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Thermo-Mechanical Stress Simulation of Unconstrained Region of Straight X20 Steam Pipe

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Abstract

The thermo-mechanical stress, strain and temperature distribution across the thickness of X20 steam pipe at region less susceptible to thermo-mechanical failure was simulated using finite element analysis software, Abaqus. The mesh convergence studies conducted showed that 10 mm mesh size was suitable for the simulation. The temperature distribution profile across the thickness of Pyrogel showed that pyrogel is an excellent insulation jacket for steam pipes. The maximum stress value obtained from the simulation shows that the pipe is operating below the yield strength of X20 steel at the region under study. Hence, the pipe's failure at this region due to thermo-mechanical stress or strain only is practically impossible over a long period of time. A deviation of 0.5% was found to exist between the analytical and simulated stress value obtained. This indicates a strong correlation between the simulated and analytical stress results.

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Keywords: *Abaqus, failure, pyrogel, simulation, thermo-mechanical stress*

1. Introduction

Steam pipes are very important component of the power generation plant. They are used for transport steam from the boiler to the turbines. Their role in the efficient performance of any power plant cannot be over emphasised. Like every other heat transferring components, steam pipes are affected by thermal stresses and deformations that are developed due to temperature distribution, heat accumulation or dissipation and other thermal related quantities while in operation [1]. In spite of these, the increasing demand for energy has forced the power generation companies to increase the operating parameters of their plants such as the temperature and pressure [2]. The operating cycle of the steam pipe typically consist of a start-up phase followed by continuous high temperature operation under sustained load in the form of pressure and eventually shutdown [3]. This sequence of operations lead to an increase in the

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development of thermo-mechanical stresses and strains in the pipe. In order to withstand the harsh operating condition of the steam resulting from its temperature and flowing pressure, martensitic stainless steel (X20 steel pipes) with excellent creep resistant and thermal properties is used for transporting steam from the boiler to the turbine. Little or no attention is paid to the steam pipes that are far away from the constrained region (boiler outlet and the turbine inlet). Hence, the unannounced failure of the pipes at this region (unconstrained) with less attention becomes inevitable.

The aim of this paper is to numerically simulate the thermo-mechanical stress and strain developed in a straight X20 steam pipe under operation at the unconstrained region. The material properties alongside operational condition that depicts the real case scenario was implemented in the finite element analysis (FEA) software, Abaqus and the steam pipe was also properly insulated with the aid of pyrogel insulation jacket.

2. Thermal Stress Distribution

The relation between the thermal stresses and strains follows the thermoelasticity formulae given below [4].

$$\varepsilon_t = \frac{1}{E}[\sigma_t - v(\sigma_r + \sigma_z)] + \alpha T = \frac{u}{r} \tag{1}$$

$$\varepsilon_r = \frac{1}{E}[\sigma_z - v(\sigma_t + \sigma_z)] + \alpha T = \frac{du}{dr} \tag{2}$$

$$\varepsilon_z = \frac{1}{E}[\sigma_z - v(\sigma_t + \sigma_r)] + \alpha T = 0 \tag{3}$$

where, T represents the rise in temperature at radius r above the initial value.

$$r\frac{d}{dr}(\varepsilon_t) + \varepsilon_t - \varepsilon_r = 0 \tag{4}$$

Substituting Eqs (1) and (2) into Eq (4), the below equation is obtained

$$\frac{1}{r^3}\frac{d}{dr}\left(r^3\frac{d}{dr}\sigma_r\right) = -\frac{E\alpha}{1-v}\frac{1}{r}\frac{dT}{dr} \tag{5}$$

Solving the above equation with boundary condidtion σ_r = zero at the inside and outside surfaces, $(r = r_i \; and \; r = r_o)$, [5, 6] gives

$$\sigma_t = \frac{\alpha E}{(1-v)r^2}\left[\frac{r^2+r_i^2}{r_o^2-r_i^2}\int_{r_i}^{r_o} Trdr - \int_{r_i}^{r} Trdr - Tr^2\right] \tag{6}$$

$$\sigma_r = \frac{\alpha E}{(1-v)r^2}\left[\frac{r^2-r_i^2}{r_o^2-r_i^2}\int_{r_i}^{r_o} Trdr - \int_{r_i}^{r} Trdr\right] \tag{7}$$

$$\sigma_z = \frac{\alpha E}{(1-v)}\left[\frac{2}{r_o^2-r_i^2}\int_{r_i}^{r_o} Trdr - T\right] \tag{8}$$

The effective stress is the calculated using von-Mises theory

$$\sigma_{vt} = \sqrt{[\sigma_t^2 + \sigma_r^2 + \sigma_z^2 - (\sigma_t\sigma_r + \sigma_t\sigma_z + \sigma_r\sigma_z)]} \tag{9}$$

2.1. Mechanical Stress

In a thick walled pressured pipe, three principal stresses namely hoop stress σ_t, radial stress σ_r and longitudinal stress σ_z are generated by internal pressure. Longitudinal stress occurs due to the thrust of pressure on the heads of the cylinders or pipes. The value of the hoop stress and radial stress varies throughout the cylinder whereas, the longitudinal stress is constant throughout [7].

For a thick walled cylinder or pipe of internal and external radii r_i and r_o respectively; and internal and external pressure P_i and P_o respectively, the radial and circumferential stresses in the cylinder were introduced by Lamé [8]. The radial and circumferential and axial stress components of a thick walled cylinder in the generalized forms are [8]:

$$\sigma_r = P_i \frac{r_i^2(r^2-r_o^2)}{r^2(r_o^2-r_i^2)} - P_o \frac{r_o^2(r^2-r_i^2)}{r^2(r_o^2-r_i^2)} \tag{10}$$

$$\sigma_t = P_i \frac{r_i^2(r^2+r_o^2)}{r^2(r_o^2-r_i^2)} - P_o \frac{r_o^2(r^2+r_i^2)}{r^2(r_o^2-r_i^2)} \tag{11}$$

$$\sigma_z = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2-r_i^2} \tag{12}$$

When only the inner pressure is assumed on the thick-walled cylinder, i.e. P_o= 0 then, the above equation can be developed for an external pressure or pressure gradient over the entire cylinder.
Eqs (10 - 12) reduces to Eqs (13-15) for a purely internal pressure ($P_i = P$).

$$\sigma_r = P \frac{r_i^2(r^2-r_o^2)}{r^2(r_o^2-r_i^2)} \tag{13}$$

$$\sigma_t = P \frac{r_i^2(r^2+r_o^2)}{r^2(r_o^2-r_i^2)} \tag{14}$$

$$\sigma_z = \frac{P_i r_i^2}{r_o^2-r_i^2} \tag{15}$$

The effective mechanical stress is the calculated using von-Mises theory

$$\sigma_{vM} = \sqrt{[\sigma_t^2 + \sigma_r^2 + \sigma_z^2 - (\sigma_t\sigma_r + \sigma_t\sigma_z + \sigma_r\sigma_z)]} \tag{16}$$

3. Material Properties

Table 1: Material properties of X20 pipe and Insulation jacket [9-11]

Material Properties	X20 Steel Pipe	Pyrogel (Insulation)
Density (Kg/m^3)	7800	171
Elasticity (GPa)	200	10×10^{-3}
Poisson Ratio	0.28	0.2
Expansion (K^{-1})	10×10^{-6}	4.0×10^{-6}
Thermal Conductivity (W/mK)	28	6.4×10^{-6}
Specific Heat Capacity (J/KgK)	460	2300

3.1. Dimensions of Pipe and Insulation Jacket

Table 2: Dimension of pipe and Insulation jacket

Description	Pipe	Insulation Jacket
Internal Diameter (m)	0.26	0.32
External Diameter (m)	0.32	0.48
Thickness (m)	0.03	0.05

Internal Diameter (m)	0.26	0.26

4. Analysis Methodology

A sequentially coupled thermo-mechanical stress analysis of the steam pipe was carried out using the FEA software, Abaqus. The procedure involves the development of a scaled down 2D model of X20 steel pipe and pyrogel insulation jacket as shown in **Fig. (1a)** and **(b)**. The material properties and dimension of the pipe and insulator are shown in **table (1)** and **(2)** respectively. The various material properties for both the insulation jacket and the steel pipes are input in the material property section of Abaqus cae. The pipe and insulation jacket are section and the section are assigned to part after which dependent instance is created between before assembling the parts as shown in **Fig. (1c)**.

Tie interaction was created between the pipe master and the insulation slave. Also, convection surface interaction was created both on the pipe inner and insulation outer. The operating temperature of the steam (550 ^{O}C) is the sink temperature in the pipe and the assumed film coefficient for steam (convective heat transfer coefficient) is 10000 W/(m^{2}K) [12]. On the insulation outer, the sink temperature is 25 ^{O}C with an assumed film coefficient of 18 W/(m^{2}K) [12]. Steam operating pressure of 18 MPa is applied to the inner pipe.

A 4-node linear heat transfer quadrilateral (DC2D4) heat transfer element type was used for the thermal analysis while a 4-node bilinear plane stress quadrilateral, reduced integration hourglass control (CPSAR) element type was used for the thermo-mechanical stress analysis. A Quad element shape, free technique and medial axis algorithm with global seed size of 10 mm was also used for the analysis. The open office database (**odb)** file obtained from the result output of the thermal analysis was imported and used as the predefined temperature in step 1 of the thermo-mechanical stress analysis.

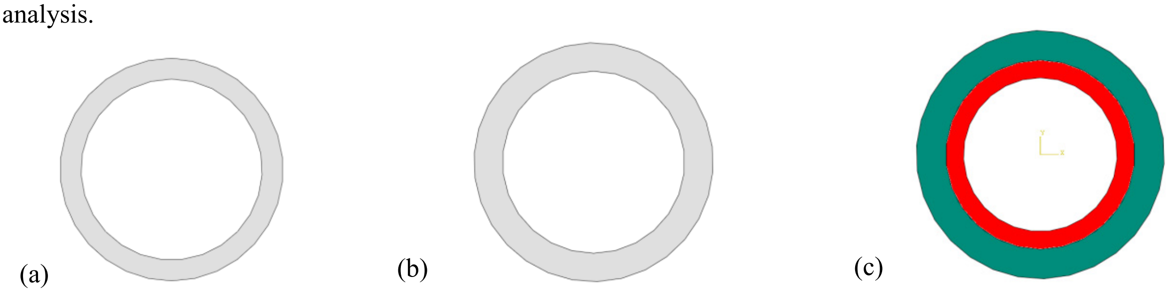

Fig. 1: 2D model of (a) X20 steel pipe (b) Pyrogel Insulation jacket and (c) assembly mode of Pipe and insulation.

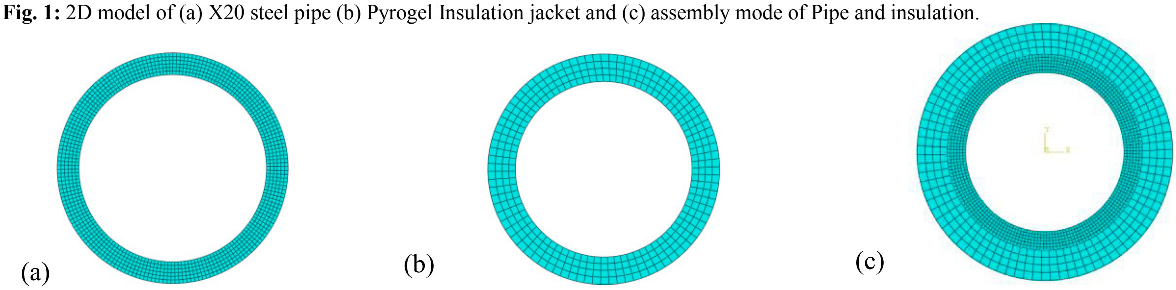

Fig. 2: Part mesh of (a) X20 steel pipe (b) Pyrogel insulation jacket and (c) assembly mesh of pipe and insulation.

5. Results and Discussion

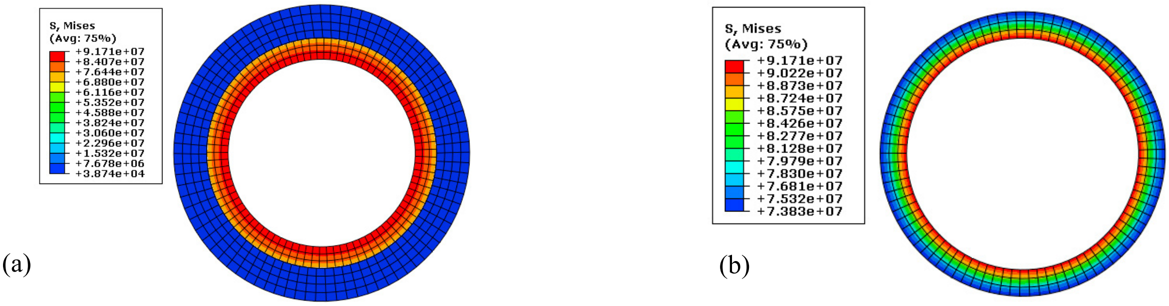

Fig. 3: Thermo-mechanical stress profile in (a) pipe and insulation and (b) pipe only.

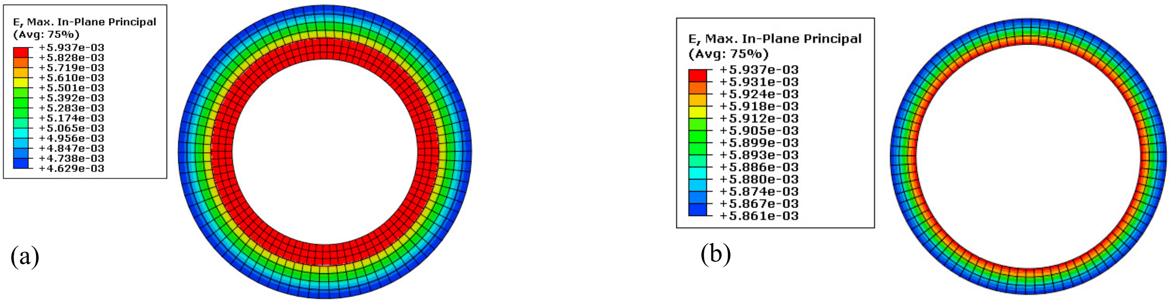

Fig. 4: Thermo-mechanical strain in (a) pipe and insulation and (b) pipe only.

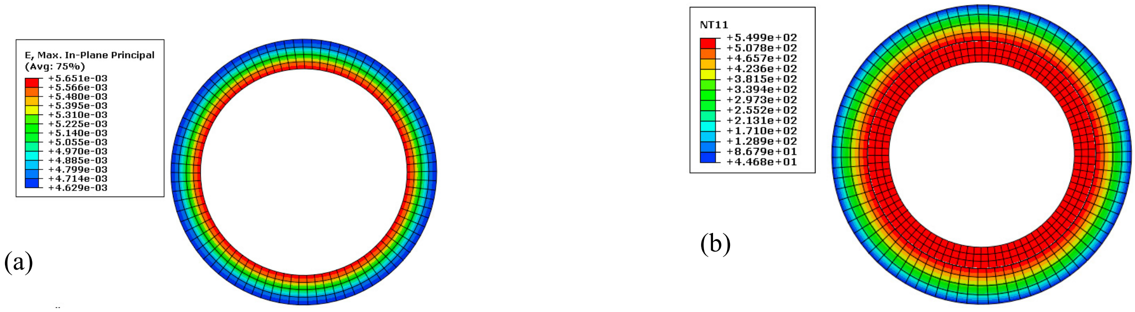

Fig. 5: Thermo-mechanical strain profile of (a) insulation jacket only and (b) temperature profile of both pipe and insulation jacket.

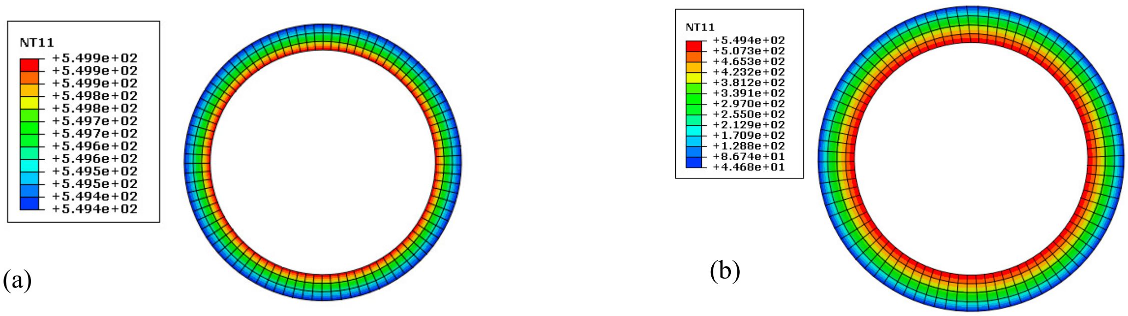

Fig. 6: Temperature profile of (a) pipe only and (b) insulation jacket only.

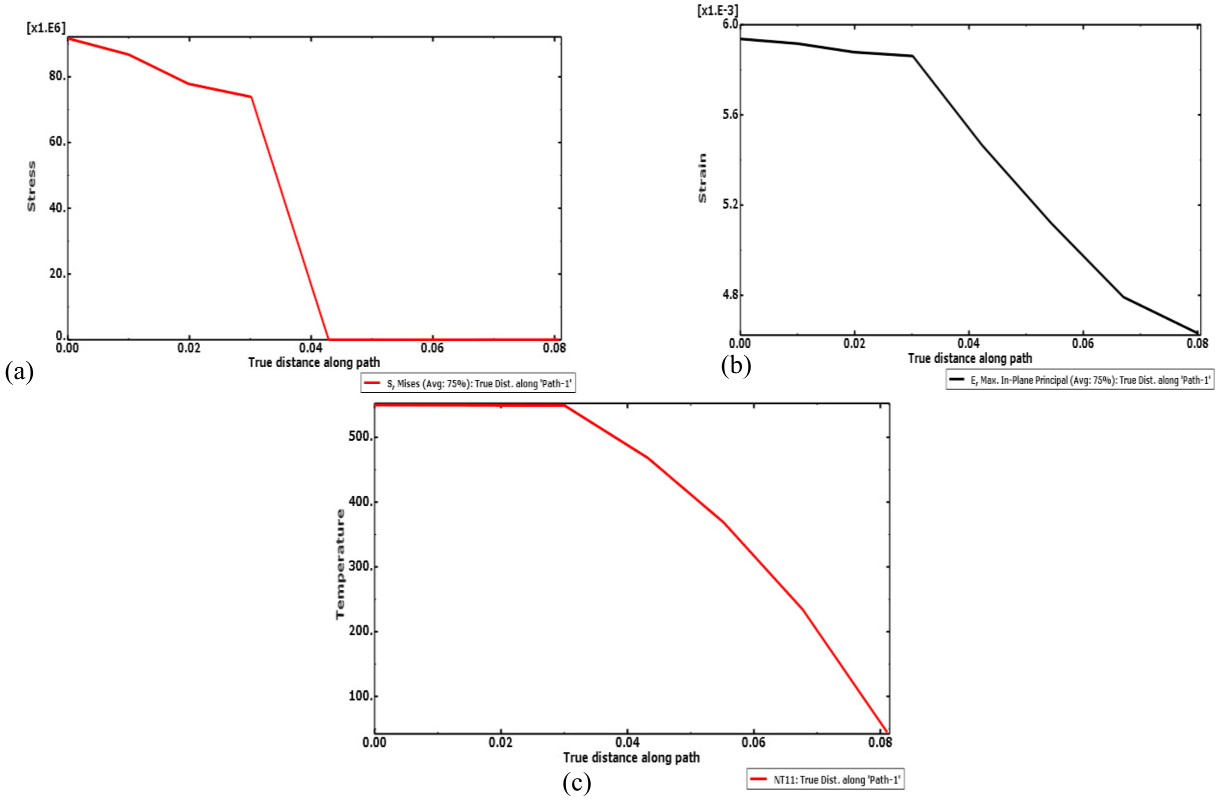

Fig. 7: Graph of thermo-mechanical (a) stress, (b) strain and (c) temperature across the pipe and insulation jacket.

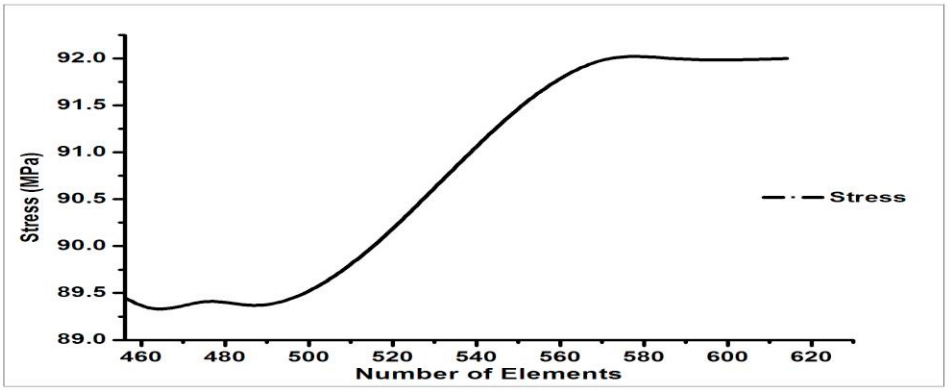

Fig. 8: Mesh convergence graph.

The mesh convergence study in **Fig. 8** shows that a global seed size of 10 mm is suitable for this analysis. The temperature field in **Fig. 5(b)** and **Fig. (6a)** show that the maximum temperature in the pipe is 549.4 ^{o}C. The distribution of temperature across the insulation jacket is also shown in **Fig. 6(b)**. The temperature of outer part of the insulation jacket is 44.6 ^{o}C. This implies that pyrogel is a poor conductor of heat and thus a good insulation material for power generation plant. **Fig. 7(b)** shows how the temperature drops across the pipe-insulation jacket thickness.

Fig. 3(a) shows the thermos-mechanical stress distribution profile in the pipe-insulation assembly while the stress distribution across the pipe alone is shown in **Fig. 3(b).** The maximum stress developed in X20 pipe at the region under study is 91.71 MPa. This value is far below the yield strength of X20. Hence, the pipe is expected to operate over a long period of time under this condition prior to failure due to thermo-mechanical stress or strain. The stress profile across the pipe thickness alone is shown in **Fig. 7(a)** and the strain distribution profile across the pipe-insulation assembly, insulation jacket and pipe alone is shown in **Fig. (3a), (4a)** and **(4b)** respectively. As expected, the maximum strain is found in the pipe inner.

5.1. Analytical Validation

Using Lame's equations and the equations of thermal stresses developed in an unconstrained pipe above, the calculated value of maximum stress developed in the pipe is 92.12 MPa.

Table 3: Analytical validation of simulated stress result

Simulated Stress (MPa)	Analytical Stress (MPa)	Deviation (%)
91.71	92.12	0.5

6. Conclusion

The thermo-mechanical stress simulation of power generation steam pipe (X20) was achieved through a sequentially coupled thermo-mechanical stress analysis procedure in Abaqus cae. The temperature distribution along the pipe-insulation jacket assembly shows that pyrogel is an effect insulation material for steam pipes. The stress and strain developed in the pipe at the region under examination indicates that failure of pipe due to thermal stress or thermal fatigue will not happen anytime soon since the developed stress is far below the yield strength of X20 steel. The stress obtained is validated analytically using Lame's equations and the thermal stress equations stated above. A deviation of 0.5 % was observed between the simulated and calculated stress. This signifies a strong correlation between the simulated and analytical result.

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