Sanaz Jahangiri Journal of Engineering Research and Application *w.ijera.com*
ISSN : 2248-9622 Vol. 9,Issue 7 (Series -III) July 2019, pp 01-13

RESEARCH ARTICLE OPEN ACCESS

Nonlinear analysis of buckling behavior and ultimate strength of a corroded pipeline under hydrostatic pressure (With ANSYS)

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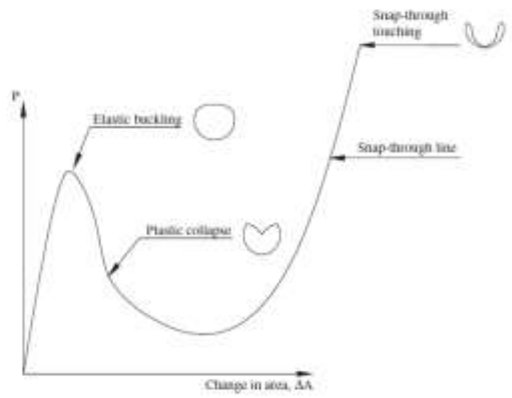
ABSTRACT:
Spillover of hazardous materials from transport pipelines can lead to catastrophic events with serious and dangerous environmental impact, potential fire events and human fatalities. The problem is more serious for large pipelines when the construction material is under environmental corrosion conditions, as in the petroleum and gas industries. In this way, predictive models can provide a suitable framework for risk evaluation, maintenance policies and substitution procedure design that should be oriented to reduce increased hazards, and also finding and introducing methods which help in Inspection and Maintenance of oil and gas pipelines seem mandatory.
In this project, various failure due to corrosion in oil and gas pipelines are predicted and there are models Using Finite Element Method, Modeling which helps in Inspection and Maintenance of oil and gas pipelines. The models released are designed, tested and evaluated with Ansys software. These models investigate different kinds of oil and gas pipeline and do predict the failure of them, failure which can occur because of rupture, fatigue and corrosion.
Keywords: Spillover of hazardous material, Corrosion and rupture, Prediction of a model

Date Of Submission: 30-06-2019 Date Of Acceptance: 19-07-2019

I. BACKGROUND

Corrosion is a phenomenon that happens in most steel structures, and causes thickness reduction, mechanical properties alteration, and loss of material. Local corrosion is a kind, which causes unsymmetrical cross section and results in change of buckling behavior and reduced load carrying capacity of pipelines. Oil and gas pipelines are commonly under axial and hydrostatic pressure that result in local dents. In critical situations, it can cause total buckling of structures, and put the total ultimate strength of the structure in danger.

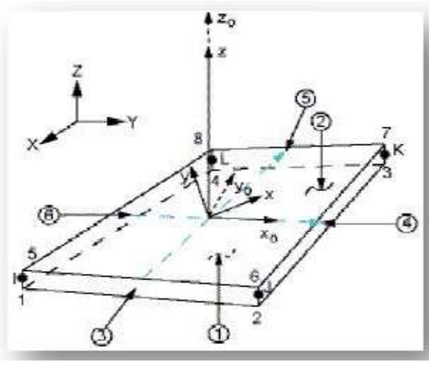
In this research, I analyzed corroded pipelines behavior under hydrostatic pressure before and after buckling. Although there are many researches in this area, all agree that the elasto plastic behavior of a corroded pipeline is similar to the figure below.



I designed the model in ANSYS software, and compare its pressure versus area's change graph to previous researches. Moreover, I calculated critical buckling pressures and compared to computed ones by Timoshenko in different corrosion cases. Additionally, I calculated the plastic pressure of my models (where the pipeline fails, and experiences maximum deformation), and compared them to Maxwell theory conclusions in these cases.

II. METHODOLOGY

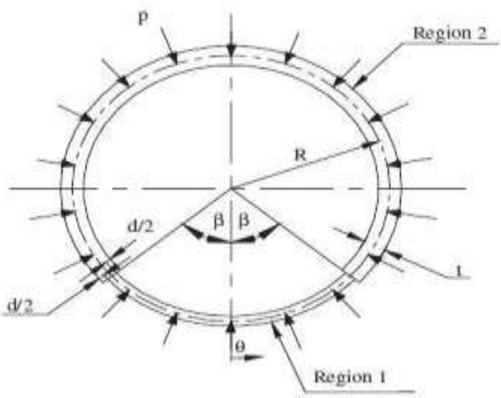
To design and analyze my models, I chose finite element method, and specifically ANSYS software, which enabled me to do the nonlinear analysis. To do the modeling I chose SHELL 181 element. This element has 4 node and 6 degrees of freedom in every node. This element is proper for linear analysis, large rotating analysis, and nonlinear analysis with large strain, and it is shown in below



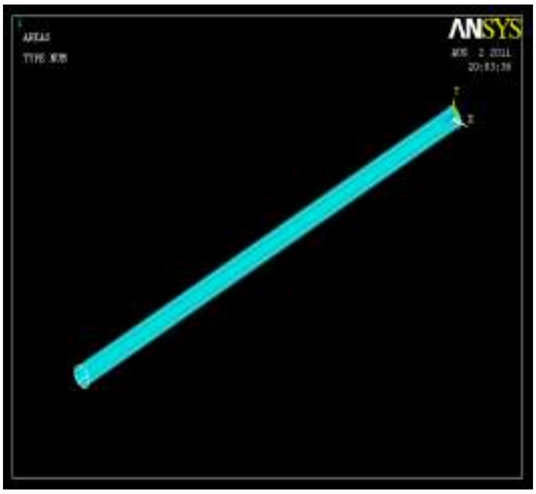
I chose my geometrical dimensions of pipelines from Norske Rules and Regulations (2004) as below:

E (gpa)	207				
v	0.3				
R (m)	0.2286				
t (m–without corrosion)	0.01829				
d (m)	0.1t	0.3t	0.5t	0.7t	0.9t
β (degree)	30˚	60˚	90˚	120˚	150˚
P (mpa)	depends on different quantities of d and β				
L (m)	11.8				
h (m)	t-d for Region 1 (-β< θ <β)				
	t for Region 2 (β < θ < 2π - β)				

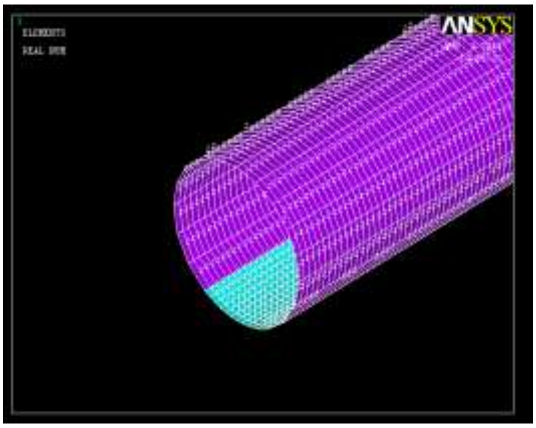
E: modulus of elasticity, v: poisson ratio, R: radius, t: original thickness, d: depth of corrosion, β: angular extension of corrosion, P: applied hydrostatic pressure, L: length, h: thickness regards to corrosion. Moreover, region 1 and 2 are shown below



In figure below, my initial modeling without meshing, applying boundary conditions and hydrostatic pressure is shown



As mentioned above, I considered corrosion as non-uniform thickness in my modeling. Corroded elements are in region 1, and the others in region 2. In a figure below I brought a sample modeling of β = 30˚ and d=0.1 t



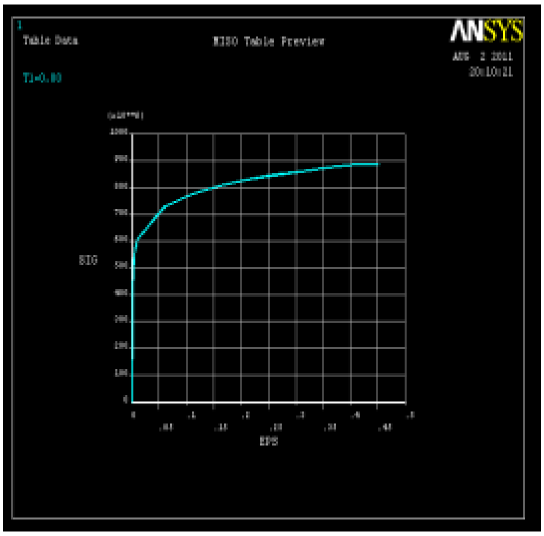
My modeling pipeline is steel and from the x-77 category. Tvergaard defines stress-strain relationship of this kind as follows

$$\sigma = \begin{cases} E\varepsilon & \varepsilon \le \varepsilon_{yp} \\ \sigma_{yp}\left(\frac{nE\varepsilon}{\sigma_{yp}} + 1 - n\right)^{1/n} & \varepsilon > \varepsilon_{yp} \end{cases}$$

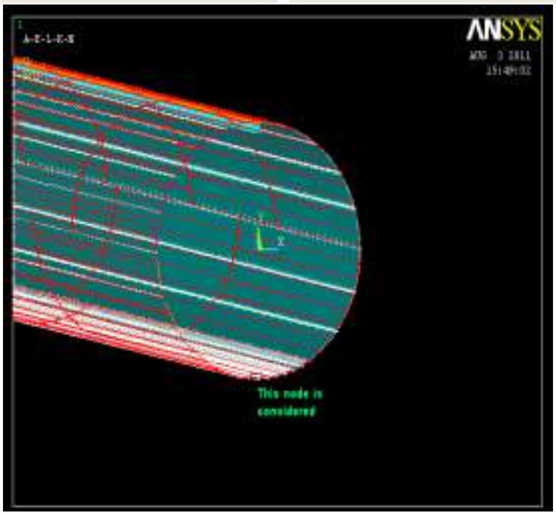
regarding that, my modeling mechanical properties is as follows

n (Strain Exponent)	10
ε_{yp} (Yield Strain)	0.002
v (Poisson Ration)	0.3
E (Young Modulus -Gpa)	207
σ_{yp} / E (Ratio Of The Yield Strength To The Young's Modulus)	0.002

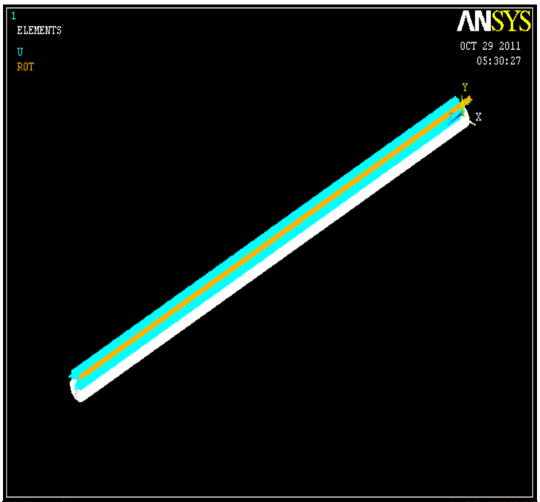
Under hydrostatic pressure, the corroded pipeline is under elastoplastic failure. Moreover, this pipeline did not fail after the buckling, and deformed to maximum extent possible. I chose the multi linear section of ANSYS and a proper limit of deformation to draw a proper stress strain graph in order to analyze the model more precisely (as shown below)

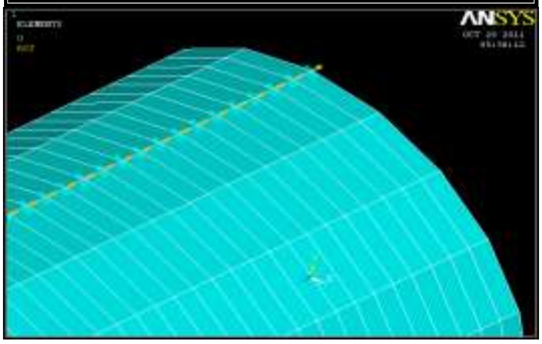


I used nonlinear analysis to achieve the ultimate strength. For that, I considered arc length method in the analysis. The purpose of my analysis was to find pressure versus transverse displacement (it must be pressure versus cross section but in here I considered a unit length) in a lowest middle node as shown below. Regarding the figure, by achieving the transverse displacement to 100 multiple of a regular displacement of the node, the analysis would be stopped (I considered the maximum amount of displacement to have the latest deformations of the pipeline).

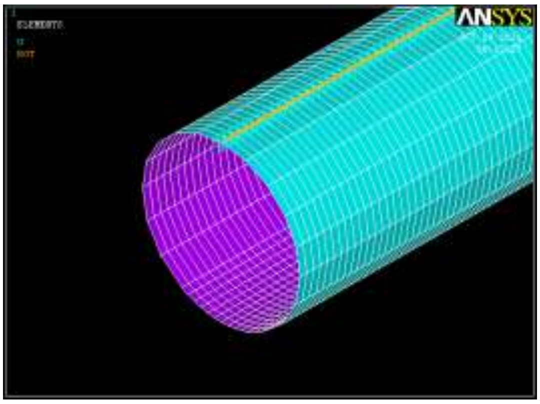


By different analysis and testing various kinds of boundary condition, I concluded to block all the upper nodes of the pipeline (displacements in x and y directions, and rotation along the length (z) are blocked). Moreover, to get the more precise results and to let the model choose its own buckling mode and plastically deform as it can, I block the displacement along the model's length in the first node of pipeline head. Any other boundary conditions would over constrain the structure and would result in higher pressures. All these explanations are shown below

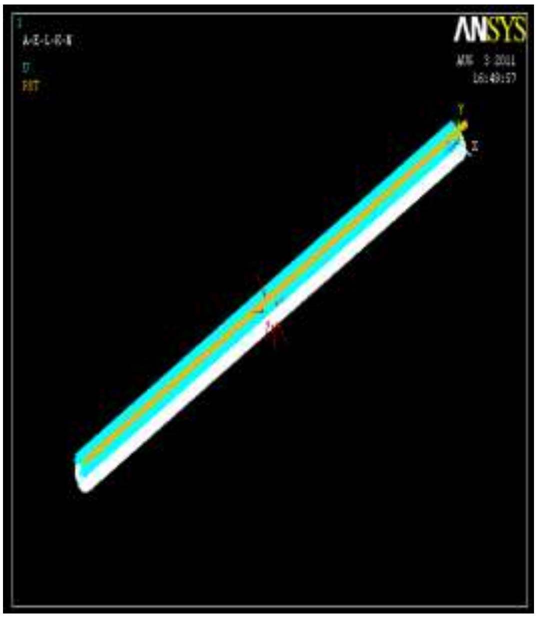




Above all, I just add the fact about the meshing that I considered the finer ones for the corroded regions as below



About the pressure applied, I should mention that this loading on the pipeline is equivalent to average hydrostatic pressure of mean depth of the sea. Moreover, this pressure is applied uniformly, and by using the arc length method, this pressure slowly increases to force the pipeline to deform plastically, to have the maximum displacement and failure, and cause the analysis to stop, as shown below

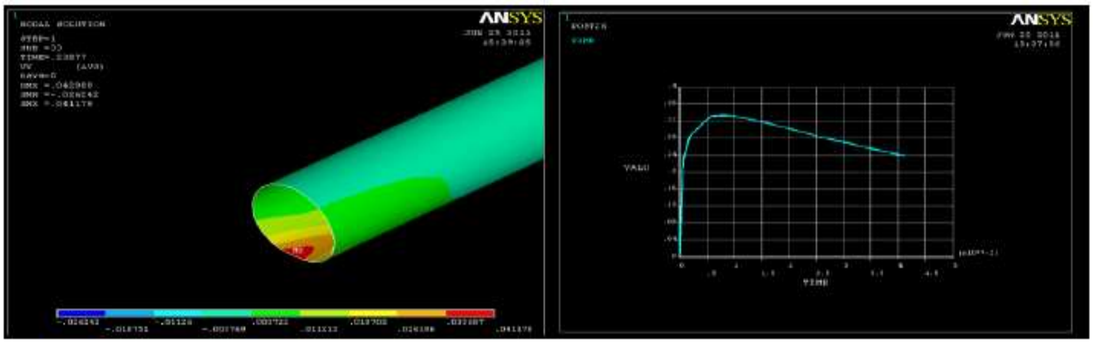


III. RESULTS AND DISCUSSIONS

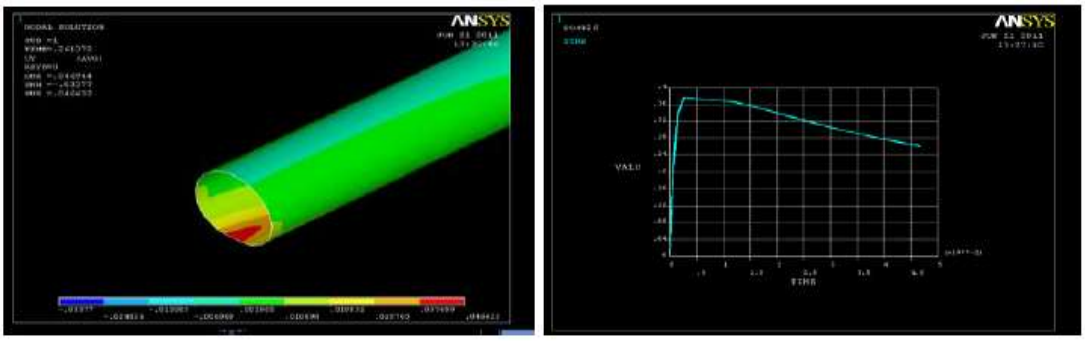
I did the nonlinear analysis, and gained the pressure changes versus displacement in the mentioned node for different modeling (all the figures below). It should be noted that the pressure changes is achieved by dividing them to pressure indexes, and they are brought in the table below along with the other related information, and also the changed section of the pipelines are showed in the figures below

β=30˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
ضرایب فشار	0.4043	12.852	141.9675	312.336	744.266
β=60˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
ضرایب فشار	0.25366	13.51	98.81	228.4	344.087
β=90˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
ضرایب فشار	0.4417	8.07	38.27	91.6453	175.87
β=120˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
ضرایب فشار	0.23504	5.009	13.42	25.39	56.7

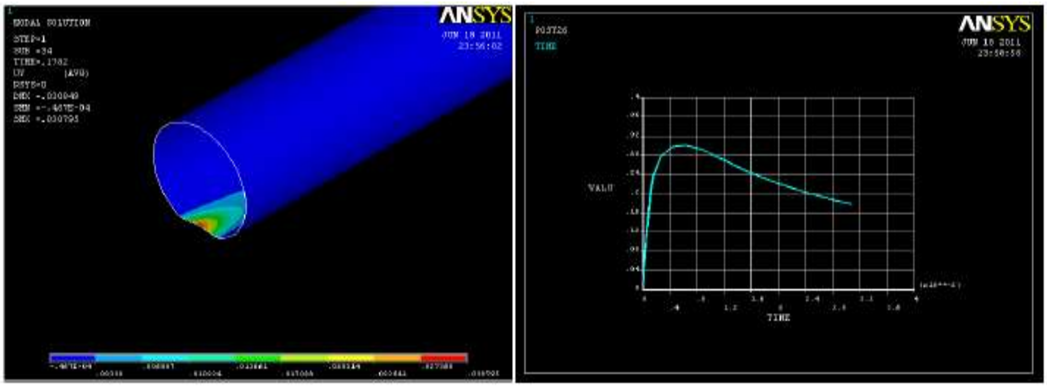
β=150˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
ضرايب فشار	0.102	1.94	16.4	24.86	51.57



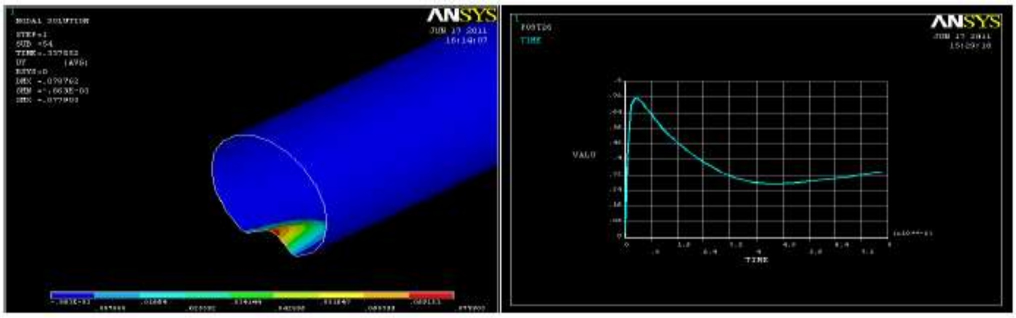
d/t = 0.1 & β = 30˚



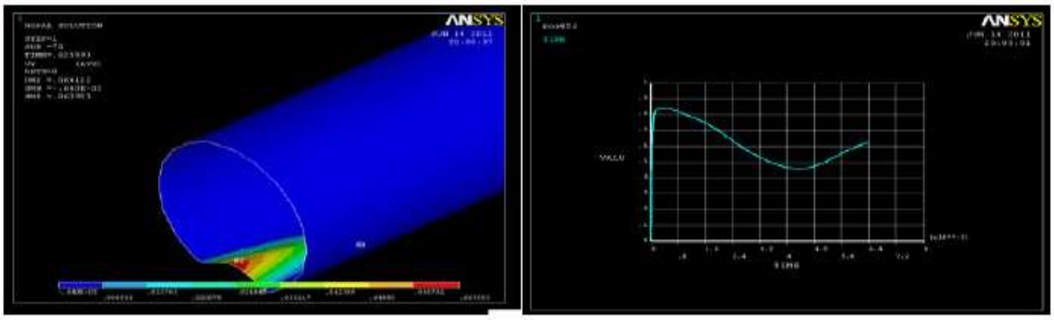
d/t = 0.3 & β = 30˚



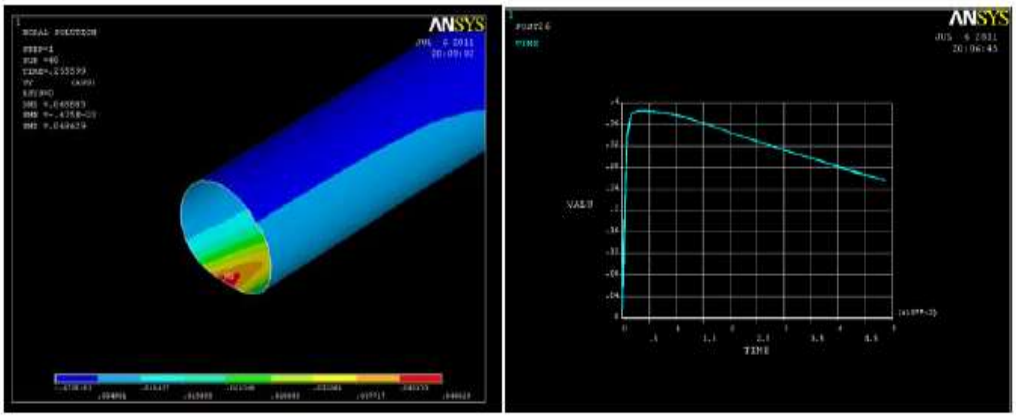
d/t = 0.5 & β = 30˚



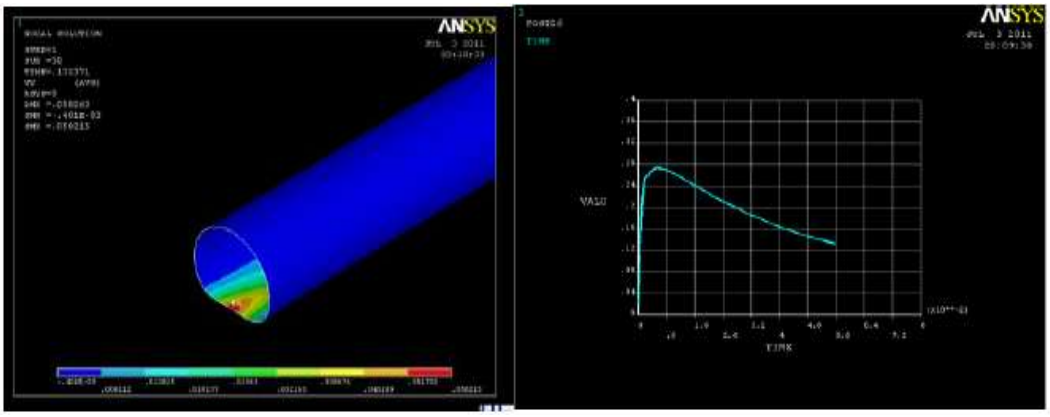
d/t = 0.7 & β = 30˚



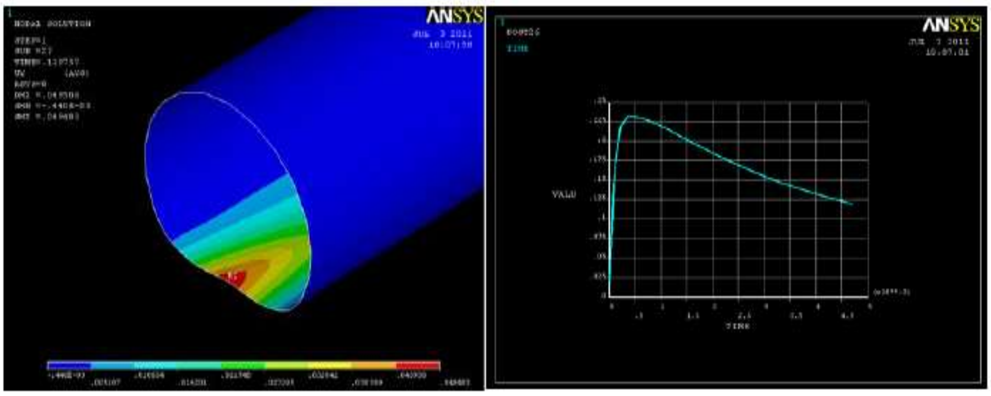
d/t = 0.9 & β = 30˚



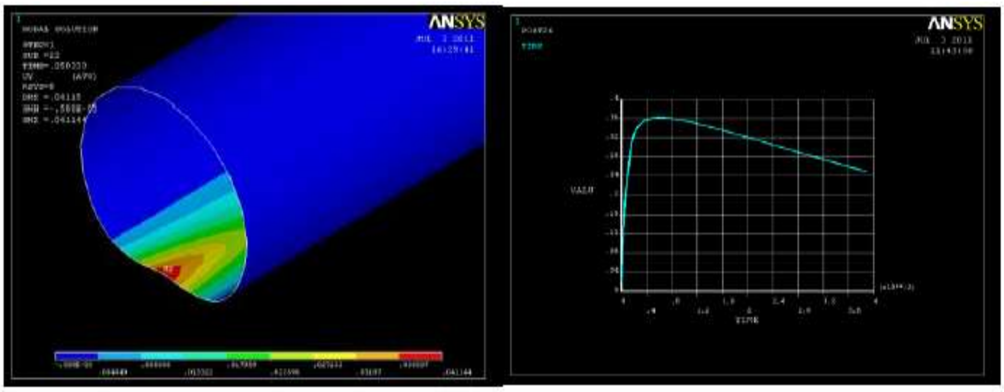
d/t = 0.1 & β = 60˚



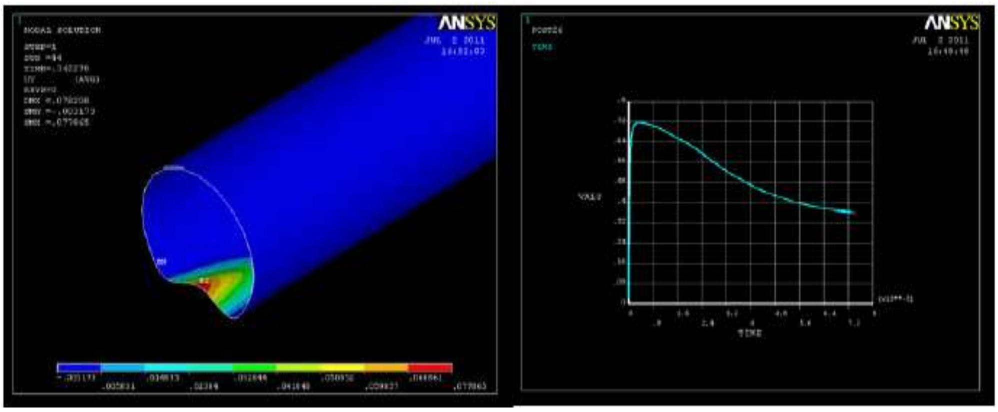
d/t = 0.3 & β = 60˚



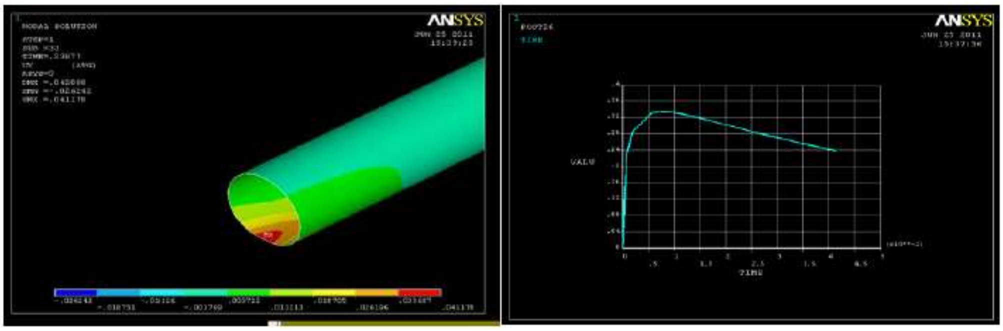
d/t = 0.5 & β = 60˚



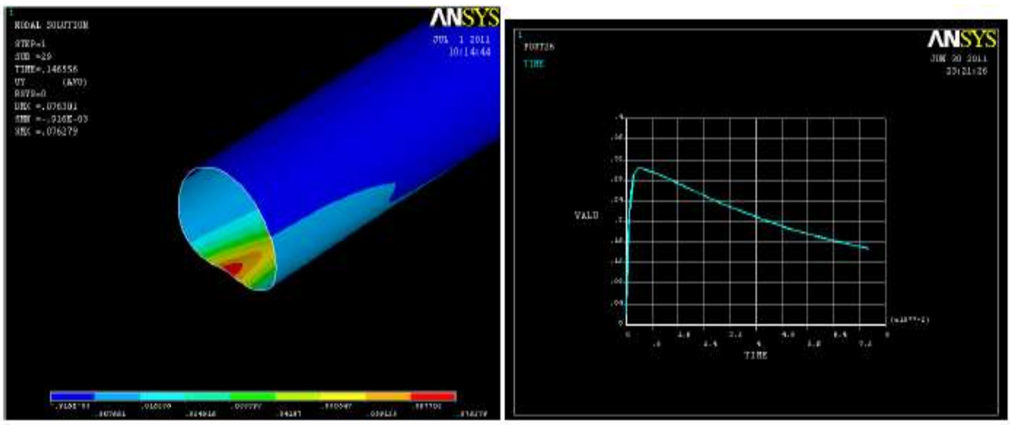
d/t = 0.7 & β = 60˚



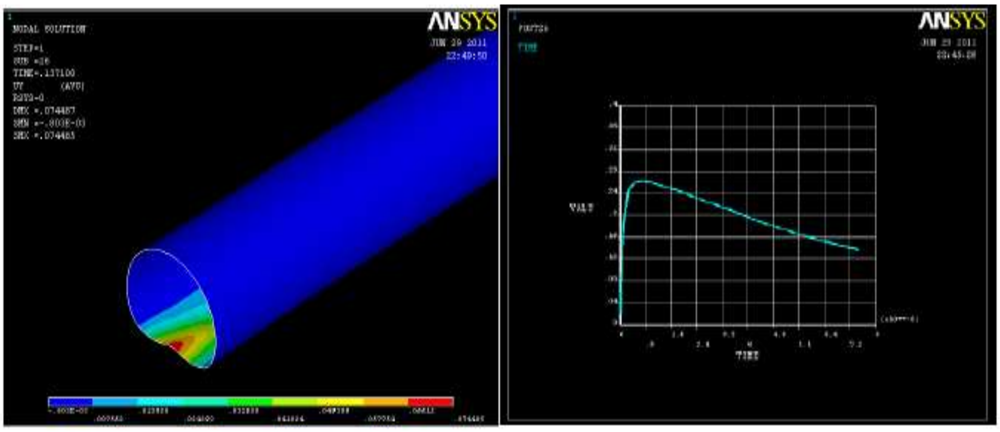
d/t = 0.9 & β = 60˚



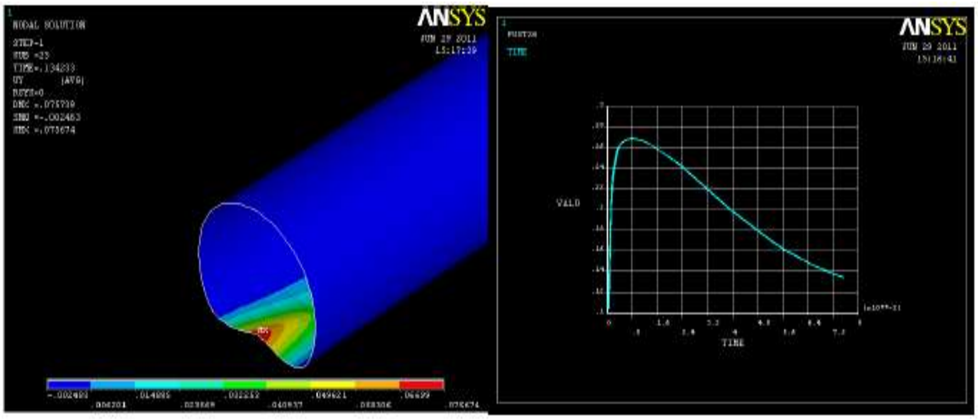
d/t = 0.1 & β = 90˚



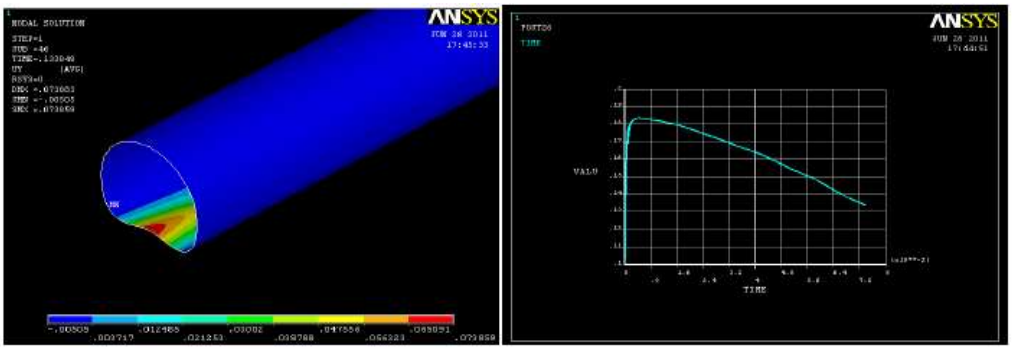
d/t = 0.3 & β = 90˚



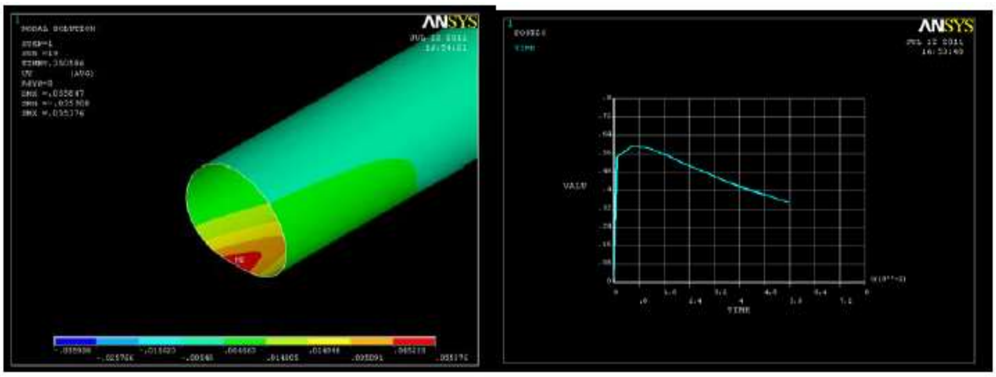
d/t = 0.5 & β = 90˚



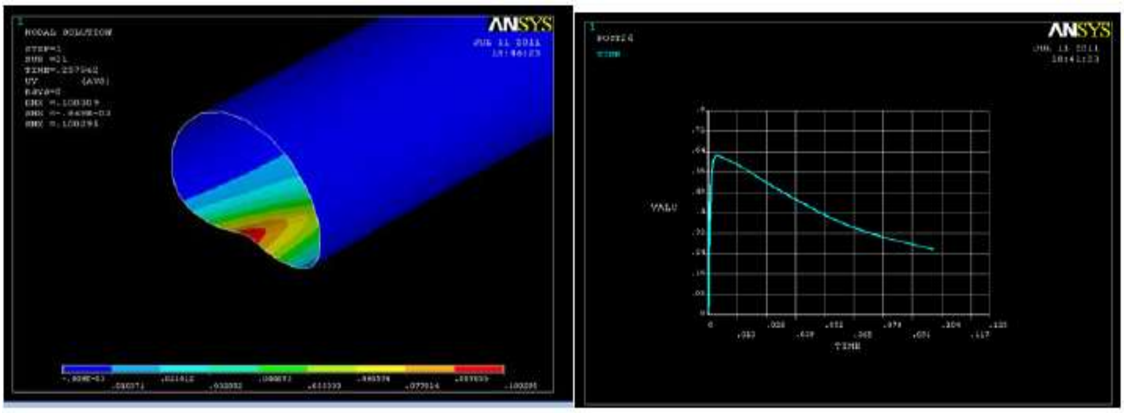
d/t = 0.7 & β = 90˚



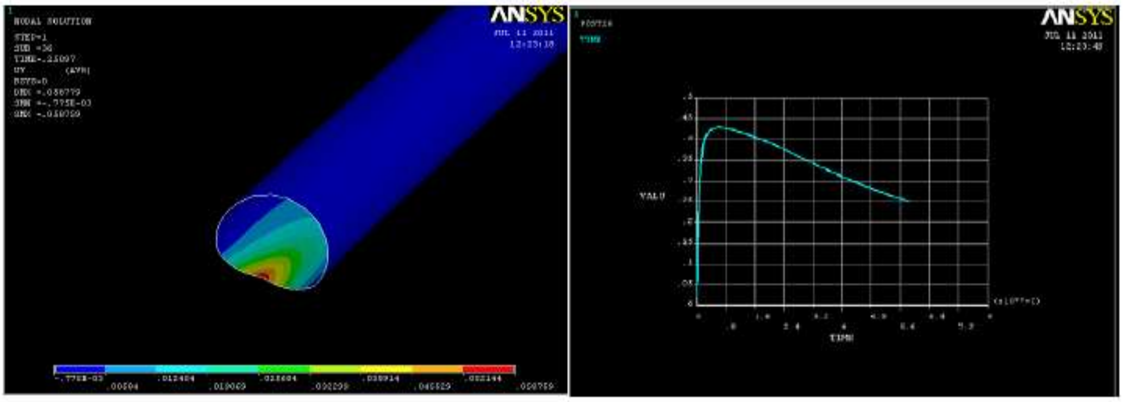
d/t = 0.9 & β = 90˚



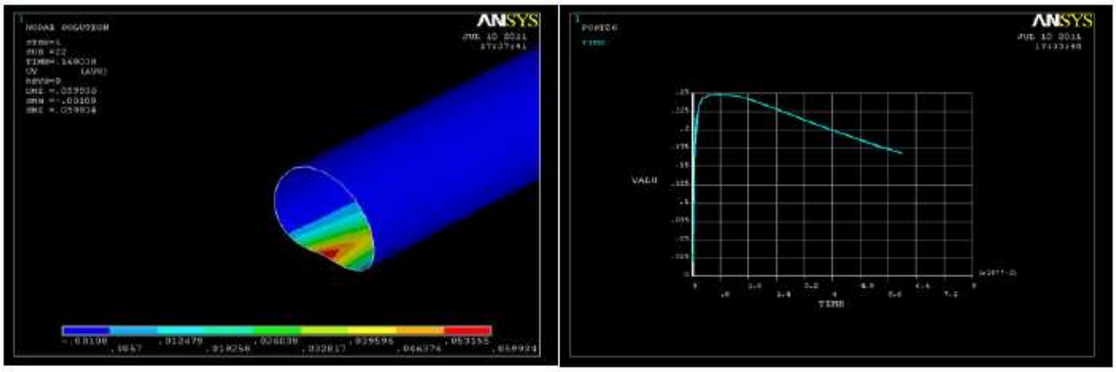
d/t = 0.1 & β = 120˚



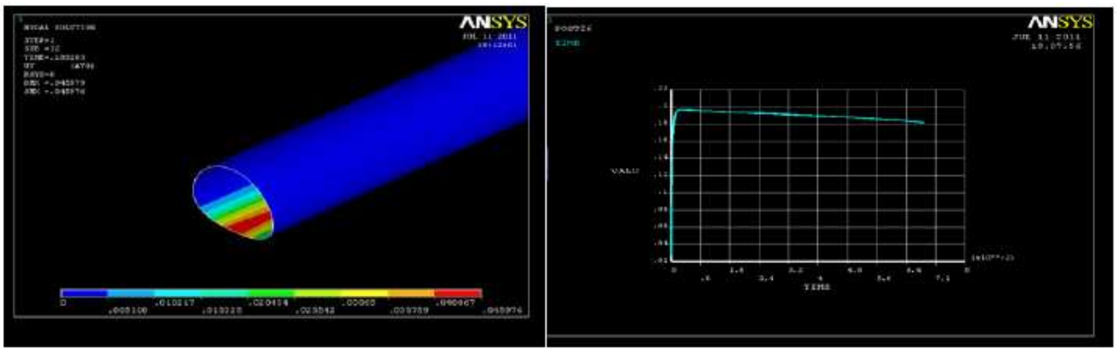
d/t = 0.3 & β = 120˚



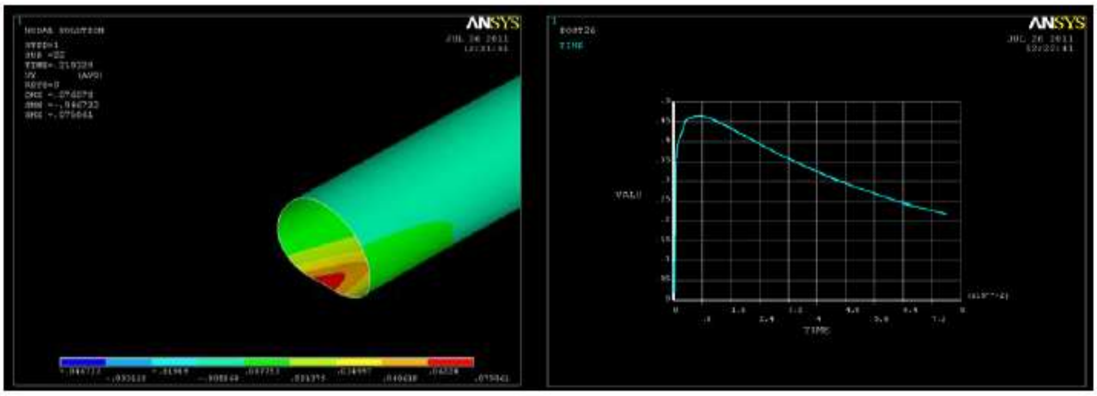
d/t = 0.5 & β = 120˚



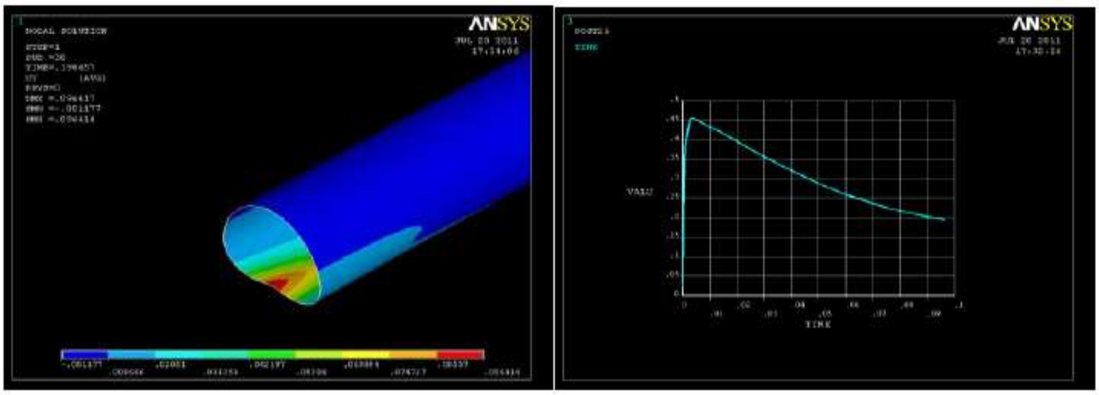
d/t = 0.7 & β = 120˚



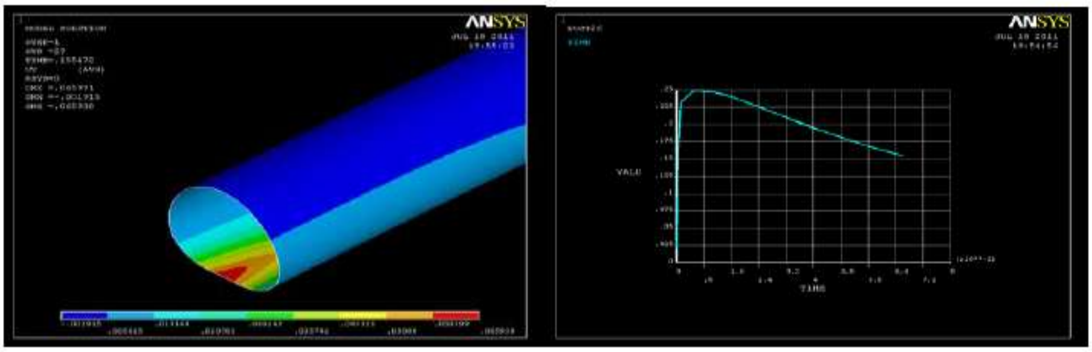
d/t = 0.9 & β = 120˚



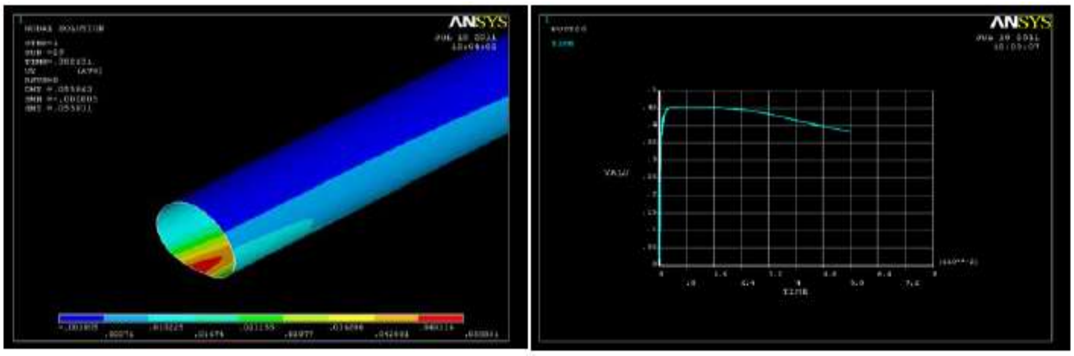
d/t = 0.1 & β = 150˚



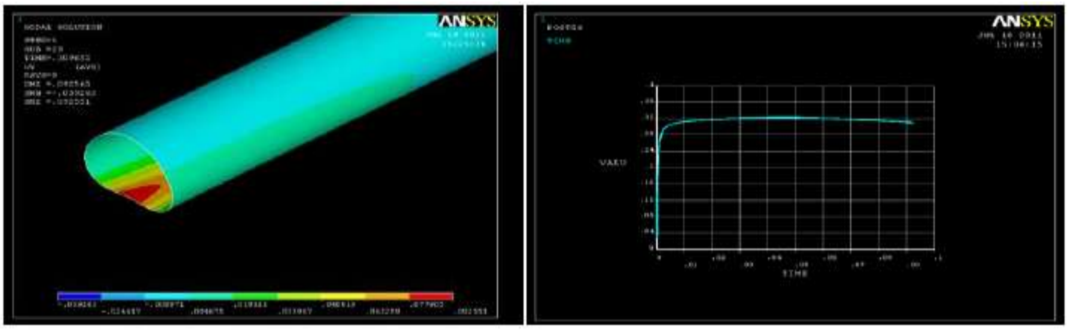
d/t = 0.3 & β = 150˚



d/t = 0.5 & β = 150˚



d/t = 0.7 & β = 150˚



d/t = 0.9 & β = 150˚

IV. CONCLUSION

By the pressure (mpa) versus displacement (m) graphs obtained from the ANSYS software analysis, it can be seen that the graphs are conformed to the previous researches (first figure in the background section). However, most of them do not achieve the snap through path, and have their maximum deformation before that and their load carrying capacity got to the minimum. I should add this fact that these changes are normal because I have analyzed the modeling in a nonlinear mode where material properties, loading, and boundary conditions are more in real condition than ideal ones.

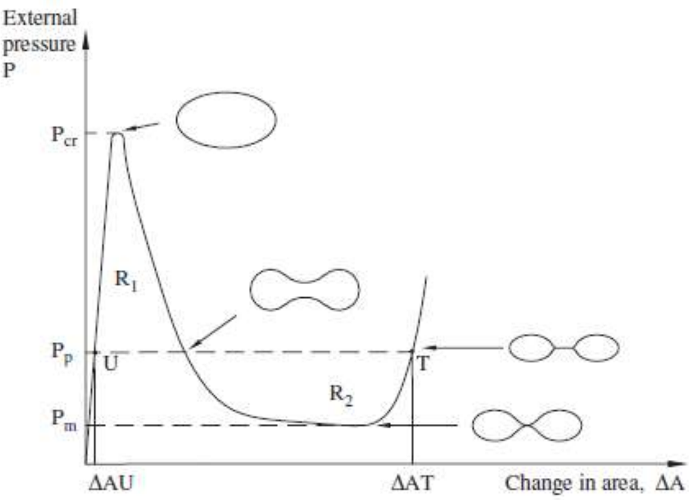
To compare my results, I have brought Timoshenko calculating method in below including the formula, and buckling parameter (k) for various amounts of β, which is visible in the shown table

$$\boldsymbol{P}_{\mathbf{cr}} = \frac{E}{12\,(1-\nu^2)}\left(\frac{t-d}{R}\right)^3(\boldsymbol{k}^2-1)$$

β	30˚	60˚	90˚	120˚	150˚
k	**5.912**	**4.375**	**3**	**2.364**	**2.066**

Moreover, the Maxwell calculating method of plastic pressure in which the structure fails and has its maximum deformation and minimum load carrying capacity is shown in the below formula and figure, and regards to these information, the calculated amount of this theory, related to my modeling is brought too.

$$\boldsymbol{P}_{\boldsymbol{p}}(\Delta \boldsymbol{A}_{\boldsymbol{T}}-\Delta \boldsymbol{A}_{\boldsymbol{U}}) = \int_{\Delta A_U}^{\Delta A_T} \boldsymbol{P}(\Delta \boldsymbol{A})\,\boldsymbol{d}\mathrm{A}.$$



β=30˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
P Plastic Real	0.261648	4.49125	26.35761	85.26496	185.2451
β=60˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
P Plastic Real	0.093	3.51023	12.27	31.421	91.3

β=90˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
P Plastic Real	0.0611	1.122	5.432	14.1	43.66
β=120˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
P Plastic Real	0.04586	0.875	3.495	6.795	20.5
β=150˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
P Plastic Real	0.0328	0.77	2.65	5.03	11.65

Results gained by my ANSYS software analysis and the references results and obtained errors are in the tables below. As it can be seen the average errors are 3 to 3.5 % which shows a normal conformity between my analysis and the references methods.

β=30˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
Hydrostati Pressure Used In Ansys(Mpa)	0.4043	12.852	141.9675	312.336	744.266
P Critical Real(Mpa)	0.329627	8.899918	41.20332	113.0619	240.2978
P Critical Ansys(Mpa)	0.34116	9.190722	42.60303	117.532	248.3541
Error (%)	3.499075	3.267495	3.397065	3.95369	3.352649
P Plastic Real	0.261648	4.49125	26.35761	85.26496	185.2451
P Plastic Ansys(Mpa)	0.252926	4.338193	25.29861	81.63526	177.7084
Error (%)	3.333472	3.407902	4.017821	4.256969	4.068506

β=60˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
Hydrostatic Pressure Used In Ansys(Mpa)	0.25366	13.51	98.81	228.4	344.087
P Critical Real(Mpa)	0.176122	4.755281	22.01519	60.40968	128.3926
P Critical Ansys(Mpa)	0.181999	4.900617	22.84487	62.35092	132.9999
Error (%)	3.336905	3.056323	3.768688	3.213458	3.588502
P Plastic Real	0.093	3.51023	12.27	31.421	91.3
P Plastic Ansys(Mpa)	0.089334	3.381958	11.83349	30.23331	87.94864
Error (%)	3.941958	3.654225	3.557575	3.779931	3.670715

β=90˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
Hydrostatic Pressure Used In Ansys(Mpa)	0.4417	8.07	38.27	91.6453	175.87
P Critical Real(Mpa)	0.077669	2.097075	9.708679	26.64062	56.62102
P Critical Ansys(Mpa)	0.081008	2.170184	10.00952	27.65122	58.68606
Error (%)	4.298148	3.486272	3.098665	3.793473	3.647133

P Plastic Real	0.0611	1.122	5.432	14.1	43.66
P Plastic Ansys(Mpa)	0.059122	1.083236	5.2472	13.43154	41.99248
Error (%)	3.238061	3.454893	3.402067	4.740885	3.819331

β=120˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
Hydrostatic Pressure Used In Ansys(Mpa)	0.23504	5.009	13.42	25.39	56.7
P Critical Real(Mpa)	0.044548	1.202802	5.568529	15.28004	32.47566
P Critical Ansys(Mpa)	0.046209	1.245989	5.766306	15.85859	33.70078
Error (%)	3.72771	3.590482	3.551678	3.786307	3.772411
P Plastic Real	0.04586	0.875	3.495	6.795	20.5
P Plastic Ansys(Mpa)	0.044253	0.841712	3.368017	6.549604	19.87845
Error (%)	3.503421	3.804302	3.633265	3.611414	3.031937

β=150˚	d/t=0.9	d/t=0.7	d/t=0.5	d/t=0.3	d/t=0.1
Hydrostatic Pressure Used In Ansys(Mpa)	0.102	1.94	16.4	24.86	51.57
P Critical Real(Mpa)	0.031731	0.856748	3.966427	10.88388	23.1322
P Critical Ansys(Mpa)	0.03286	0.882913	4.09836	11.29837	23.99862
Error (%)	3.557674	3.053998	3.326232	3.808348	3.745473
P Plastic Real	0.0328	0.77	2.65	5.03	11.65
P Plastic Ansys(Mpa)	0.031584	0.741332	2.549708	4.839248	11.25928
Error (%)	3.706402	3.723091	3.784604	3.792294	3.353836

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Sanaz Jahangiri" Nonlinear analysis of buckling behavior and ultimate strength of a corroded pipeline under hydrostatic pressure" International Journal of Engineering Research and Applications (IJERA), Vol. 09, No.07, 2019, pp. 01-13