Finite Element Analysis for Predicting Residual Stresses of Autofrettaged Spherical vessels considering Bauschinger Effect

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Abstract:- This paper provides FE model analysis of high pressure vessel considering von Mises yield criterion to predict behavior within the plastic zone. Residual stress distribution in autofrettaged spherical vessel subjected to different autofrettage pressure are evaluated. The optimum auttofrettage pressure and residual stresses are determined for different percentage of overstrain .The material model is currently bilinear and allows consideration of strain hardening. whether re -autofrettage results in a more beneficial compressive stress distribution and, therefore, in extension of life is examined in this study. The effect of Bauschinger effect and yield criterion on residual stress is discussed based on the FE model. The increasing application of spherical vessels for high pressure application motivates the use of autofrettage technique for an efficient and economic design.

Keywords:- Autofrettage, Re- Autofrettage, Spherical vessel ,Strain hardening, FE Analysis, Residual stress, Bauschinger Effect ,

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1.INTRODUCTION:

Numerical stress analysis of the relatively complex behaviour of a vessel during autofrettage pressurization and depressurization requires implementation of an appropriate yield criterion, appropriate subdivision of the region and implementation of physically realistic boundary conditions. All of these requirements are met in the work reported herein as part of the initial development and validation of a finite element(FE) procedure. Accordingly, the results from an FE model of a thick-walled cylinder are here compared to results from an analytical model [1]and FE model of spherical vessels. All configurations are pressurized to cause initial plastic deformation throughout an equal proportion of the tube wall thickness. This proportion is termed overstrain and is often defined as a percentage of the wall thickness. In particular, spherical pressure vessels, due to their inherent stress and strain distributions require thinner walls compared to cylindrical vessels; therefore, they are extensively used in gas-cooled nuclear reactors, gas or liquid containers rather than heads of close-ended cylindrical vessels. A simple numerical fit allows all autofrettage pressures to be replicated to within 0.5 percent and Compare with relevant sections of the ASME code.Paolo Livieri & Paolo Lazzarin [2],2002, reported analytical solutions valid for residual stresses in cylindrical pressure vessels subjected to autofrettage. . The influence on residual stresses, both of the hardening law and of the shape of the unloading σ-ε curve, is discussed.R.Thumser ,J.W.Bergmann, &M.Vormwald, [3]2002, addressed the calculation of residual stresses due to autofrettage and the resulting increase of the endurance limit. It is shown that large plastic penetrations arising from bending and autofrettage can residually stress the section beyond its yield point: in tension and in compression across both its halve.Anthony P. Parker[4]2004, In his procedure involved initial autofrettage; one or more ‘‘heat soak plus autofrettage’’ sequences and an optional final heat soak. Stresses are calculated numerically for traditional, single autofrettage and compared with those created by the new procedure.X. P Huang & W. C. Cui [5], 2006 ,showed an autofrettage model considering the material strain-hardening relationship and the Bauschinger effect, based on the actual tensile-compressive stress-strain curve of material, plane-strain, and modified yield criterion, has been proposed. Hamid Jahed , Babak Ahmadi Moghadam &Mojtaba Shambooli ,[6],2006, conducted at plastic strains up to 3.4% for unloading and reloading. Re-autofrettage is the process of reapplication of overload pressure on an already autofrettaged tube. C. Levy a,*, M. Perl b,1, S. Kotagiri a , [7]2006 studise influence of the Bauschinger effect on the three-dimensional, Mode I, stress for arrays of longitudinal coplanar, surface cracks emanating from the bore of a thickwalled cylinder is investigated. A. P. Parker & X. Huan[8]2007, numerically solved the analogous problem of a spherical, thick walled steel vessel.

An equivalent new analytical solution for the case of a spherical vessel is also formulated.R. Adibi-Asl1& P. Livieri[9] ,2007 studied the different material models incorporating the Bauschinger effect depending on the loading phase are considered in the present study. Some practical analytical expressions in explicit form are proposed for a bilinear material model and the modified Ramberg–Osgood model.M.H. Hojjati_, A. Hassani,[10]2007, studied the optimum autofrettage pressure and the optimum radius of the elastic–plastic boundary of strain-hardening cylinders in plane strain and plane stress theoretically and by finite-element modeling.Gibson, Amer Hameed, Anthony P. Parker, John G. Hetherington[13] discussed that general

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purpose finite element analysis for a range of end conditions: plane stress and several plane-strain states (open and closed ended, plus true plane strain .Huang has developed a von Mises solution of an elastic-plastic tube. The model considers the tube material to behave linearly in the elastic phase both loading and unloading, and either linearly or according to a power law in the plastic phase (loading and unloading) may be treated independently. Gibson done comparison between Huang model and FE model. Accordingly, the results from an FE model of a thick-walled cylinder are here compared with the results from model of spherical vessels.

2. THEORETICAL CONCEPT:

General Equation

The radial and tangential stresses σ_r and σ_θ must satisfy the equilibrium equation

$$\frac{d\sigma_r}{dr} - \frac{2(\sigma_\theta - \sigma_r)}{r} = 0 \quad \text{……………………………(1)}$$

According to Huang the material's elasticplastic loading curve for the elastic stresses and plastic stresses ,

$$\sigma = E\varepsilon \qquad (\varepsilon \le \varepsilon_S) \quad \text{………………………..(2)}$$

The material behaves plastically. The strain hardening region can be expressed as

$$\sigma_i = A_1 + A_2 \varepsilon_i^{B_1} \qquad (\varepsilon \ge \varepsilon_S) \quad \text{………………(3)}$$

This is unloading elastic region, during which the steel behaves elastically up to yield point $\sigma_d\left(\varepsilon_s^*\right)$. The elastic module over this range E'.the region can be expressed as ,

$$\sigma^* = E'\varepsilon^* \qquad \left(\varepsilon^* \le \varepsilon_S^*\right) \quad \text{……………..(4)}$$

The material then behaves plastically. This region can be expressed as

$$\sigma^* = A_3 + A_4\left(\varepsilon_i^*\right)^{B_1} \qquad \left(\varepsilon^* \ge \varepsilon_s^*\right) \quad \text{…….(5)}$$

Autofrettage Pressure

Elasto-plastic radius rc is a basic design parameter in autofrettage of a spherical vessel. The autofrettage pressure p_a depends upon the parameter r_c and can be derived using the condition,

$$(\sigma_r)_e\big|_{r=r_c} = (\sigma_r)_p\big|_{r=r_c}$$

$$\frac{2}{3}\sigma_S r_c^3\left[\frac{1}{r_o^3} - \frac{1}{r_c^3}\right] = 2A_1 \ln\left(\frac{r_c}{r_i}\right) + \frac{2(\sigma_S - A_1)}{3B_1} r_c^{3B_1}\left[\frac{1}{r_i^{3B_1}} - \frac{1}{r_c^{3B_1}}\right] - p_a$$

The smaller Bauschinger effect coefficient causes the reverse yielding to take place more easily and affects the residual stress distribution. In the present model, the Bauschinger effect is considered by parameter σs*[5]

$$\sigma_s^* = A_1 + A_2\varepsilon^{B_1} + b_{ef}\ \sigma_s$$

$$\text{………………………………………………………(3)}$$

from equation for plastic zone

$$\varepsilon_i^{B_1} = \left(\frac{2c_P}{r_c^3}\right)^{B_1}$$

$$= \frac{2^{B_1}\left[\frac{1}{2}\left(\frac{\sigma_S - A_1}{A_2}\right)^{\frac{1}{B_1}} r_c^{\,3}\right]^{B_1}}{r_c^{\,3B_1}}$$

$$= \frac{\frac{(\sigma_S - A_1)}{A_2} r_c^{\,3B_1}}{r_c^{\,3B_1}}$$

$$= \frac{(\sigma_S - A_1)}{A_2} \quad \text{…………………………………………(4)}$$

Now putting this value in equation (3)

$$\sigma_s^* = A_1 + A_2\frac{(\sigma_s - A_1)}{A_2} + b_{ef}\sigma_s$$

$$= \sigma_s\left(1 + b_{ef}\right)$$

The FE model was tested in different percentage of overstrain with Huang's mode For different percentage of wall ratios., The Young's and Tangent moduli were kept constant in loading and unloading (i.e., E1=E2=E, ,H1=H2=H).

Autofrettage pressures were determined by using the corresponding value from the program as an initial figure; the precise autofrettage pressures (for the relevant ANSYS model) were then obtained by interpolating the autofrettage stresses and iterating to give different overstrain.

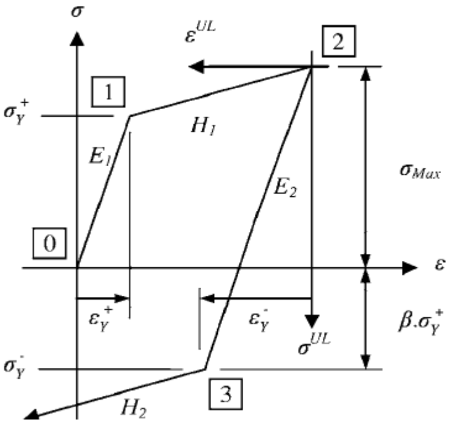

Fig.1. Material Stress Strain diagram

3.COMPERISONS AND DISCUSSION:

The effectiveness of autofrettage lies in its ability to create compressive residual bore stresses to enhance service life by inhibiting the growth of surface cracks and increasing the safe working pressure of the vessel. The results from the first stage of the comparison are shown below. It is important to summarize autofrettage stresses separately from residual stresses. Figure 6 and 10 showing loading stress and unloading stress with radius ratio k=2 .Figure 12 to 18and plots the autofrettage stresses from the ANSYS model for different percentage of overstrain against those predicted by Huang's method for K=2.0; In figure12 and 13 shows the ''Ideal Elastic Unloading'' residual stresses that could be achieved in the absence of Bauschinger effect. This is the residual stresses actually achieved after single autofrettage . Fig.15,16,17 and 18 indicates the residual stresses after second autofrettage(re -autofrettage). The loss of bore compressive hoop stress and radial stress due to Bauschinger effect .The loss of bore compressive hoop stress is significant than radial stress.Fig.19 and 20 shows the effect of Bauschinger effect over residual stress during Ideal Elastic Unloading and Elastic-Plastic Unloading respectively.Fig. 7 and 11 shows von misses stress during elasto-plastic loading and unloading for k=2.Fig.3 and 4 shows the nodal solution of loading hoop stress and radial stress for k=2.Fig.8 and 9 shows the nodal solution of Unloading hoop stress and radial stress for k=2.Re -yielding occur after more than 60% overstrain. The residual stress are highly dependent on the Bauschinger effect. A large reduction in bore hoop stresses as a result of Bauschinger effect. Decrease the value of reautofrettage radius (r_d) with increase in Bauschinger effect factor (b_{ef}).

For bilinear kinematic and isotropic hardening quadratic axis symmetric 8-node elements have been used for inelastic finite element analysis. The material properties used here, E=206 GPa, Et=Etu=10 GPa, σy=850 MPa, and v=0.3.

All three principal stresses show good agreement with the Huang's model. with increasing pressure plastic zone is increased. During unloading re yielding occurred and with more than 70% overstrain loosing compressive hoop stresses near bore region .

A very close agreement can be seen throughout the wall thickness, including at the bore. This indicates the ANSYS model can accurately reproduce results from Huang's model, when using a bilinear material.

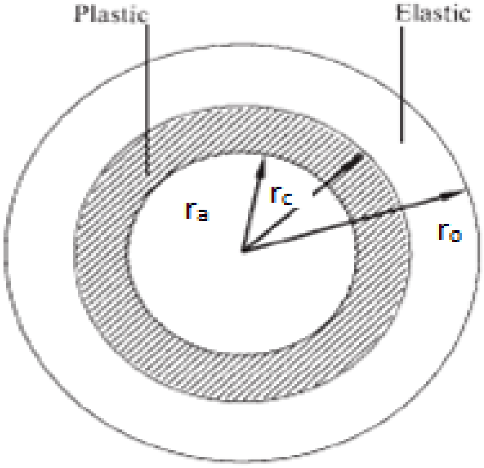

Fig.2.Elastic and plastic zone

Loading Results:

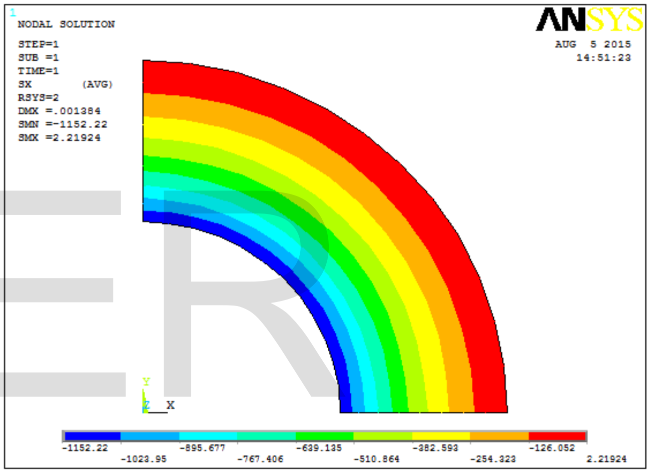

Fig.3. Nodal solution of Loading radial stress for k=2

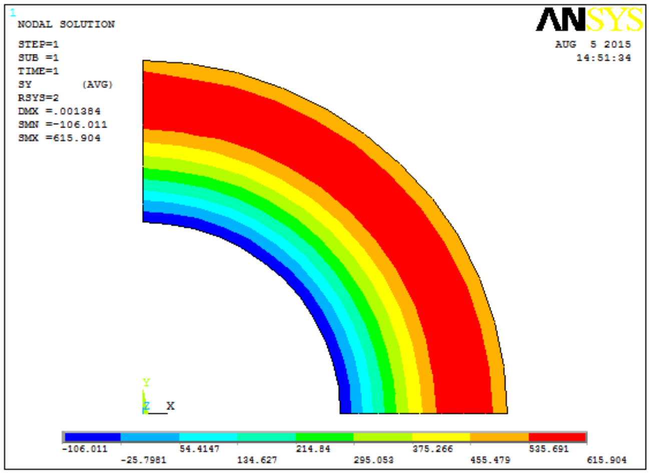

Fig. 4. Nodal solution of loading hoop stress for k=2

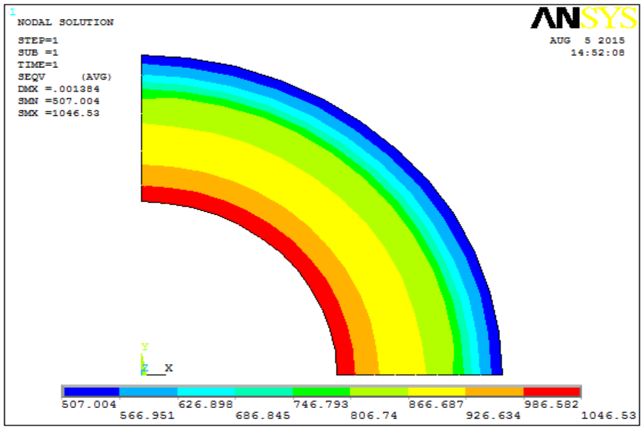

Fig.5. Nodal solution of loading vonMises for k=2

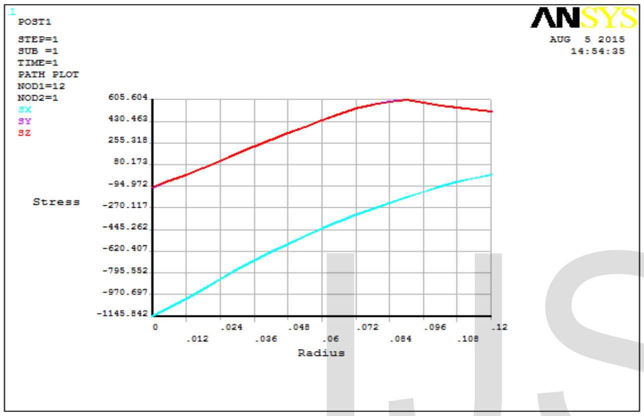

Fig.6. Loading radial and tangential hoop stress for

k=2,p=1200Mpa

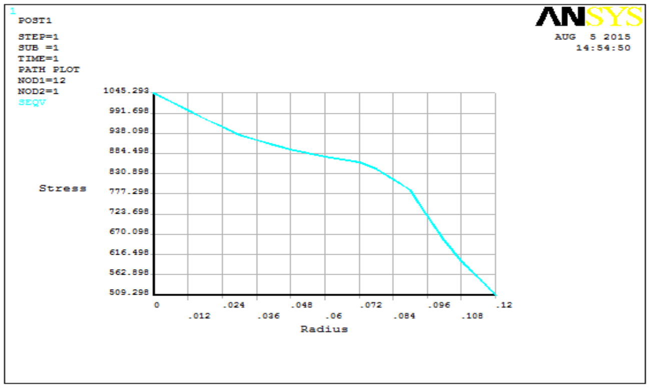

Fig.7. Loading vonMises stress, k=2,p=1200Mpa

Unloading Results:

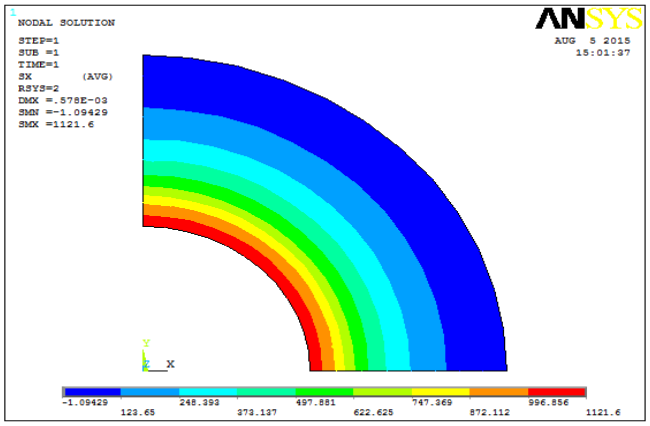

Fig.8. Nodal solution of Unloading radial stress for k=2

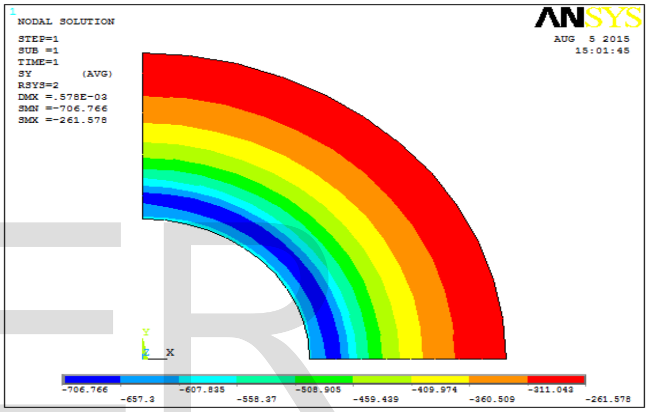

Fig. 9. Nodal solution of Unloading hoop stress for k=2

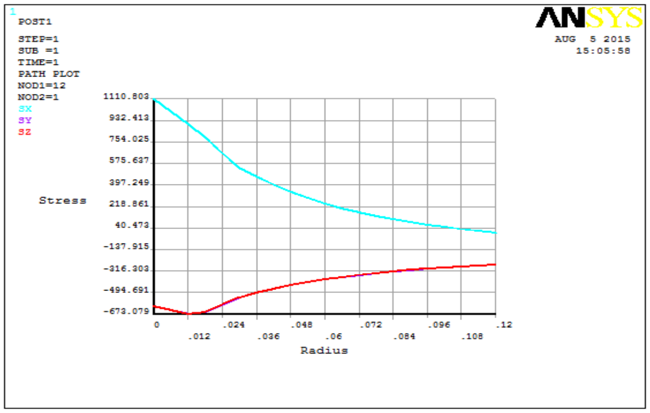

Fig.10. Unloading radial and tangential hoop stress for k=2,p=1200Mpa

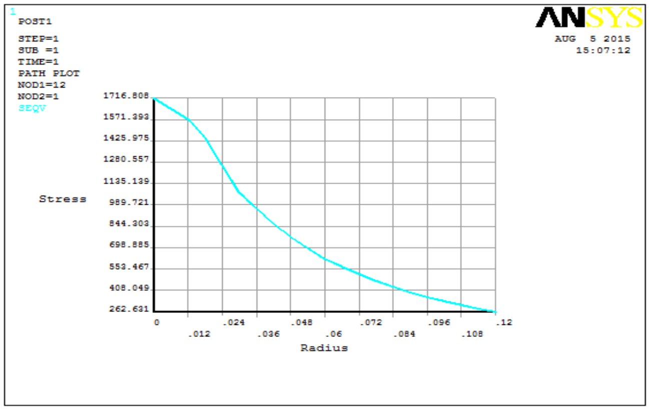

Fig.11. Unloading vonMises stress, k=2,P=1200Mpa

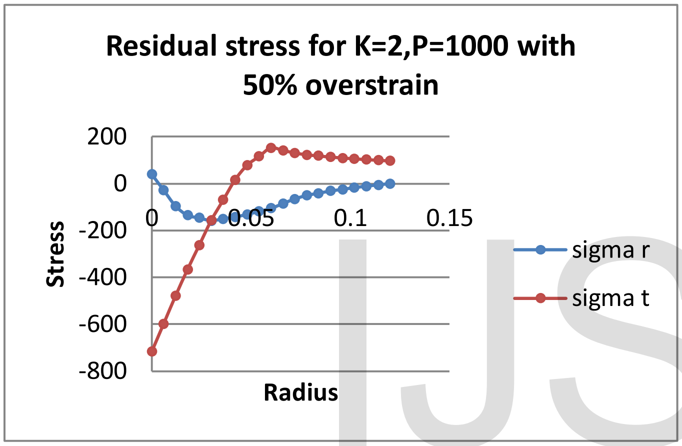

Fig.12. Residual stress without re- yielding, fork=2, P=1000Mpa.

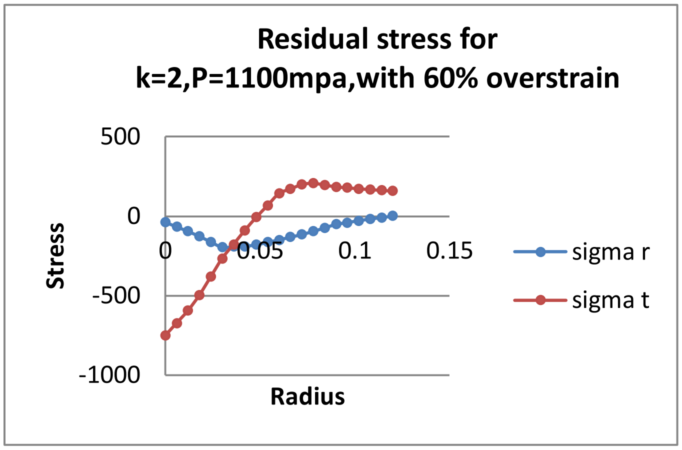

Fig.13. Residual stress without re- yielding, fork=2, P=1100Mpa.

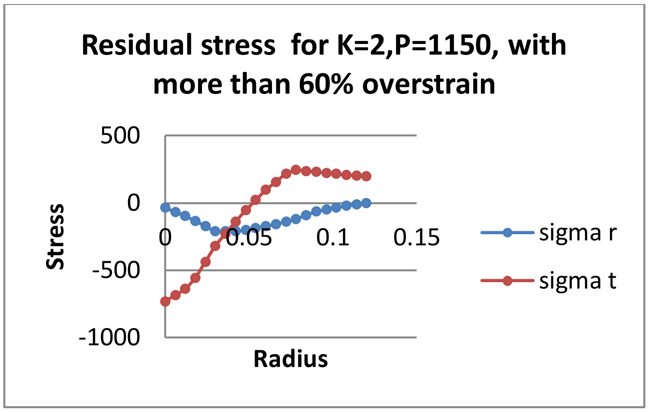

Fig.14. Residual stress with out re- yielding, fork=2, P=1150Mpa.

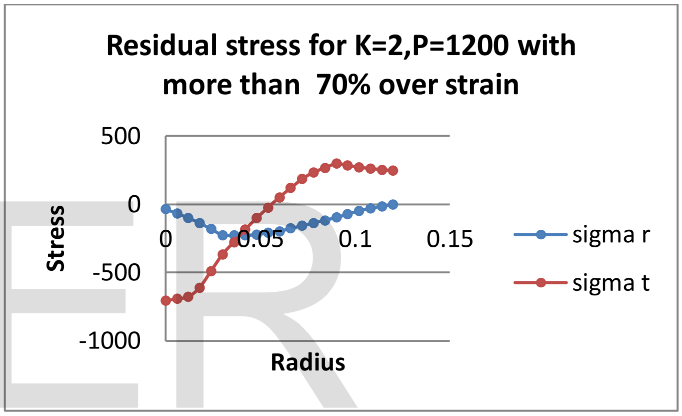

Fig.15. Residual stress with re- yielding, fork=2, P=1200Mpa

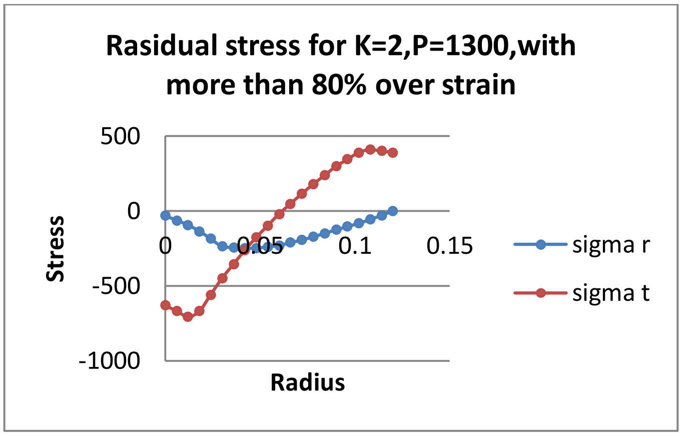

Fig.16. Residual stress more than 70% over strain with re- yielding,

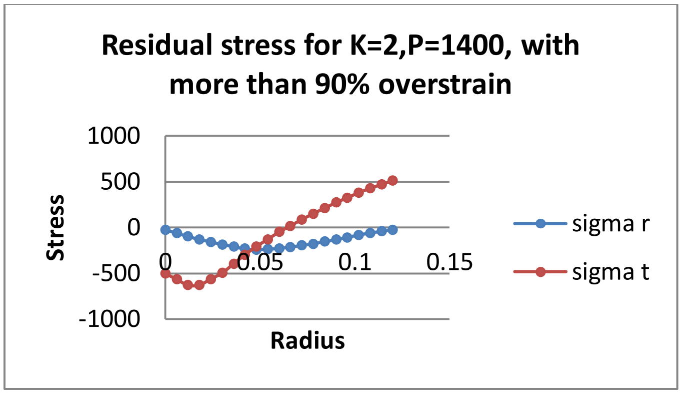

Fig.17. Residual stress with re- yielding, fork=2,

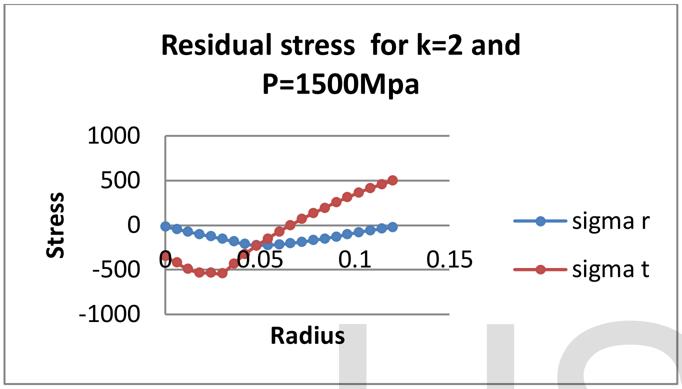

Fig.18. Residual stress of fully autofrettaged vessel with re-yielding, for k=2,P=1500Mpa.

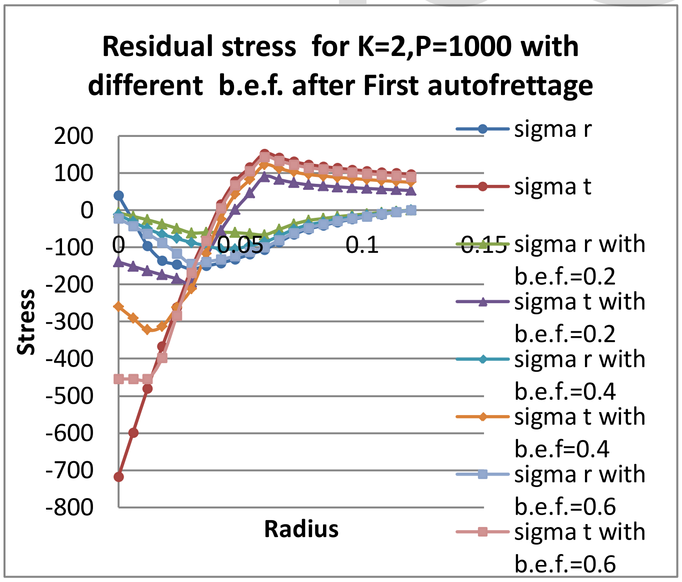

Fig.19.Residual radial and hoop stresses considering different Bauschinger effect factor during Ideal Elastic Unloading.

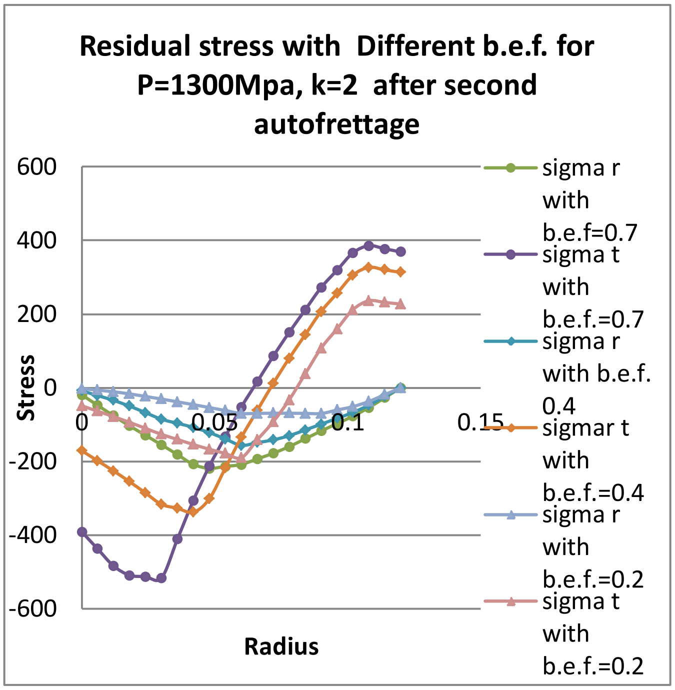

Fig.20.Residual radial and hoop stresses considering different Bauschinger effect factor during Elasto-Plastic Unloading .

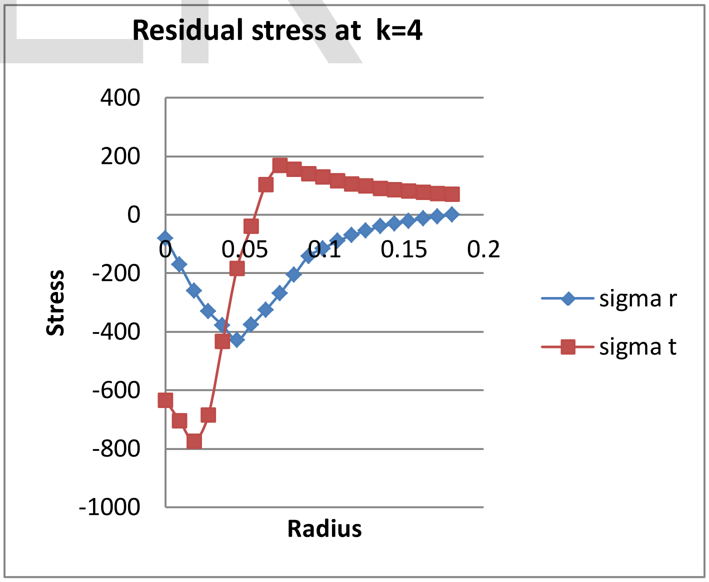

Fig. 21. More than 70% overstrain

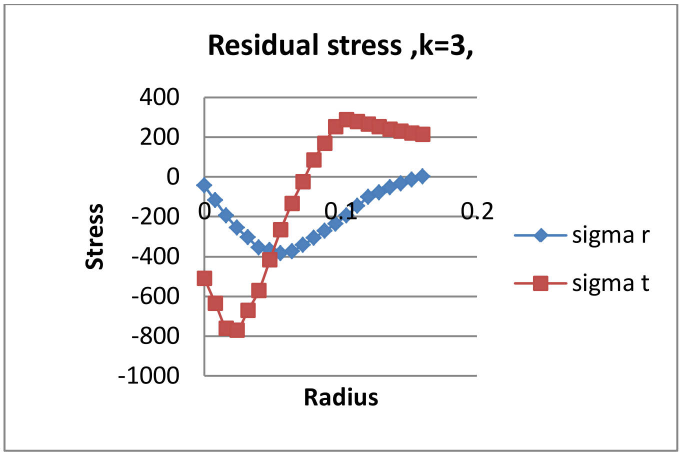

Fig.22. More than 70% overstrain

4 .CONCLUSION:

1. FE analysis of Autofrettage procedure, previously proposed for Cylindrical vessel, may also be extremely beneficial for spherical vessel .
2. FE analysis Stress behaviour making good agreement with Huang ,s analytical model. However, the bilinear stress-strain profile used here an approximation.
3. If the combination of stresses[loading & unloading] exceeds some yield criterion, the sphere will re-yield from the bore, thus losing much of the potential benefit of autofrettage
4. Prediction of re-yielding pressure.
5. Very limited benefit (in terms of increased compressive hoop stresses in the near bore region)as a result of overstrain above 70%.

6. Autofrettage above 70% is disadvantageous because of the significant increase in tensile Residual hoop stress at the outside diameter.

7. The residual stress are highly dependent on the Bauschinger effect. A large reduction in bore hoop stresses as a result of Bauschinger effect. The consideration of variable Bauschinger effect factor in prediction of reverse yield initiation is important and decrease the value of re-autofrettage radius (r_d) with increase in Bauschinger effect factor (b_{ef}).

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LIST OF NOTATION

P = Pressure

p_e =yield pressure at inside radius

p_a =Autofrettage pressure
p_{crt} =Critical Autofrettage pressures
r = Radius
r_o = Outside diameter
r_i = Inside diameter
ε = Deformation (strain)
$\sigma_{\theta,}\sigma_{\phi,}\sigma_r$ =Principal stresses
$\varepsilon_{\theta,}\varepsilon_{\phi,}\varepsilon_r$ =Principal strain
σ_r = Radial stress
σ_θ = Hoop stress,
ν = Poisson's ratio
E = Young's modulus; modulus of elasticity
u = Displacement
A1-4 = Material model parameters
B1,2 = Material model exponent
E1,2 =Loading and unloading Young's moduli
H1,2 = Loading and unloading reverse tangent moduli

K ,wall ratio = Outside radius / Inside radius
σY+, - = forward and reverse yield stresses, in simple tension and compression
$\epsilon^{+,-}$ tensio = forward and reverse yield strains, in simple
σ_S = Yield strength for Loading
σ_S^* = Yield strength for Unloading
σ_m = Meridian stress
b_{ef} = Bauschinger effect factor