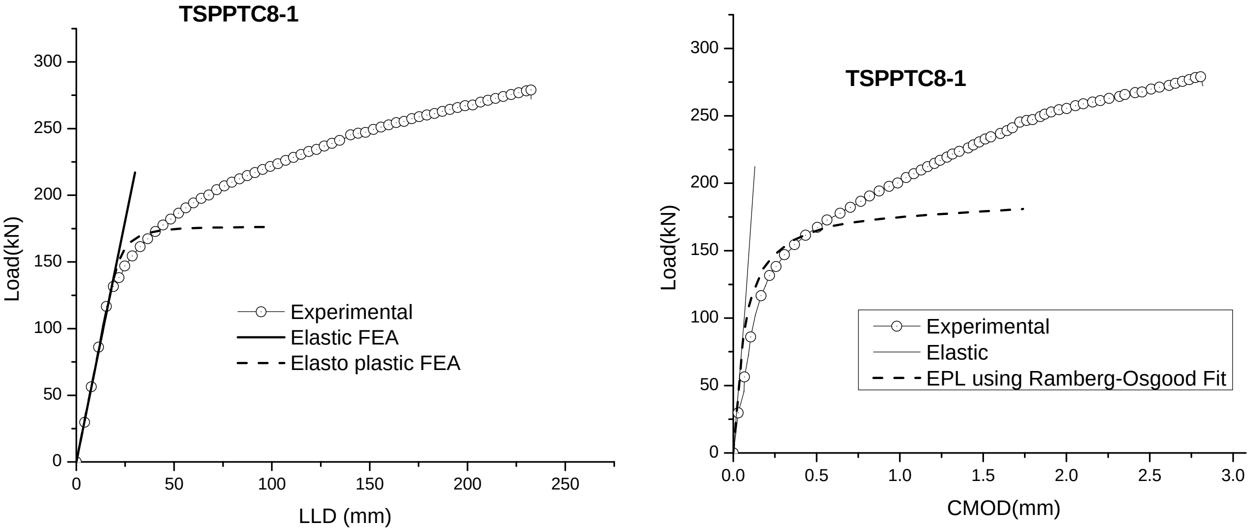
## RESULTS AND DISCUSSION

### *Comparison between experimental and FEA results for pipe*

Figure 5 (a) depicts the comparison of load vs. load-point displacement data predicted from finite element analysis with the experimental result for TSPPTC8-1. Load vs. load-point displacement is showing good agreement between FEA results and experimental result in linear loading part. After LLD of 50mm, the results are deviating from experimental results. After deviation, the FEA result is reaching to an asymptotic value, while experimental result are increasing continually or in other words it is keeping constant positive slope. Similar trend is also observed in the plot of load vs. CMOD as shown in Figure 5(b).

This deviation may be due to difference in the temperature distribution under experimental condition and FEA modelling. The heating elements were wrapped upto some distance and then rest portion of pipe is exposed to environment. So there must be a gradient in the temperature distribution along length and it must be varying from 300°C to some definite temperature. While FEA analysis is performed assuming that the whole pipe is maintained at 300°C. Hence to investigate this issue, an identical analysis is performed with the material properties of SA333Gr6 at room temperature [Tarafder et. al.] given in Table 3 and Figure 6(a). The corresponding load vs. LLD plot is depicted in Figure 6(b). It can be observed that asymptotic load value is shifted upward from 175kN to 230kN. From this study it can be concluded that the better agreement in non linear region can be achieved by changing the material properties from 300°C to room temperature along length when one moves from notch to the end of pipe.

Figure 7(a) shows the load vs. LLD data computed by FEA and experiment for TSPPTC16-1. They are in agreement in the elastic regime and beyond LLD value of 90mm. Similar trend can be observed in the plot of load vs. CMOD data as shown in Figure 7(b). This deviation between FEA and experimental results may be due to local overheating of the notch of pipe.



(a) (b)

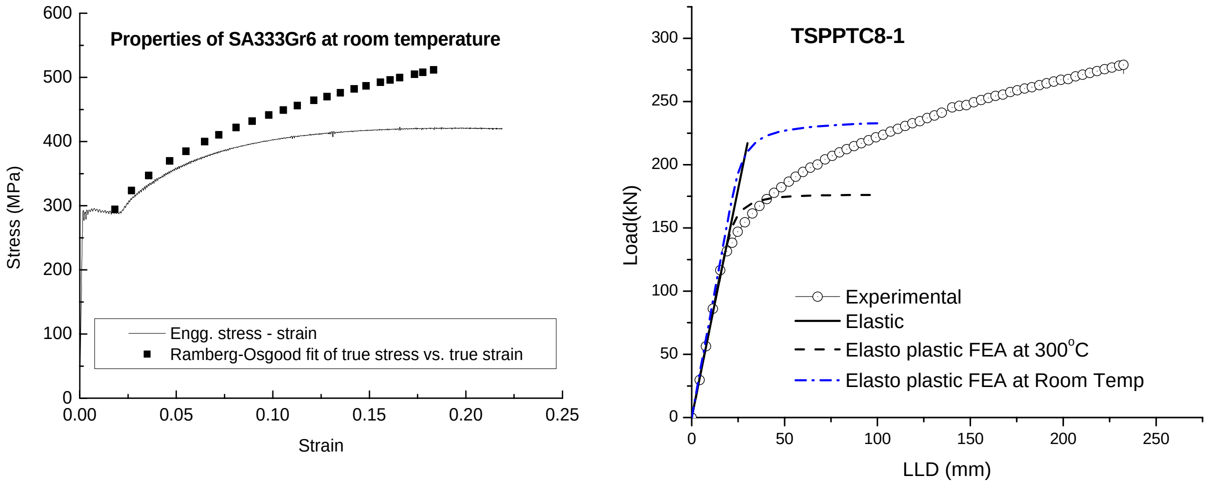
Figure 5. Comparison between experimental and FEA results for TSPPTC8-1. (a) Load vs. load line displacement data. (b) Load vs. CMOD data

Table 3: Mechanical properties of piping material (SA333Gr6 steel) at room temperature

| | |
|---|---|
| Yield Strength, $\sigma_0$ | 288MPa |
| Ultimate Tensile Strength, $\sigma_u$ | 420MPa |
| Young's modulus of elasticity, $E$ | 203GPa |
| Poisson's Ratio, $\nu$ | 0.3 |

### *Observation of crack propagation*

For both of the pipes there was no crack initiation till the final loading. Because of lower yield stress at 300oC, the crack tip is blunting because of higher amount of plastic deformation than the condition of room temperature. Hence it can be stated that the governing failure criterion for these pipes will be NSCL (Net Section Collapse Load Criterion) and not the fracture mechanism. Maricchiolo et al have already performed fracture tests on straight pipes with circumferential throughwall cracks at elevated temperature of 300°C. These pipes were also subjected to monotonic loading and the material investigated was A106B carbon steel. Test showed that pipes with small crack or no crack at all, behave as predicted by NSCL (Net Section Collapse Load Criterion). SA333Gr6 pipes having part through circumferential crack can be equalized with the pipes with smaller circumferential throughwall cracks. Hence this finding is in agreement with the literature.



(a) (b)

Figure 6. (a) Stress and strain data at room temperature for PHT piping material. (b) Comparison between experimental and FEA results of Load vs. load line displacement data for TSPPTC8-1.

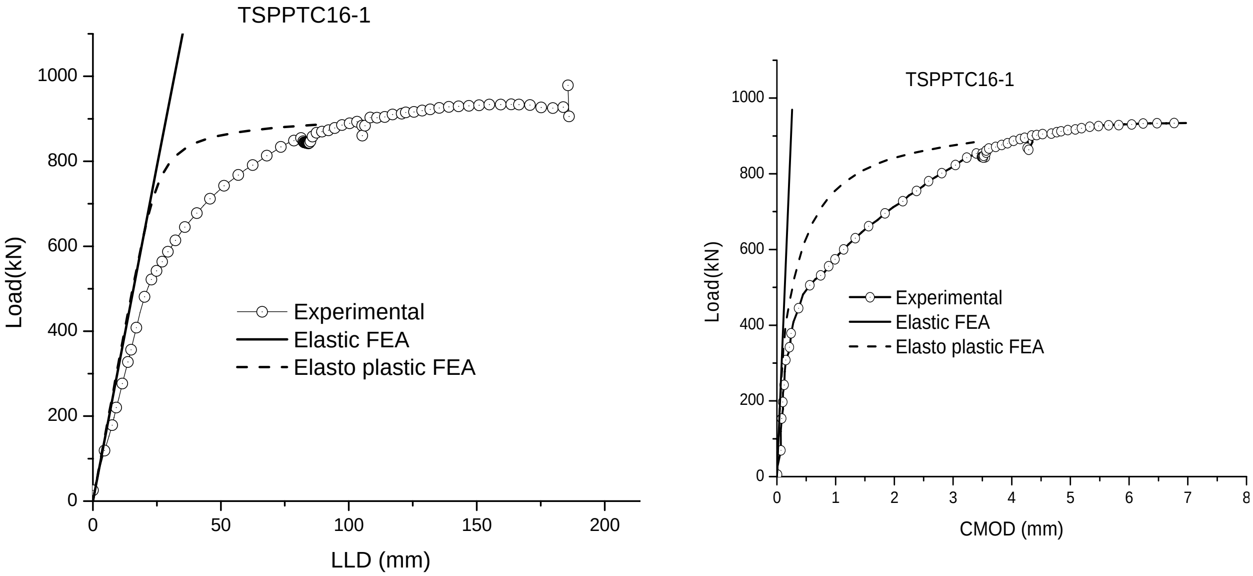


Figure 7.Comparison between experimental and FEA results for TSPPTC16-1. (a) Load vs. LLD data. (b) Load vs. CMOD data

## SUMMARY AND CONCLUSIONS

The following points may be summarized and concluded from this experimental and FEA study:

- Fracture test were conducted on a two numbers of 8 inch diameter pipe and a 16 inch diameter pipe with a part-through crack at outer surface.
- These pipes were subjected to monotonically increasing four point bending moment load. During entire testing the temperature was maintained at 300°C.
- Different experimental results like load, LLD and CMOD have been monitored and recorded during the experiment.
- Crack initiation is not predicted till final loading. Hence it can be concluded that the governing failure criterion for the elevated temperature condition is NSCL (Net Section Collapse Load Criterion).
- Experimental results like load versus load line displacement and load versus CMOD are in agreement in elastic regime but there is considerable deviation beyond elastic limit for both pipes.
- For TSPPTC8-1 this deviation is attributed to the prevalent temperature gradient in pipe.
- The difference in the experimental and FEA results for TSPPTC16-1 is attributed to the overheating of notched portion of the pipe.

## ACKNOWLEDGEMENTS

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