Demonstrating the Effects of Autofrettage on Thermal Fatigue Resistance of Thick Walled Cylinder Using Finite Element Simulations for Space Applications

M. Latif[1], F. Qayyum, M. Z. Khan, M. R. Shah

Abstract— **Experimental prediction and evaluation of thermal fatigue is an uneconomical and time consuming procedure. Thermal fatigue has been one of the major causes in reducing life of thick walled pressure vessels working at high temperatures. To increase thermal fatigue resistance of materials, a Finite Element Model has been proposed which includes the effect of autofrettage on thermal fatigue resistance of AISI 4340 Stainless Steel thick walled cylinder. These simulations are verified using an analytical model selected from previous studies and by simulating a cracked specimen model. FEA model takes into account different boundary conditions and material parameters such as coefficient of thermal expansion, density, heat conductivity, elastic modulus and yield stress for thermal stress calculations. Simulations were performed in Abaqus 14. Cylinder model was pressurized internally with five different constant internal pressure values to cause plastic deformation on inner side of the wall. Effect of this pressure on hoop stresses and plasticity of the material was determined. Another cracked specimen model was simulated for validation of proposed autofrettaged model and to observe whether it is reliable for increasing thermal fatigue resistance of thick walled cylinders. These results were then compared to the analytical model and it was observed that both analytical and simulation results showed fair conformance. This model can, therefore, be used for future studies for predicting and evaluating how autofrettage can be used for increasing thermal fatigue resistance of thick walled cylinders for space applications at high temperatures.**

Keywords— AISI 4340 Stainless Steel, Autofrettage, Numerical Simulations, Thermal Fatigue, Thick Cylinders.

I. Introduction

It has been a common practice for several decades that autofrettage is being used for enhancing fatigue properties of metallic components and to improve their structural integrity[1]. Therefore, this phenomenon has become very popular among many industrial fields such as automobiles, artillery, fuel injection systems in diesel engines, aerospace, nuclear power plants or any other applications which undergo abrupt changes in temperature causing thermal fatigue of metallic parts [2].

The principle of autofrettage is based on introducing residual stresses on the inner wall of cylindrical vessels. These stresses contribute to fatigue strength of the material. These stresses are usually introduced by internally pressurizing the cylindrical wall.

Several experimental techniques have been developed for measuring residual stresses in metallic components. Strain gauges can be used for measuring stresses in both hoop and axial directions using Sach's method [3, 4]. This method involves the measurement of strains at four different angles thus providing us with results to compare if strains in the angular directions are same. Another method can be devised using a drilled hole along the tube thickness and measuring its and diameter and position through six, eight or ten different positions along the hole [5]. After the tube has gone through pressurized conditions, the position and diameter of that drilled hole can be measured again and compared to the previous results. These distortions can then be used for measuring residual strains and stresses. An innovative neutron diffraction method can be used for finding out residual stresses for components which are still in service [6]. This is a non-destructive method and based on simple principle of detection of diffracted neutron rays falling on the specimen. Another improved but simple method is also being used for calculating residual stresses due to autofrettage. This method uses a ring cut from the pressurized cylinder as the test specimen. All parameters are used for measuring released hoop stresses which will show the level of autofrettage of the specimen. This method is known as Split-Ring method. Autofrettage can be measured by using by extension of a slot. This method is known as crack compliance method [7, 8]. All the procedures described above are being used extensively but the preparation of samples and all the experimental setup formation is quite expensive and time consuming.

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Several analytical models have been proposed for finding out autofrettage in thick walled cylinders. Calculations on finding out optimum radii and internal autofrettage pressure for thick cylinders have been performed and how autofrettage helps in enhancing the maximum pressure that a cylinder can retain are studied. Analytical models for finding out distribution of radial and hoop stresses have been proposed for elastic-perfectly plastic and elasto-plastic materials and optimum solutions for these stresses have been provided [9-13].

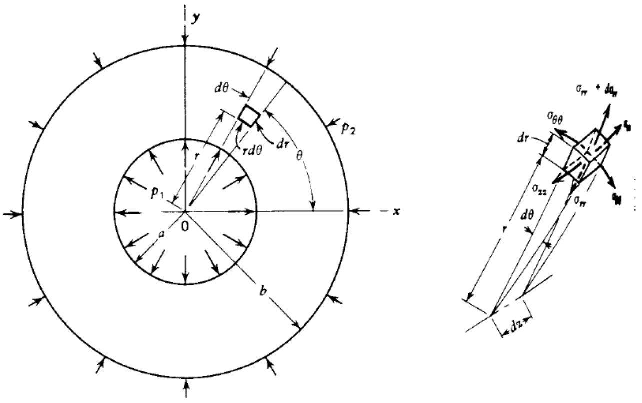

Fig. 1. Stress in thick walled cylinder[14]

Based on Bauschinger effect, an analytical technique is devised for calculating residual hoop and radial stresses in thick walled cylinders.

$$\sigma_{\theta\theta} = \frac{2\sigma_y}{\sqrt{3}}[1 + ln\frac{r}{b} - \frac{a^2}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)ln\frac{b}{a} \quad (1)$$

$$\sigma_\theta = \begin{cases} \frac{\sigma_y}{\sqrt{3}}\left[\left(2ln\frac{r}{\rho} + 1 + \frac{\rho^2}{R_o^2}\right) - P_1\left(\frac{1}{R_o^2} + \frac{1}{r^2}\right)\right]; & R \le r \le \rho \\ \frac{\sigma_y}{\sqrt{3}}(\rho^2 - P_1)\left(\frac{1}{R_o^2} + \frac{1}{r^2}\right); & R \le r \le \rho \end{cases} \quad (2)$$

$$\sigma_\theta = \begin{cases} \frac{\sigma_y}{\sqrt{3}}\left[\left(2ln\frac{r}{\rho} - \frac{\rho^2}{R_o^2}\right) - Q\left(\frac{1}{R_o^2} + \frac{1}{r^2}\right)\right]; & R \le r \le \rho \\ \frac{\sigma_y}{\sqrt{3}}(\rho^2 - Q)\left(\frac{1}{R_o^2} + \frac{1}{r^2}\right); & R \le r \le \rho \end{cases} \quad (3)$$

$$\sigma_{\theta\theta} = \sigma_y[1 - \ln\left(\frac{b}{r}\right) - \frac{a^2}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)\ln\frac{b}{a}] \quad (4)$$

In this method, stress intensity factors for both ideal and realistic i.e. Bauschinger effect independent and dependent autofrettage respectively, are calculated and compared with one another [15]. It has been noted that in a thick walled cylinder, stresses generated due to thermal loading are approximately same as produced in an autofrettaged cylinder [16]. The differences lie only on the basis of material or geometric constants. All the described models were developed using basic Lame theory of plasticity for thick walled cylinders.

Different software have been developed to create models and fabricate working conditions. Simulations are run using any type of loading conditions and material properties to predict how a component will behave in future. The prediction of fatigue life of an autofrettaged thick walled cylinder can be exercised by simulating required conditions. Residual stresses in autofrettaged parts can be modeled and calculated using Finite element analysis (FEA) [17].

Gun barrel models can be generated and simulated under high thermal conditions using both elastic and plastic material properties for finding out hoop and radial stresses and level of plasticity due to high temperature gradients in cylinder wall caused by heat flux of barrel shots [16]. Pressure limits of thick walled cylinders can be calculated using FEA. Strength to weight ratio of cylinders has been increased using autofrettage along with increase in fatigue life [17].

A finite element idealization for both Bauschinger effect dependent and independent autofrettage has been simulated using thermal loads [18]. An FEA code in ANSYS has been generated to run these simulations. And, to obtain better results the problem was divided into two steps using submodeling method. Stress intensity factors (SIF) can also be extracted from FEA simulations.

Thermal fatigue is a repeated stress-strain phenomenon occurring due to rapid change in temperature. Cyclic heating and cooling of a component leads to generation of volume expansion and contraction resulting in strains in the material. Autofrettage is one of the processes that are being used to increase maximum thermal stresses a material can endure without failing. The important variables that should be considered while dealing with thermal fatigue resistance are number of thermal cycles N, cyclic stress σ, cyclic strain ε, temperature range and time. Most of the failures that occur at high temperature are due to fatigue. Due to high temperature application, material undergoes some structural changes which lead to decrease in its fatigue resistance properties. That material component will endure lesser stresses when in service and will eventually fail long before its predicted life under normal working conditions. The aims and objectives of this research include creating an autofrettage FEA model of thick cylinder and finding out how autofrettage can help in improving thermal fatigue resistance of AISI 4340 SS thick cylinders using another thermal fatigue resistance model of a cracked thick cylinder.

II. NUMERICAL SIMULATIONS

A. Boundary Conditions

The dimensions of the cylinder were collected from an authentic military source. Internal diameter was taken 10mm and outer diameter 50mm. After every shot a slight increase in temperature occurs and material properties keep fluctuating with in temperature range of 200-600℃. Several grades of steel were studied for high temperature applications and AISI grade 4340 stainless steel is considered best for this application. A slight modification in alloy composition was used for desired applications. Very small percentages of Silicon, sulfur, Manganese and phosphorous have been added to enhance its properties according to the desired application. With all the pros, there are cons of this material. AISI 4340 SS is quiet susceptible to hydrogen ebrittlement and has extremely poor resistance towards stress corrosion cracking but can be nitride to further improve its fatigue life.

Heat flux was calculated analytically using heat flux equation as given below.

$$heat\ absorbed = Q = cm\Delta T \quad KJ \tag{5}$$

$$heat\ flow = Q' = \frac{Q}{t} \quad KJ/s \tag{6}$$

$$Heat\ Flux = H.F = \frac{Q'}{A} \quad W/m^2 \tag{7}$$

B. Modeling

1. Autofrettage Model

A portion from thick cylinder was taken under consideration for finding out effects of autofrettage.

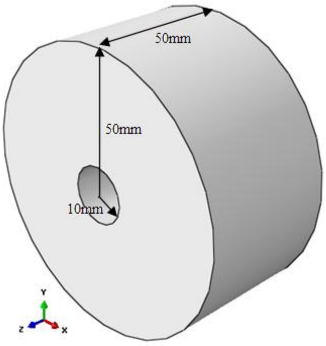

Fig. 2. Cross section of thick cylinder

Simulations were performed using two dimensional model of the above shown cylinder portion. Major steps toward collecting the desired results include modeling, defining material properties, creating section, assigning that section to the geometry, assembly, meshing, boundary conditions, loading and job submission.

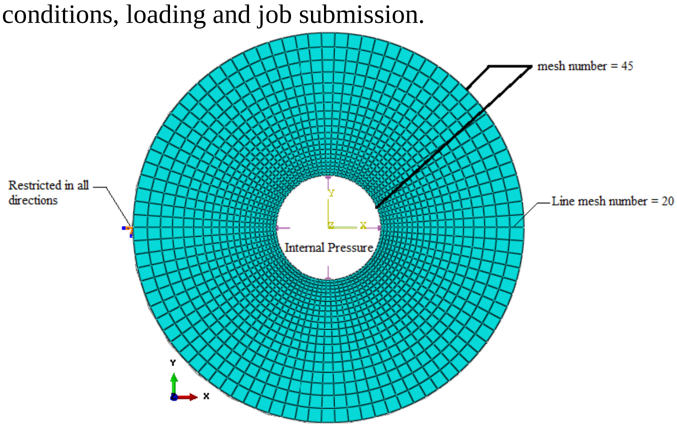

Fig. 3. Autofrettage model mesh and dimensions

In Elastic properties, Elastic modulus was taken to be 210 GPa with 0.3 Poisson's ratio. The plastic data was collected from the internet. In simple mechanical simulation, room temperature values for both elastic and plastic properties were taken. After assigning material properties, a solid-homogenous section was assigned to the model. Then the model was assembled to convert all local coordinates to global coordinates.

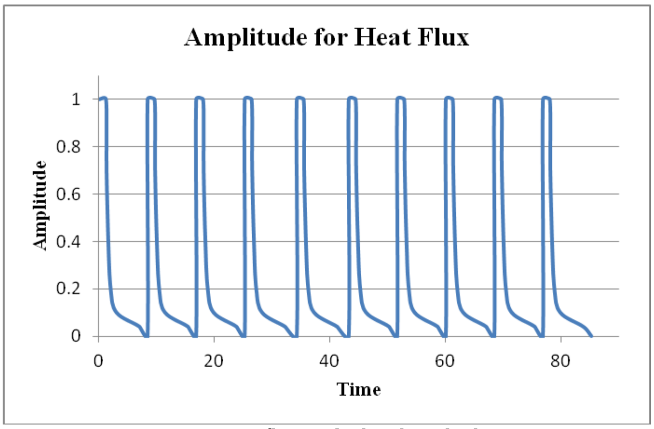

Fig. 4. Heat flux applied to the cylinder

For simple mechanical loading two steps were created. The initial step included restricted boundary condition of the cylinder. The second step covers the history and field output requests along with application of five different uniform pressures i.e. 400, 600, 800, 1000 and 1200 MPa at inner wall of the cylinder. After setting all the mesh and material attributes, model is ready to be submitted for the job.

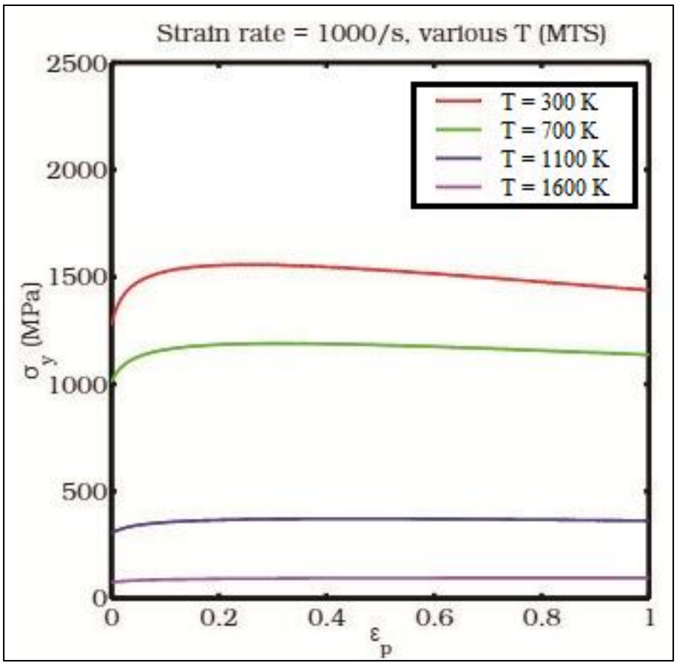

Fig. 5. Plastic properties of AISI 4340 SS at different temperatures[19]

2. Thermal Fatigue Model

For thermal fatigue model temperature data, coefficient of thermal expansion, specific heat, thermal conductivity etc. are required in material properties section as shown in tables below.

TABLE I

CONSTANT THERMAL PROPERTIES AND DENSITY OF AISI 4340 SS

Sr. no.	Material property	
1	Density	7830 Kg/m3
2.	Thermal conductivity	44.5 W/mK
3.	Specific heat	0.00475J/g˚C

TABLE II

COEFFICIENT OF THERMAL EXPANSION OF AISI 4340 SS AGAINST DIFFERENT TEMPERATURES

	Coefficient of thermal expansion	Temperature °C
1.	1.23E-005	20
2.	1.37E-005	250
3.	1.45E-005	500

TABLE III

ELASTIC MODULUS OF AISI 4340 SS AGAINST DIFFERENT TEMPERATURES

Sr. No.	Young's Modulus GPa	Temperature °C
1.	213	27
2.	195	200
3.	185	300
4.	175	400
5.	165	500
6.	155	600
7.	15	650

This model uses same dimensions for thick walled cylinder as for the autofrettage model. Only difference is crack formation at internal wall of cylinder along radial thickness. Fig. 6. shows cracked thick walled cylinder geometry.

Crack length was kept 1mm with Type Contour Integral. Crack geometry and assigned properties are being shown in Fig. 7. First, crack was modeled and its properties were defined using Engineering Features in Assembly. Crack seam was defined, then crack tip and direction of movement of the crack was defined and finally Second-order mesh options were selected according to requirement. Two circles were constructed at the tip of crack for better meshing around crack surroundings. These circles are necessary for structured mesh and for better results at crack tip. Structured mesh with triangular elements was used for inner circle, with one tip of every triangle starting at crack tip. Outer circle was meshed with Quadrilateral elements. After completing the cracked model, loading conditions were applied. All the pre-defined temperature and flux conditions were applied as were in simple thick cylinder model. Amplitude was also kept same. Boundary conditions were kept the same too. Only thermal loading was applied and internal mechanical pressure was deactivated for these simulations.

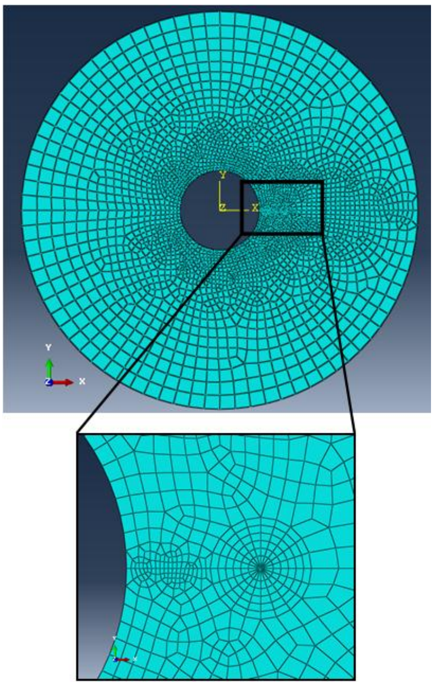

Fig. 6. Crack close-up showing meshed region around the crack tip

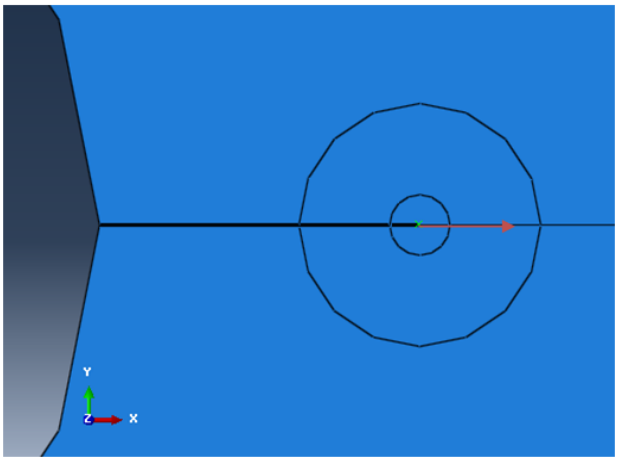

Fig. 7. Close- up with assigned seam and crack propagation direction

The results are then collected after the job is completed successfully. A large number of elements will lead to more time to run the simulations. Similarly, structured mesh will give us same results in every direction. Element type has a great influence for deducing better results. In short, every aspect has to be considered for better accuracy in results.

III. RESULTS AND DISCUSSIONS

For simple mechanical loading, results are obtained for two different load steps

1. Applying internal pressure and
2. Removing internal pressure

For cracked thick walled cylinder, only thermal loading was applied using pre-defined field of sink temperature and applied heat flux. Effect of induced residual stresses was observed on crack growth.

This situation is analogous to first loading the specimen and finding stresses and plasticity in it and then repeating same procedure after unloading that specimen and applying thermal loading on a crack induced specimen. A simple straight path was defined along the meshed region for collecting values at nodes in order to generate graphs.

C. *Autofrettage Model*

1. Load Step

This step is based on applying mechanical pressure on inner wall of the cylinder. Five different pressure values were selected to determine hoop residual stresses and plasticity across wall thickness.

400 MPa
600 MPa
800 MPa
1000 MPa
1200 MPa

Results obtained for all these pressure values are shown in Figs. 8 to 12.

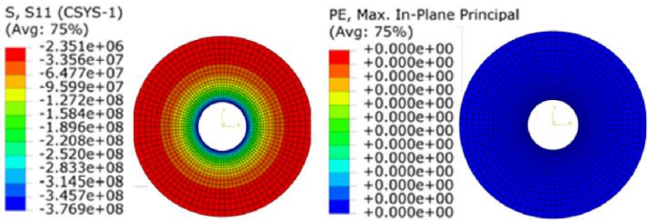

Fig. 8. (a) Hoop stress (b) Plasticity for 400 MPa internal pressure

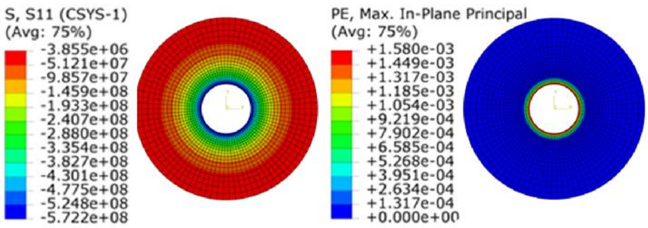

Fig. 9. a) Hoop stress (b) Plasticity for 600 MPa internal pressure

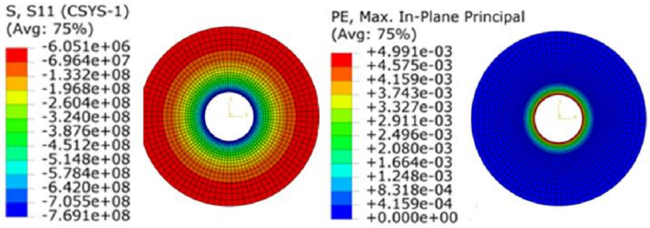

Fig. 10. a) Hoop stress (b) Plasticity for 800 MPa internal pressure

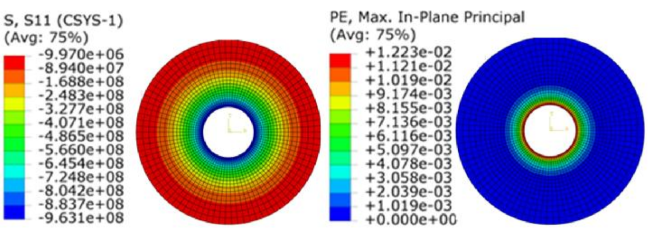

Fig. 11 (a) Hoop stress (b) Plasticity for 1000 MPa internal pressure

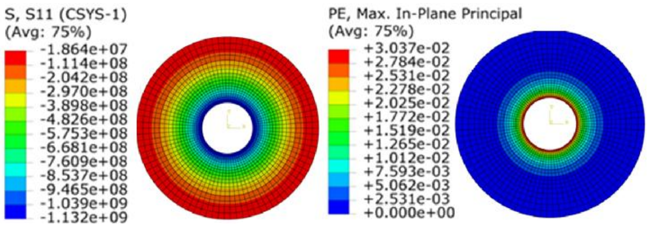

Fig. 12. (a) Hoop stress (b) Plasticity for 1200 MPa internal pressure

The graphs of plasticity and hoop stress are given in Fig. 13 and Fig. 14 respectively, providing better comparison of the properties.

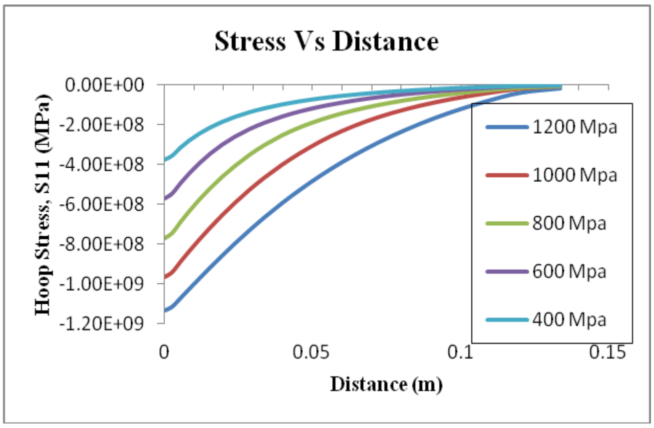

Fig. 13. Hoop Stress distribution along the radius of the cylinder against different internal pressures for Load Step

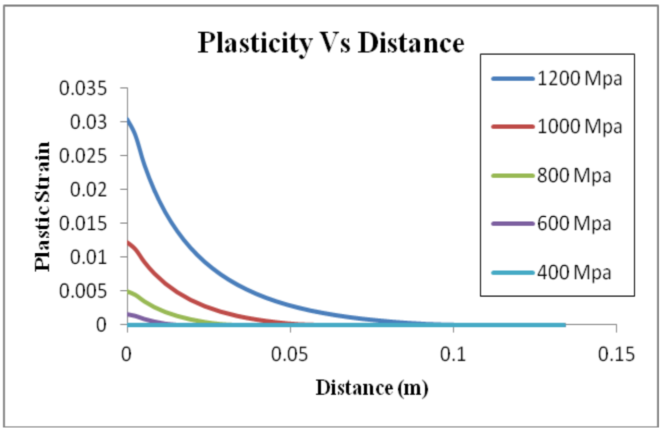

Fig. 14. Plasticity distribution along the radius of the cylinder against different internal pressures for Load Step

2. No Contact Pressure Step

In this step, results are obtained after removing internal pressure.

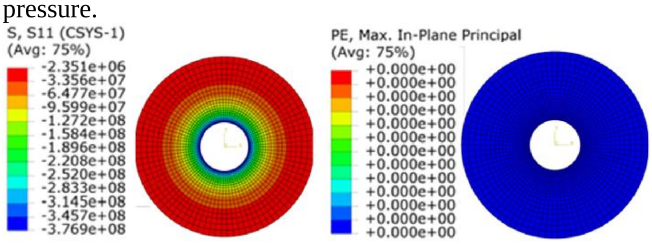

Fig. 15. (a) Hoop stress (b) Plasticity for 400 MPa internal pressure

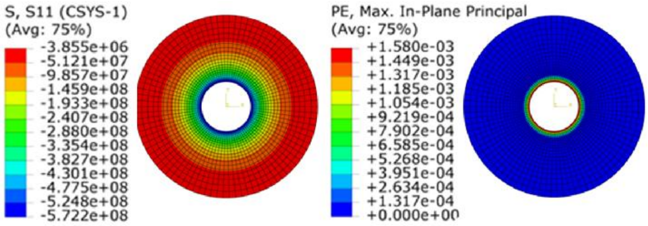

Fig. 16. (a) Hoop stress (b) Plasticity for 600 MPa internal pressure

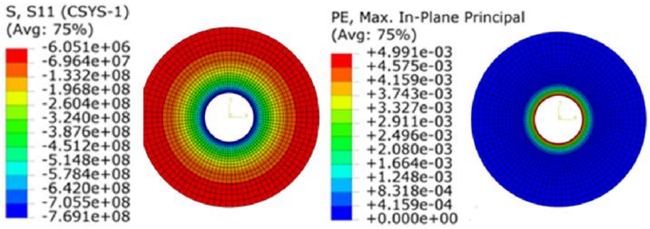

Fig. 17. (a) Hoop stress (b) Plasticity for 800 MPa internal pressure

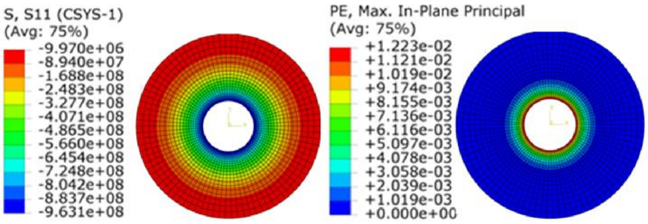

Fig. 18. (a) Hoop stress (b) Plasticity for 1000 MPa internal pressure

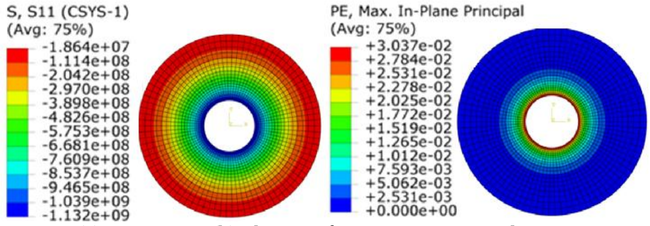

Fig. 19. (a) Hoop stress (b) Plasticity for 1200 MPa internal pressure

The graph below (Fig. 20) shows the distribution of Hoop Stress along the radial distance of the cylinder. It can be observed that with increasing pressure, the amount of induced compressive stress also increased. On the other hand, Fig. 21 shows the plasticity behavior along the radius of the cylinder. Internal diameter is under highest strains which also increased for higher pressure values.

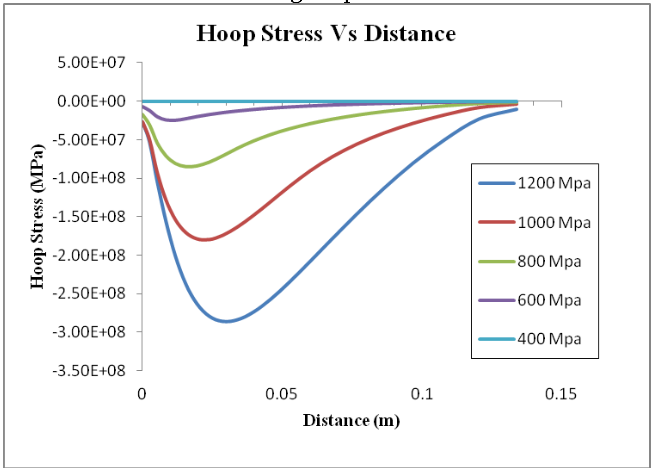

Fig. 20. Hoop Stress distribution along the radius of the cylinder against different internal pressures for no contact pressure steps

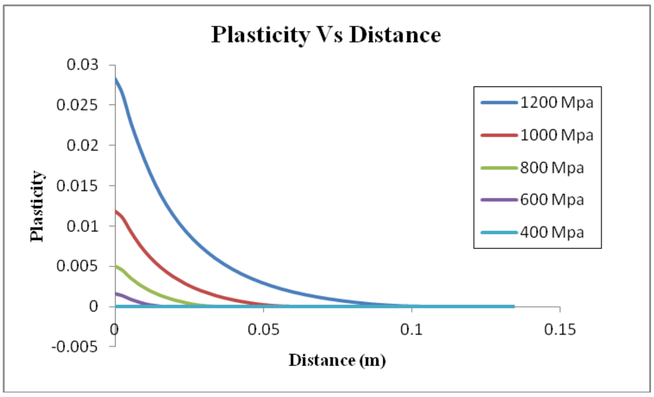

Fig. 21. Plasticity distribution along the radius of the cylinder against different internal pressures for no contact pressure steps

D. *Thermal Fatigue Model*

Following graph (Fig. 22) shows Temperature versus Time for thermal loading on the cracked thick walled cylinder. This graph shows each thermal cycle that the specimen under-went during thermal loading. Data for ten cycles was collected. Corresponding graph for J- integral was plotted to interrogate whether applied mechanical loading is helping reduced crack growth rate.

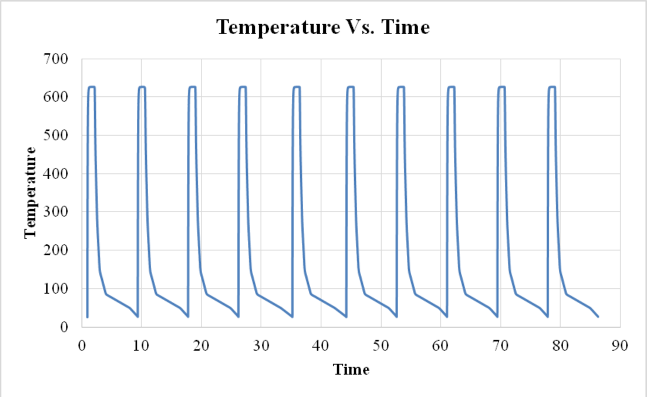

Fig. 22. Temperature vs. Time graph for thermally loaded thick walled cylinder

Fracture toughness of a material is usually defined as its resistance to crack initiation and propagation. Brittle materials will undergo abrupt propagation of crack through them as soon as initiation of the crack. This means that brittle materials require lesser energy for crack initiation and propagation. Theory of elasticity is employed on such materials for characterizing their linear elastic fracture mechanics. While on the other hand, as ductile materials are capable of absorbing large amount of energy before crack initiation or propagation, this simple theory of elasticity cannot be applied on these materials. Hence, to calculate the energy required for crack initiation and propagation in ductile materials, an alternative theory of plasticity is utilized. In this research, J-integral is being used for these calculations. J-integral is equivalent to energy release rate. Graph of J-integral vs time for crack growth and propagation due to thermal loading on thick walled cylinder is shown in Fig. 23. It has been observed that J-integral values are negative due to the presence of compressive stresses. This negative value proves that induced compressive stresses due to autofrettage are helping in crack growth arrest thus validating this autofrettage model for increasing fatigue resistance of AISI 4340 SS thick walled cylinders.

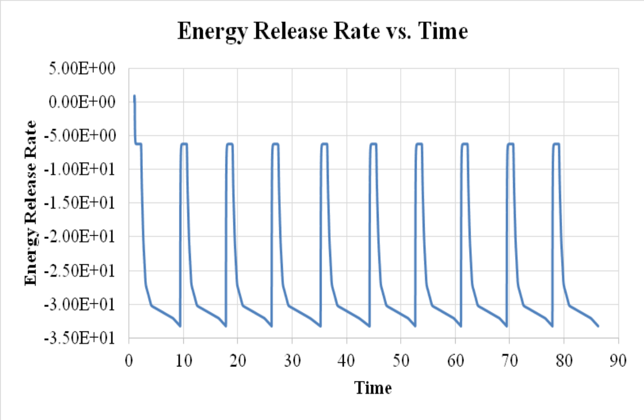

Fig. 23. Energy release rate vs. time for cyclic thermal loading on thick walled cylinder

E. Comparison of Results

Comparison of hoop stresses obtained from analytical and simulation models is shown in Fig. 24. As depicted in the graph, the behavior shown by both the models is similar. The analytical model used for validating the results for hoop stresses is given in equation 8 below.

$$\sigma_{\theta\theta} = \begin{cases} \frac{\sigma_y}{\sqrt{3}}\left[\left(2ln\frac{r}{\rho} - \frac{\rho^2}{b^2}\right) - Q\left(\frac{1}{b^2} - \frac{1}{r^2}\right)\right] & a \le r \le \rho \\ \frac{\sigma_y}{\sqrt{3}}(\rho - Q)\left(\frac{1}{b^2} - \frac{1}{r^2}\right) & \rho \le r \le b \end{cases} \quad (8)$$

Where, a is the internal radius, b is the external radius, ρ is the radius of elastic-plastic interface, σ_y is the Yield stress of the material, Q is found by the following equation;

$$Q = \frac{a^2 b^2}{b^2 - a^2}[1 - \frac{\rho^2}{b^2} + 2ln\frac{\rho}{a}] \quad (9)$$

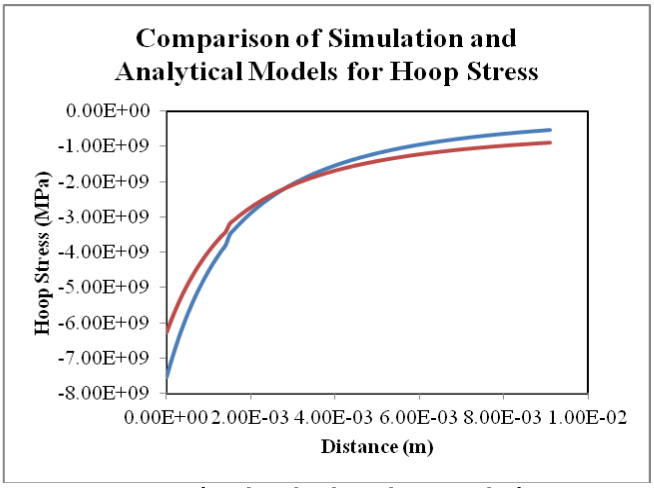

Fig. 24. Comparison of Analytical and Simulation Results for Hoop Stress along the radius of the cylinder

The values for a and b are taken as 0.05 m and 0.185m respectively. ρ is taken to be 0.02m. The yield stress is collected from the material plastic data to be 717.8 MPa. Putting the values in equation 15 gave the value for Q equal to 2.27x10-3. Putting the value of Q in equation 14 and substituting different values for r, hoop stress along the radius of the cylinder was calculated and then plotted as in Fig. 24.

The comparison of the analytical model to that of the results obtained from the simulations is shown in Fig. 39. Both models showed good conformance. Difference between both simulation and analytical results has been observed and calculated and it came out to be within reasonable ranges. This difference can be reduced further using greater number of elements and nodes. But, increasing these parameters will result in more complicated simulations and time consuming procedures. Therefore, we have to keep the modeling and meshing parameters as optimized as possible.

IV. Conclusion

Obtained results clearly showed the effect of autofrettage on mechanical strength of thick walled cylinders. Hence, introducing compressive stresses within inner wall of the cylinder can increase its endurance to external forces. Autofrettage can thus be used for increasing cylinder life. Further, changing boundary conditions completely changes the simulation procedures thus providing us with unnecessary complications. So, one has to be very careful while assigning attributes in simulations, especially in choosing suitable boundary conditions. As autofrettage pressure is increased, depth of compressive stresses increases up to 5mm with the depth of plastic region up to 1mm. It has also been concluded from simulations that maximum internal pressure cannot be more than 1200 MPa because material reaches its ultimate strength.

Negative J integral values give us positive prediction of crack growth resistance due to presence of compressive residual stresses thus validating this model for autofrettage of thick walled cylinders. Selection of analytical model has to be done carefully too since different analytical models use different variables and different boundary conditions. The analytical model in this very research has been chosen according to the specifications and hence the results from simulations and analytical model are quiet conforming to each other.

This research can be further extended using other variables and using different temperature conditions. This will be a great outburst in the field of thermal fatigue, since; fatigue experimentation and prediction take very long time in producing results and are not economical too. Experimental setup can be established for measuring residual hoop stresses and results can be compared with those of analytical and FE simulations.

Acknowledgment

Sincere thanks to Dr. Zubair Khan for his enthusiastic help and keeping the motivation alive. Huge gratitude towards Dr. Masoodur Rehman Shah for his dedicated help in finishing this research. And greatest obligation towards Mr. Faisal Qayyum, for his assistance and time and intellectual input for this research work.

REFERENCES

[1] N. Tomita, "Autofrettage process," ed: Google Patents, 1986.
[2] I. Y. Al-Zaharnah, BS; Hashmi, MSJ, "Pulsating Flow In Circular Pipes - The Analysis Of Thermal Stresses," *INTERNATIONAL JOURNAL OF PRESSURE VESSELS AND PIPING,* vol. 78, pp. 567-579.
[3] A. P. Parker, "A critical examination of Sachs' material-removal method for determination of residual stress," in *ASME 2003 Pressure Vessels and Piping Conference*, 2003, pp. 1-4.
[4] J. Perry and J. Aboudi, "Elasto-plastic stresses in thick walled cylinders," *Journal of Pressure Vessel Technology,* vol. 125, pp. 248-252, 2003.
[5] D. George and D. Smith, "The application of the deep hole technique for measuring residual stresses in an autofrettaged tube," *ASME-PUBLICATIONS-PVP,* vol. 406, pp. 25-32, 2000.
[6] A. Stacey, H. J. MacGillivary, G. A. Webster, P. J. Webster, and K. R. A. Ziebeck, "Measurement of residual stresses by neutron diffraction," *The Journal of Strain Analysis for Engineering Design,* vol. 20, pp. 93-100, April 1, 1985 1985.
[7] M. B. Prime, "Residual Stress Measurement by Successive Extension of a Slot: The Crack Compliance Method," *Applied Mechanics Reviews,* vol. 52, pp. 75-96, 1999.
[8] A. M. Venter, R. R. de Swardt, and S. Kyriacou, "Comparative measurements on autofrettaged cylinders with large Bauschinger reverse yielding zones," *The Journal of Strain Analysis for Engineering Design,* vol. 35, pp. 459-469, January 1, 2000 2000.
[9] G. Majzoobi and A. Ghomi, "Optimisation of autofrettage in thick-walled cylinders," *Journal of Achievements in Materials and Manufacturing Engineering,* vol. 16, p. 2, 2006.
[10] R. Zhu and J. Yang, "Autofrettage of thick cylinders," *International Journal of Pressure Vessels and Piping,* vol. 75, pp. 443-446, 1998.
[11] V. Radu, N. Taylor, and E. Paffumi, "Development of new analytical solutions for elastic thermal stress components in a hollow cylinder under sinusoidal transient thermal loading," *International Journal of Pressure Vessels and Piping,* vol. 85, pp. 885-893, 12// 2008.
[12] M. A. Malik and S. Khushnood, "A REVIEW OF SWAGE – AUTOFRETTAGE PROCESS," *11th International Conference on Nuclear Engineering,* 2003.
[13] P. B. H.J. Schindler, C.H. Nguyen, R. Knobel, "Determination and evaluation of residual stresses in thick walled cylinders due to autofrettage," ed. Dübendorf, Switzerland: Swiss Federal Laboratories for Materials Testing and Research (EMPA).
[14] E. J. Hearn, "Chapter 3 - Strains Beyond the Elastic Limit," in *Mechanics of Materials 2 (Third Edition)*, E. J. Hearn, Ed., ed Oxford: Butterworth-Heinemann, 1997, pp. 61-116.
[15] C. Levy, M. Perl, and S. Kotagiri, "The Bauschinger effect's influence on the SIFs of multiple longitudinal coplanar cracks in autofrettaged pressurized cylinders," *Engineering Fracture Mechanics,* vol. 73, pp. 1814-1825, 2006.
[16] J. R. F. A. P. PARKER, "Stress intensity factors for multiple radial cracks emanating from the bore of an autofrettaged or thermally stressed,thick cylinder," *En&wing Fracfure Mechanics* vol. Vol. II, pp. pp. 237-241, 1981.
[17] H. Brünnet, D. Bähre, T. J. Rickert, and D. Dapprich, "Modeling and Measurement of Residual Stresses Along the Process Chain of Autofrettaged Components by using FEA and Hole-Drilling Method with ESPI," in *Materials Science Forum*, 2014, pp. 79-86.
[18] R. Adibi-Asl and P. Livieri, "Analytical Approach in Autofrettaged Spherical Pressure Vessels Considering the Bauschinger Effect," *Journal of Pressure Vessel Technology,* vol. 129, pp. 411-419, 2006.
[19] B. Banerjee, "The Mechanical Threshold Stress model for various tempers of AISI 4340 steel," *International Journal of Solids and Structures,* vol. 44, pp. 834-859, 2007/02/01/ 2007.