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ON STANDARD PREDICTIONS OF REFORMABILITY AND COLLAPSE RESISTANCE FOR EXPANDABLE TUBULARS BASED ON ELASTO-PLASTICITY MODEL

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Abstract. The exploitation of geothermal power is an innovative energy source with great potential. However the exploration for deep geothermal sources is still costly and high risk operations. Recently, an expandable tubulars technology for casing is proposed with the potential to construct monobore completions. These lead to a smaller borehole and significantly reduce the cost of drilling process. Technically the expandable tubulars will be initially reduced by a folded plasticity condition and be expanded again downhole. In our studies, the performances of using them were studied in terms of reformability (foldability and expandability) and collapse resistance based on numerical approach. Elasto--plasticity models were investigated, conventional finite element method (FEM) was used for dicretizations combined with other necessary numerical algorithms. The standard predictions of expandable tubular performance were finally proposed, the numerical results were also presented at the final part of this paper.

1 INTRODUCTION

An innovative energy source such as geothermal is exploitation with very high potential. In deep geothermal source, the operations include high cost and risk. The major cost come from a part of drilling bore completion. Recently, a new technology is being developed, namely expandable tubulars technology, the diameter of tubulars will be initially reduced by a folded plasticity condition and could be expanded again downhole. This technology offered the expandable tubulars on using with maximizing through bore, reducing cost and improving productivity.

The fundamentals of mechanical reforming process involved an application of sufficient forces to overcome the yields strength of tubular material and taking the advantages of plastics deformation to reform a new geometry of tubular. The reforming process consists of folding and expansion process. The method of folding process is typically using contact with hard material. The methods of expansion process have been established alternatively [6], such as hydraulic pressure, cone expansion, rotary expansion or combination between them. With hydraulics pressure, the high pressure may require in some cases and the capacity of machine has to be considered. It could be used for initial expansion process for other methods. Cone expansion method is an extrusion process in which a tubular is subjected to the expansion forces acting around entire inner circumference. The tubulars will be radially expanded when the cone move in axial direction. The rotary expansion consist of a roller set which is discrete the position of expansion force in circumference. To apply acting expansion force to entire inner circumference, the roller set will be moved in longitudinal axis. The cone expansion and rotary expansion require minimizing frictions and vibrations of reforming system.

The concepts of productions are two possibilities of producing expandable tubulars. The first may produce expandable tubulars directly from tube in which available in market. This reforming process will include both folded reforming and expanded reforming. For the second concept, tubulars may be completely formed with expected geometry from factory directly, using them just complete only the expansion process.

As we have mentioned with some different of producing expandable tubulars or different of reforming methods. With this expandable tubulars technology, drilling operation can now using smaller hole for drilling deeper vertical wells or it can be used for extending the holes horizontally to reach untapped reservoir. In such a case, these expandable tubulars can provide very effective cost solutions and significantly save the drilling cost.

However to use expandable tubulars there still have some difficulties remaining. There is plastics flow deformation during the reforming process. Tubular structure will be reformed repeatly as folding and expansion, plastic behavior could be complicated. The Bauschinger effect [2] occurs during plastics deformation process. Tubular might be collapsed before the reforming process has completed. Furthermore, after completing reforming process the high pressure resistance, namely collapse pressure must be examined. This collapse pressure occurs due to different of pressure between inside and outside tubing. The different of pressure could be very high pressure and making catastrophically deform to tubular, especially in the area of salt at downhole.

In this research work, we studied the reformability and collapse resistance of expandable tubular by using modeling of elasto-plasticity [4,5], combined with conventional finite element method (FEM) and necessary numerical algorithms. The different geometries of expandable tubulars have been tested numerically combined with different types of steel, e.g. mild steel, TRIP steel and TWIP steel. Note that TRIP is stand for Transformation Induced Plasticity and TWIP is stand for Twinning Induced Plasticity.

2 REFORMING PROCESS FOR EXPANDABLE TUBULARS

The expandable tubulars includes plastic deformation due to reforming process (folding and expansion), also bending and straightening during transportations and installation process. After reforming process this tubular must satisfy the resistance of collapse pressure at downhole. In Fig.(1) shown the overview of reforming process and collapse pressure resistance. The tubulars begin with an initial geometry (G1), tubulars are perfectly round. These tubulars will be folded with plastic deformation at the folding process, typically this process could be done by pressing with hard material. After folding process the tubulars have reformed one time, the geometry is shown in (G2). Now the diameters of tubulars are significantly reduced with no round geometry. This will make the transportations more efficiently economically. The tubulars may be deformed again by bending on reeling and unreeling process. In order to prepare the tubulars for installation into drilling hole, the straightening is required. These tubulars must be reversely deform again by bending until the straight tubulars have found or atleast having possibility to install into drilling hole, this is shown in (G3).

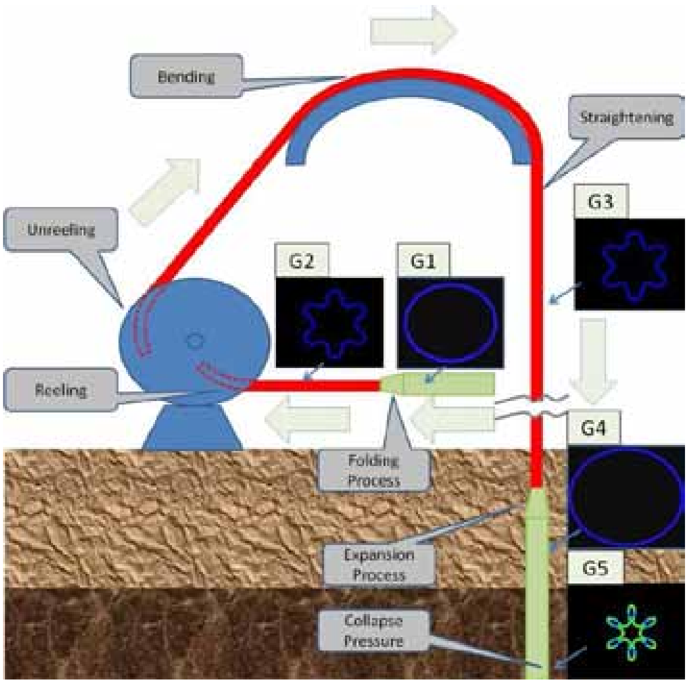

Figure 1: Overview of reforming process and collapse pressure resistance for expandable tubulars

After the folded tubulars are installed into drilling hole, the expansion processes can be now started, may be with different methods as we have mentioned before. The expansion process will make the tubular round with plastic deformation. After installation the tubulars will be applied by namely collapsed pressure. This pressure in some condition could make the tubulars catastrophically deform as in (G5). There are clearly shown that the reforming process and collapse pressure resistance will make tubulars repeatly plastically deform. The analysis of these tubulars requires the suitable model, especially plastic flow deformation. This elasto-plastic deformation model will be discussed in the next section.

3 MODEL THEORY OF ELASTO-PLASTICITY

According to applied forces, material deforms with elastic properties until some magnitude of this force, stress may not increase but strain is significantly increased. This is the physical phenomena for typical elasto-plastic model. The strain rate ($\dot{\boldsymbol{\varepsilon}}$) which describe the total deformation is divided into strain rate of elastic deformation ($\dot{\boldsymbol{\varepsilon}}^{el}$) and strain rate of plastic deformation($\dot{\boldsymbol{\varepsilon}}^{pl}$) , given by the following function.

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{el} + \dot{\boldsymbol{\varepsilon}}^{pl} \ . \quad (1)$$

On elastic deformation, the structural response is assumed to be derivable from strain energy (**U**), so that stress fields can be directly defined by gradient of strain energy respect to the elastics strain $\boldsymbol{\sigma} = \partial \boldsymbol{U} / \partial \dot{\boldsymbol{\varepsilon}}^{el}$. In order to implement hardening law, it is a proper combinations of isotropic and kinematics hardening model. The particular yield surface condition is described by

$$f(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - \boldsymbol{\sigma}^{\boldsymbol{o}} = 0 \ , \quad (2)$$

combine with the equivalent Mises stress $f(\boldsymbol{\sigma} - \boldsymbol{\alpha}) = \sqrt{3/2(\boldsymbol{S} - \boldsymbol{\alpha}^{dev}) : (\boldsymbol{S} - \boldsymbol{\alpha}^{dev})}$, where (**:**) denotes the tensor operator, $\boldsymbol{S}$ denotes the deviatoric stress tensor and $\boldsymbol{\alpha}^{dev}$ is the deviatoric part of back stress tensor and $\boldsymbol{\sigma}^{\boldsymbol{o}}$ denotes current yield stress.

During the plastic deformation, material behaves as flow plastically. The plastics deformation can be obtain by namely the flow rule, it is given by

$$\dot{\boldsymbol{\varepsilon}}^{pl} = \dot{\boldsymbol{\lambda}} \frac{\partial \boldsymbol{\Psi}}{\partial \boldsymbol{\sigma}} \ , \quad (3)$$

where $\boldsymbol{\Psi}$ denotes flow potential and $\dot{\boldsymbol{\lambda}}$ is time rate parameter here the equivalent plastics strain rate is used.

Considering the hardening law, the nonlinear isotropic /kinematics hardening model is used to describe the stress evolution. This consists of two components: one is the nonlinear kinematics hardening which describe the translation of yield surface in stress space through backstress [3]; another is an isotropic hardening in which describe the size of yield surface. The formulation is given by

$$\dot{\boldsymbol{\alpha}} = C \frac{1}{\boldsymbol{\sigma}^{\boldsymbol{o}}} (\boldsymbol{\sigma} - \boldsymbol{\alpha}) \dot{\boldsymbol{\lambda}} + \gamma \boldsymbol{\alpha} \dot{\boldsymbol{\lambda}} \, , \quad (4)$$

where C and γ are material constant, when γ is zero become the linear kinematics model and when C and γ are zero so become the isotropic hardening model.

The model has been implemented in material property subroutine in Abaqus/CAE [1], combination with nonlinear finite element and some other numerical necessary algorithms in the computation. The tool for standard prediction of plastic behavior for expandable tubular can be performed and simulated the mechanism of expandable tubular, which will be discussed in the next section.

4 NUMERICAL RESULS OF REFOMABILITY AND COLLAPSE RESISTANCE

4.1 Expandability of folded tubulars

In this computation, we deal with expandability of folded tubulars. The hydraulics pressure is used for expansion process. The folded geometry may already be obtained by tubulars production manufacturing. We start with the geometry G2 (see in Fig.(1)) and concerning only on expansions process The analysis of plastic deformation are performed with different tubular geometry and different material. The main objective of this computation is to find out the mechanism of plastics deformation with different optimized geometry and different tubular material.

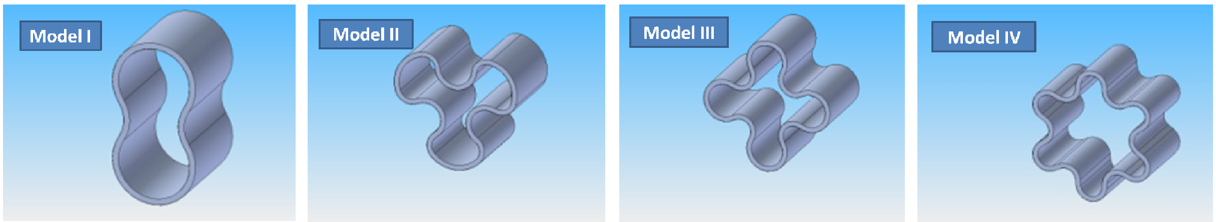

Figure 2: Geometry of tubulars

The optimized geometries are obtained by our project partner [5] at Institute of Production Engineering and Machine Tools, University of Hannover. The different geometries are shown in Fig. (2). The parameters shown in Table (1) with the maximum outer diameter (*OD*), thickness (*t*) and maximum ovalidity (*OD/t*). Tubular geometry is analyzed with different kind of tubular material.

Table 1: Geometry parameters of Tubulars

Max. OD (mm.)	Thickness (mm.)	Max. OD/t
165.0	6.0	27.5

Table 2: Material properties

Descriptions	Modulus of Elasticity *(N/mm^2)*	Poison's ratio	Yields stress *(N/mm^2)*	Rupture stress *(N/mm^2)*	Max. Strain %
Mild steel	2.10E+05	3.00E-01	4.00E+02	5.00E+02	8.20E+00
TRIP steel	2.10E+05	3.00E-01	4.80E+02	1.10E+03	5.00E+01
TWIP steel	2.10E+05	3.00E-01	4.50E+02	6.99E+02	9.00E+01

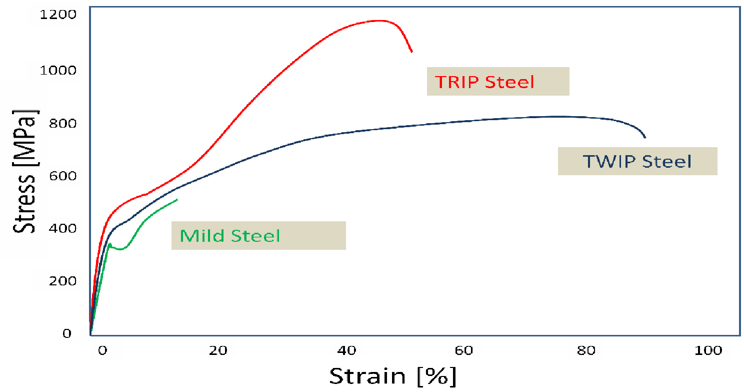

Figure 3: Stress-strain curve for different steel materials

There are mild steel, TRIP steel and TWIP steel, the mechanical properties can be found in Fig. (3) and Table (2). Mild steel represents the steel which is normally used for tube and available in market, typically rupture strain is less than 20 %. TRIP steel is used for representing high strength steel, the strength is higher than 1000 N/mm^2 and rupture strain can reach 50 % approximately. The TWIP steel is used for representing high deformation which is 90 % approximately.

For TRIP steel, the plastic flow process occurs with phase transformation from austenite to martensite. The molecule builds the new structure during the plastics flow process, which is the reason why strength can be increased significantly. Also the strain can be increased but only depending on new form of molecular structure. For TWIP steel, the strength can be increased but smaller amount compare to TRIP, while rupture strain increase significantly due to the so-called Twinning effect. TRIP and TWIP are now widely used in auto-industry.

Table 3: Summary results.

Descriptions	Material	Max. Stress (N/mm^2)	Pressure (N/mm^2)	Evaluation deformation	Expansion Ratio %
Model 1 Set # I	Mild steel	5.00E+02	5.71E+00	*Rupture*	-
Model 1 Set # II	TRIP steel	6.05E+02	3.00E+01	*Plastic*	-1,41E+01
Model 1 Set # III	TWIP steel	5.89E+02	3.00E+01	*Plastic*	-1,41E+01
Model 2 Set # I	Mild steel	5.00E+02	8.16E+00	*Rupture*	-
Model 2 Set # II	TRIP steel	7.23E+02	2.98E+01	*Plastic*	2,01E+01
Model 2 Set # III	TWIP steel	6.18E+02	3.00E+01	*Plastic*	1,96E+01
Model 3 Set # I	Mild steel	5.00E+02	6.61E+00	*Rupture*	-
Model 3 Set # II	TRIP steel	8.46E+02	3.00E+01	*Plastic*	2,15E+01
Model 3 Set # III	TWIP steel	6.28E+02	3.00E+01	*Plastic*	2,06E+01
Model 4 Set # I	Mild steel	5.00E+02	4.33E+00	*Rupture*	-
Model 4 Set # II	TRIP st eel	7,46E+02	3.00E+01	*Plastic*	2,27E+01
Model 4 Set # III	TWIP steel	6,30E+02	3.00E+01	*Plastic*	2,29E+01

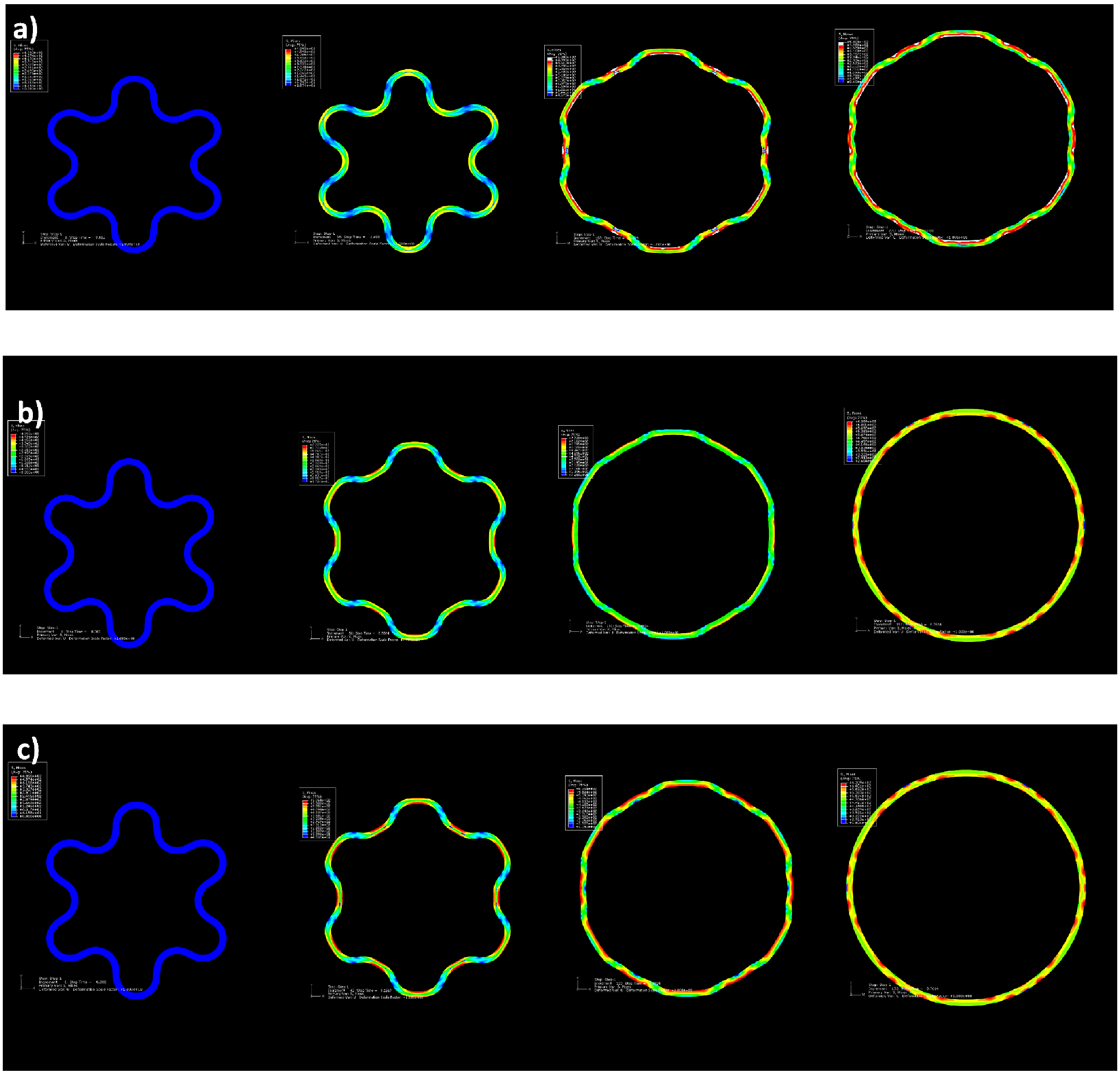

Figure 4: Mechanism of expansion process for model 4; a) mild steel; b) TRIP steel; c) TWIP steel.

To obtain reasonable solutions with acceptable accuracy, high requirements towards the modeling technique and the numerical treatment are necessary. The nonlinearity in this computation includes geometrical nonlinearity due to the large deformations and the material nonlinearity which describes the nonlinearity of the material laws. The iterative Newton method is used to obtain the nonlinear solution, while the system equation solver is the direct method. The element meshes are implemented with rectangular element type. The resolutions are obtained with global mesh refinement, beginning with course mesh and then refine until convergence occur.

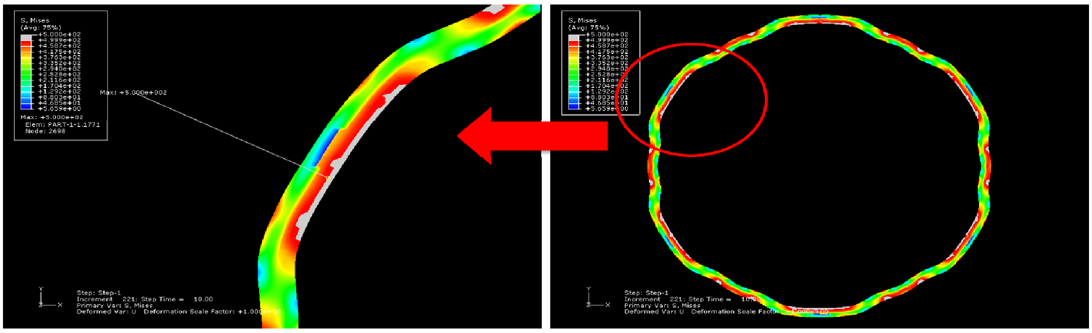

Figure 5: Expansion process at critical part of structure.

Concerning numerical results, the plastic strain occurred after the pressure was increased. At some pressure the tubular were reformed. Theoretically, if materials do not arrive at the rupture point when increasing the internal pressure; they should be reformed until the round geometry occurs. If they arrive rupture point, they will be damaged before the round geometries have formed.

Three different types of steel (mild steel, TRIP steel and TWIP steel) are considered. The results showed very clearly that, for all model geometry of mild steel is damaged before round geometry could be formed. Oppositely, TRIP and TWIP steel can be formed until round geometry occur without any damages. Concerning again maximum stress, the TRIP steel has higher magnitudes compared with TWIP steel at the same internal pressure. These came from the nonlinearity of the material, or TRIP steel is harder and TWIP steel can be reformed easier than TRIP steel. The results of the expansion process with different geometries and different materials are presented in Table (3). The expansion mechanisms can be found in Fig.(4) and in Fig.(5), where the critical part of the structure in the expansion process is shown.

4.2 Testing of resistance collapse pressure

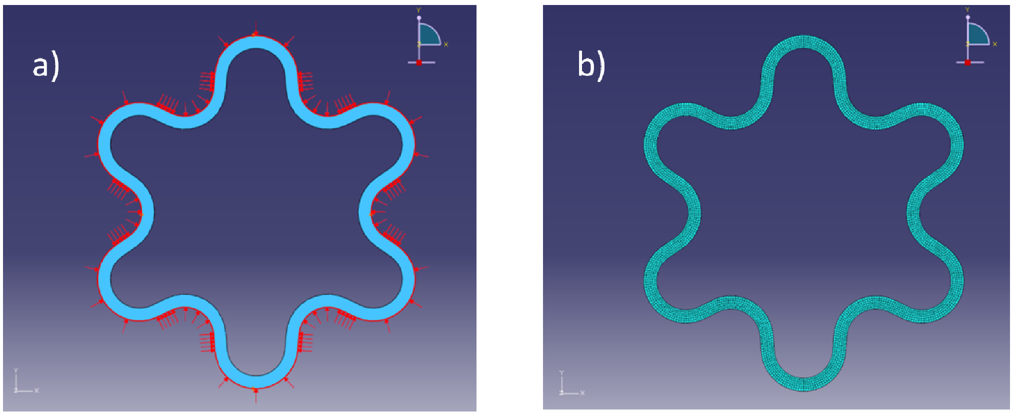

Figure 6: Setting problem for collapse pressure test; a) collapse pressure; b) 3456 rectangular meshes

Extension from previous example (4.1) the numerical testing of collapse pressure resistance is investigated. The main objective for this computation is to study the deformed mechanism of resistance collapse pressure and the influence of geometry imperfection on the capacity of resistance collapse pressure. As we have mentioned when using expandable tubular downhole, it has a possibility to get high pressure due to movement of salt. In this computation, the collapse pressure is applied directly from outside with perfectly uniform distribution, see in Fig.(6). The tubular geometries are the same as in example (4.1). For material properties, TWIP steel is used for this testing. The expansive pressures are varied from lower magnitude (10 N/mm^2) to higher magnitude (40 N/mm^2), while the collapse pressure is linearly increased from zero to 40 N/mm^2.

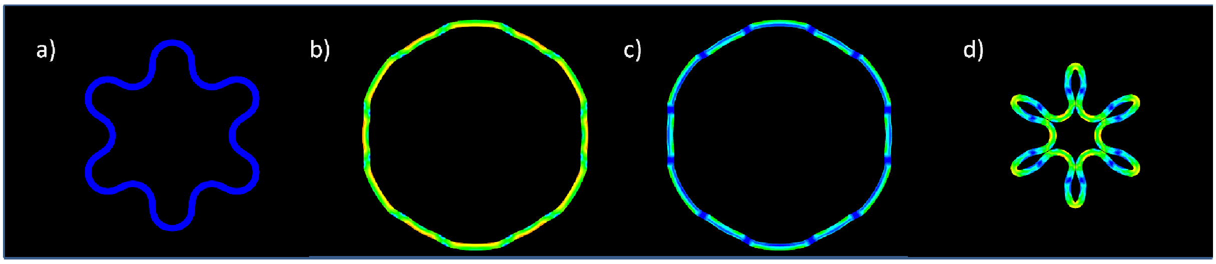

Figure 7: Mechanism of expansion and collapse pressure; a) Initial geometry; b) Expansive pressure; c) Unloading expansive pressure and d) Collapse pressure.

The results shown that, model 1 can be expanded with increasing expansive pressure until 40 N/mm^2 without damaged while others model were collapsed at expansive pressure about 32 N/mm^2 approximately. In expansion mechanism the tubulars are expanded and slowly deform until plastic deformation occurred as shown in Fig.(7 b). After that the expansive pressure is linearly unloaded the elastic deformation part can be reversely deformed, while the plastic deformation does not reverse as shown in Fig.(7 c). Thus this geometry is the beginning form for analysis of resistance collapse pressure. The different expansive pressure will give different final geometry, some of them are completely round some of them are not depending on the expansive pressure itself, in Fig.(9) shown the different final geometry of tubular with varying expansive pressure. In Fig.(8) shown the results of collapse pressure when the expansive pressures are varied. There is an interested observation that when the expansive pressure is increased the collapsed pressure is increased as well. There could be explained that, when expansive pressure increase tubular is reformed and giving more a round geometrical property as shown in Fig.(9), until at some expansive pressure the tubular become completely round. At this point tubular begin namely perfection geometry, this kind of geometry is completely round and it has more capacity for resistance collapse pressure. Oppositely, before arriving this perfection point the geometry has some geometrical imperfection, the geometry is not completely round. Also it reduce the capacity of resistance collapse pressure as shown in Fig.(8).

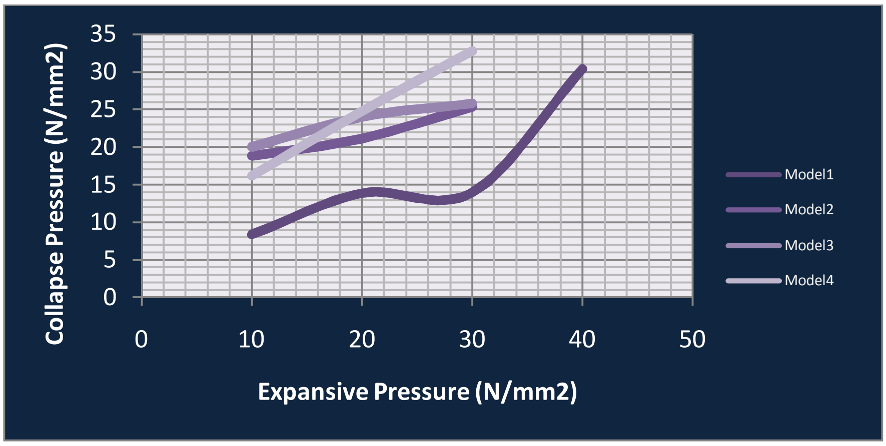

Figure 8: The relations of expansive pressure and collapse pressure

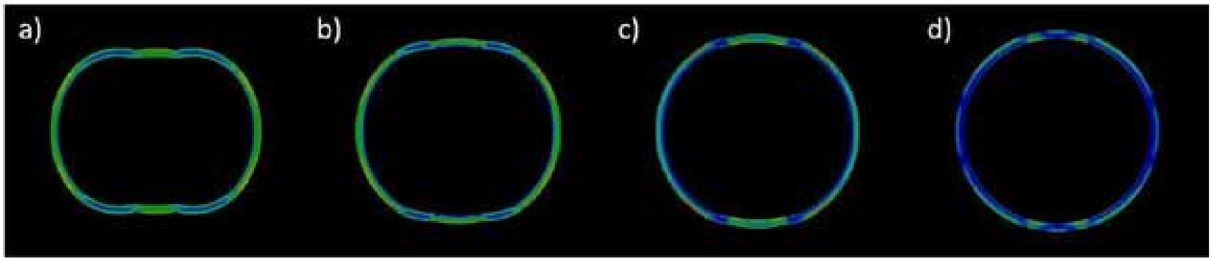

Figure 9: Tubular geometry after unloading expansive pressure of model 1 ; a) Expansive pressure 10 (N/mm^2) ; b) Expansive pressure 20 (N/mm^2) ; c) Expansive pressure 30 (N/mm^2) ; d) Expansive pressure 40 (N/mm^2)

4.3 Expandability of folded tubulars with cone expansion

As we mentioned in examples (4.1) and (4.2) the expansion process have involved with hydraulics pressure. In this example, we interested in cone expansion method. Tubulars will be expanded by contact forces between cone expander and tubular, the cone expander has to be moved inside through tubing with the expected diameter. The 10 % expansion rate is considered in these cases. We interested on mechanism of model 1 with different material (mild steel, TRIP and TWIP). The main questions are these 3 materials could be used with cone expansion method and what are the magnitudes of driving force for cone expander. As the contact between cone expander and tubular are main consideration, the model of contact mechanics is included by penalty methods [3] with the Coulomb's friction coefficient 0.1.

The results shown that mild steel damaged before cone expander has completely drived through the tubular, oppositely for TRIP and TWIP, did not damage and the cone expander can drive through the tubular. Considering mechanism of expansion process, the expander is moved forward by driving force. Due to the geometry of the cone, the tubular will be automatically expanded when the cone pass through. The plastic deformation occurred and reforming the round geometry while the elastic deformations did some reversely reform after the cone expander has already pass through.

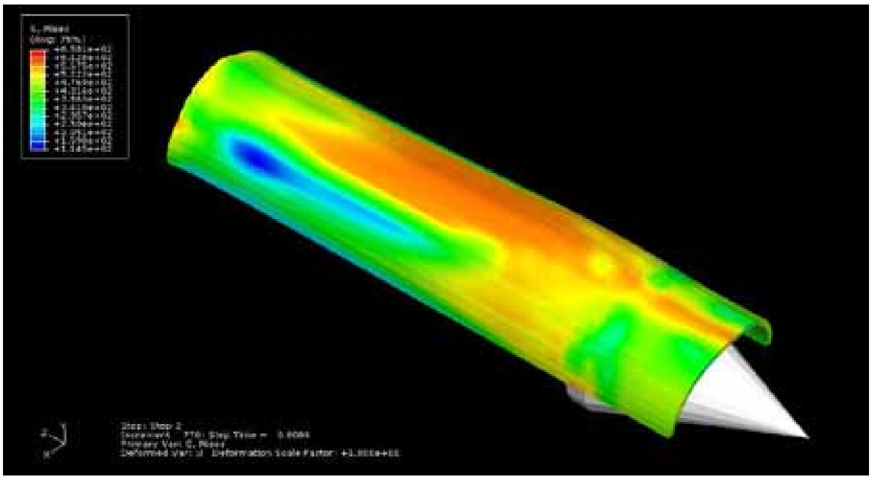

Figure 10 : Expansion process with cone expander for model 1

In Fig.(10) shown the result of expansion process for model 1 with TWIP steel, the high plastic deformation occurred at red part. Concerning the driving force in different material, the mild steel required low magnitude of driving force as this material is already damaged and cannot resist the force due to contact of the expander. TRIP steel requires higher magnitude of driving force compare to TWIP steel. This could be explained that TRIP steel has higher strength property compare to TWIP steel which has extremely high deformation property. This high strength property could make the cone expander difficult to drive forward and required driving force too high. The comparison of driving force for different materials are shown in Fig.(11).

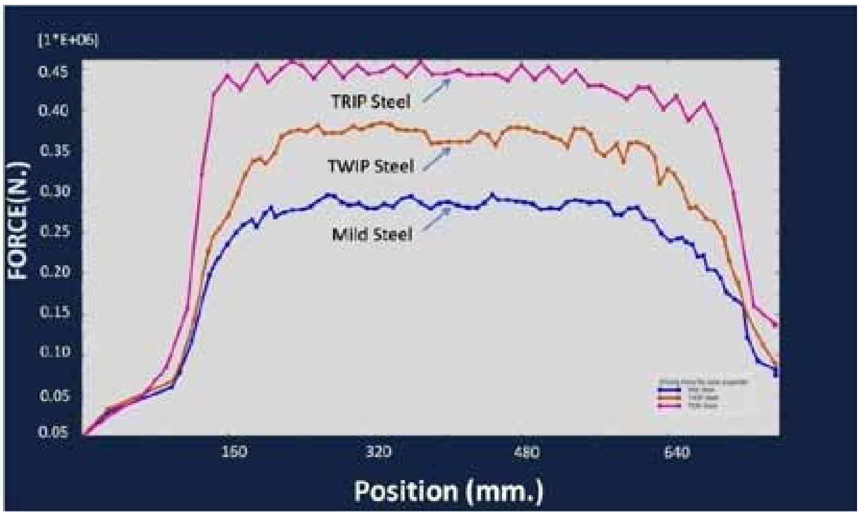

Figure 11: Driving force for moving cone expander forward with different material.

5 CONCLUSIONS

The performance of using an innovaive expandable tubular technology was studied interm of reformability which including foldability and expandability, and collapse resistance based on numerical approaches. Typical models of elasto-plasticity were investigated espcieally with the combined isotropic and kinematics model, in which the Bauschinger's effect [2] can be taken into account. The conventional nonlinear finite element method was used combined with the necesary numerical algorithm in order to solve the model and perform the standard tool for prediction of the expandable tubular performance. According to the numerical results, there are some interested observation as :

- In term of material the high strength such as TRIP and TWIP steel are recommended to use for expandable tubular later than mild steel.
- In term of geometry, imperfection geometry of expansion has significantly influence to the capacity of collapse pressure resistance. The perfectly round geometry has significantly more capacity for resistance collapse pressure than the imperfection.
- The imperfection of collapse pressure itself is also interested in term of the distribution pattern and the magnitude, it is still an open question in this field.
- For the cone expansion type, the influence of friction is also interested; it will be investigated and published later.

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