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ON THE RELIABILITY OF THE NUMERICAL MODELS FOR OIL INDUSTRY APPLICATIONS.

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Abstract. Establishing manufacturing tolerances for steel pipes to be used in the oil industry, such as amplitude of the out-of-roundness, specially its second mode in Fourier decomposition, eccentricity, residual stresses, etc., is an involved issue that should balance production cost with expected performance.

Finite element simulations are nowadays a standard industrial tool for exploring the effect of those tolerances on the structural behavior as well as on the performance of tubular goods, and to study the technological windows (the locus in the space of the process control variables that defines a given process set-up) of the pipes production process that will render products within the expected tolerances.

Hence, it is of the utmost importance that sound computational techniques are used and that the model results are validated using experimental results.

Regarding the modeling of steel pipes collapse and post-collapse behavior, in this paper we propose some guidelines for the development of finite element models that simulate collapse tests.

Some of the aspects that we discuss are: applicability of 2D models, shell elements for the 3D models, nonlinearities to include in the models, material modeling, residual stresses modeling, boundary conditions for simulating different pressure tests, code verification and results validation.

Regarding the link between production process and manufacturing tolerances we briefly review some results that we obtained for the case of the UOE process and threaded connections for OCTG (oil country tubular goods).

1 INTRODUCTION

Establishing manufacturing tolerances for steel pipes to be used in pipelines, such as amplitude of the out-of-roundness specially its second mode in Fourier decomposition, eccentricity, residual stresses, etc. is an involved issue that should balance production cost with expected performance.

Finite element models are nowadays a standard tool for exploring the effect of those tolerances on the collapse and collapse propagation pressure of tubular goods and to study the technological windows (the locus in the space of the process control variables that defines a given process set-up) of the pipes production process that will render products within the expected tolerances.

Since technological decisions, with high influence on the ecological impact of industrial facilities and pipeline installations, on labor conditions and on revenues, are reached based on the results provided by numerical models, it is evident that these models have to be highly reliable. Therefore, it is of the utmost importance that sound computational techniques are used and that the model results are subjected to experimental validation.

In this paper we propose some guidelines for the development of finite element models that simulate collapse tests.

Some of the aspects that we discuss are,

- The applicability of 2D and 3D models.
- Shell elements for the 3D models.
- Long vs. short models.
- Nonlinearities to include in the models.
- The use of follower loads.
- Material modeling.
- Modeling of residual stresses.
- Code verification and results validation.

Regarding the link between production process and manufacturing tolerances, we briefly review some results that we obtained for the case of the UOE process and threaded connections for OCTG (oil country tubular goods).

2 MODEL DEFINITIONS

In this section we discuss the decisions that we have to make for defining the finite element models that are going to be used for investigating the effect of manufacturing tolerances on the collapse and post-collapse behavior of steel pipes.

2.1 The applicability of 2D and 3D models

Material properties, residual stresses and pipe dimensions like eccentricity, out-of roundness, thickness, etc. vary along the length of a specific pipe.

When the collapse behavior of a specific pipe is investigated, then a 3D model that incorporates a detailed geometrical and material description needs to be developed.

However, we may also need to perform parametric studies to investigate the effect of manufacturing tolerances on the collapse and collapse propagation pressures; in these cases we consider an infinite pipe with uniform properties along its length and we use a 2D plane strain model built using continuum elements or 3D short shell models, if we need to include bending in the analysis.

2.2 Two dimensional finite element model of very long pipes

To study the effect of ovality, eccentricity and residual stresses on the collapse external pressure, we developed a model using 2D continuum elements QMITC (Dvorkin and Vassolo, 1989; E.N.Dvorkin, Assanelli and Toscano, 1996), with the mesh shown in Fig.1. Half of the pipe is modeled due to symmetry. To assess on the quality of this mesh we analyzed the plane strain collapse of an infinite pipe and we compared our numerical results with the analytical ones obtained using the formulas developed in (Timoshenko and Gere, 1961).

From the results in Table 1 we concluded that the proposed 2D mesh of QMITC elements is accurate enough to represent the collapse of very long specimens.

OD (outer pipe diameter)	245.42 mm
Wall thickness	12.61 mm
Ovality	0.18%
Yield stress	890 MPa
Theoretical p_{cr} (collapse pressure)	64.36 MPa
$\dfrac{\left[p_{cr}\right]_{theoretical}}{\left[p_{cr}\right]_{2D}}$	0.992

Table 1: Qualification of 2D continuum elements model

In this work, the ovality (Ov) and eccentricity (ε) are defined as,

$$Ov = \frac{OD_{\max} - OD_{\min}}{OD_{average}} \tag{1}$$

$$\varepsilon = \frac{thickness_{\max} - thickness_{\min}}{thickness_{average}} \tag{2}$$

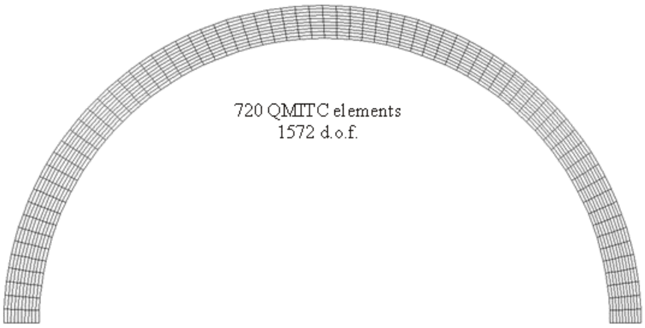
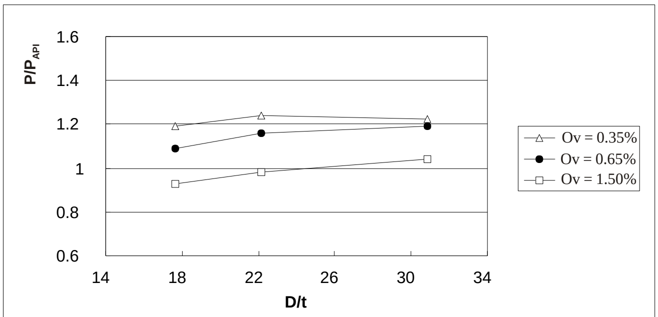


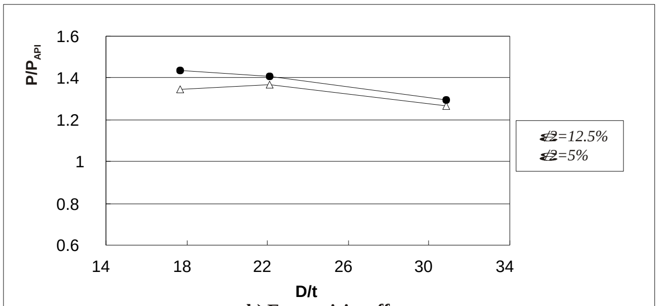
Figure 1. 2D continuum mesh

The ovality is considered to be concentrated in the shape corresponding to the first elastic buckling mode and the eccentricity is modeled considering non-coincident OD and ID centers.

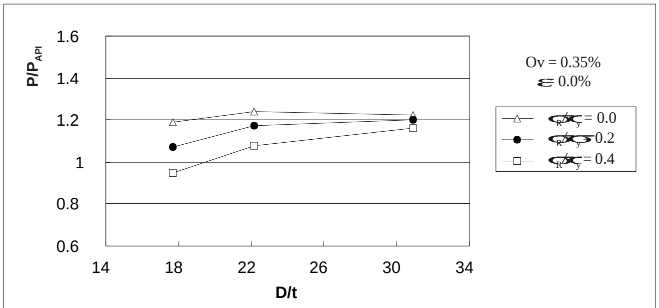
Fig. 2 (Assanelli, Toscano, Johnson and Dvorkin, 2000) summarizes the results of a parametric study, normalized with the collapse pressure calculated according to API Bulletin 5C3 (1994). It is obvious from these results that the ovality has always a strong detrimental effect on the collapse pressure, the effect of the eccentricity is quite moderate and the effect of the residual stresses diminishes when the ratio (D/t) evolves from the plastic collapse range to the elastic collapse range.



a) Ovality effect



b) Eccentricity effect



c) Residual stresses effect

Figure 2. Parametric analyses performed using a 2D model

2.3 Shell elements: 3D finite element model of very long pipes

For the range of (D/t) values that are relevant for pipelines we can model the pipes collapse and post-collapse behavior using shell elements. In particular we selected a shell element that is free from the locking problem: the MITC4 element (Dvorkin and Bathe, 1984; Bathe and Dvorkin, 1985; Bathe and Dvorkin, 1986). In ADINA (ADINA System) this element was implemented improving its in-surface behavior via incompatible modes.

To include bending in the analyses, we developed a numerical model to simulate the behavior of a very long pipe (infinite pipes) and determine its pre and post-collapse equilibrium path (Toscano, Amenta and Dvorkin, 2002). Using this model we performed parametric studies in order to investigate the significance of the different geometrical imperfections and of the residual stresses on the collapse and collapse propagation pressures. Fig. 3 shows the mesh we used.

Regarding the boundary conditions, in these models we used constraint equations to impose the planarity of the transversal sections.

For the cases with external pressure plus bending we first imposed the bending and then the external pressure keeping constant the imposed curvature.

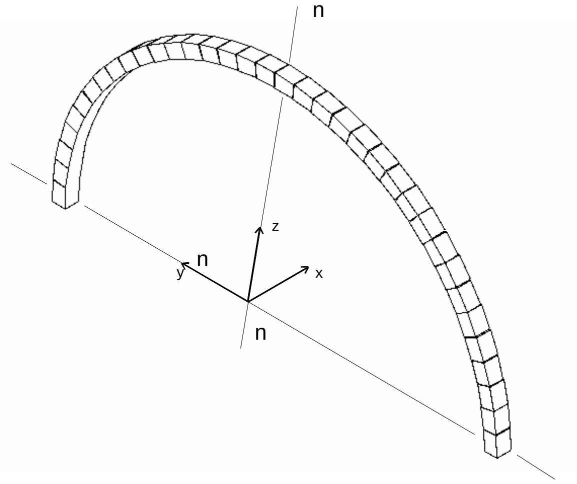


Figure 3.3D finite element model of very long pipes

Figures 4a and 4b show the curve External pressure vs. ovality and the evolution of the pipe cross section of a pipe under external pressure plus bending.

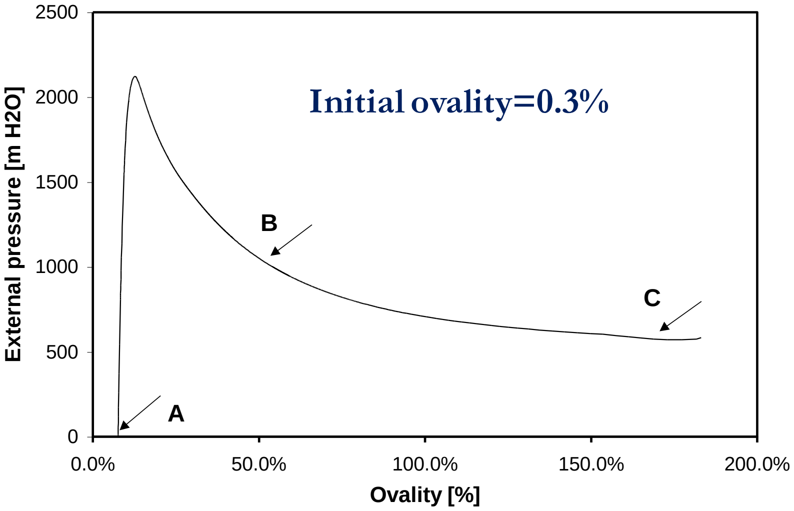


Figure 4a. External pressure vs. ovality

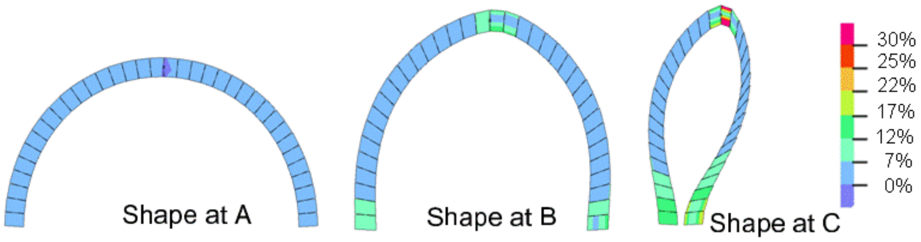


Figure 4b.Initial, intermediate and final shapes of the pipe cross section. Equivalent logarithmic strains.

In Fig. 5 we measured the applied curvature with the radius "R" and with the maximum bending strain (as a reference we indicated the radius of a typical reel used to lay marine pipelines). Even though the pipes initial ovality has a strong influence on the pipes critical collapse pressure when no bending is applied, the effect of the initial ovality on the pipes critical collapse pressure diminishes when the imposed curvature is increased. When a perfectly round tube is bent the cross section is ovalized ("Brazier effect"), when the bending increases, the Brazier-ovality grows and therefore the pipes initial ovality becomes less important as compared with this bending-induced ovality.

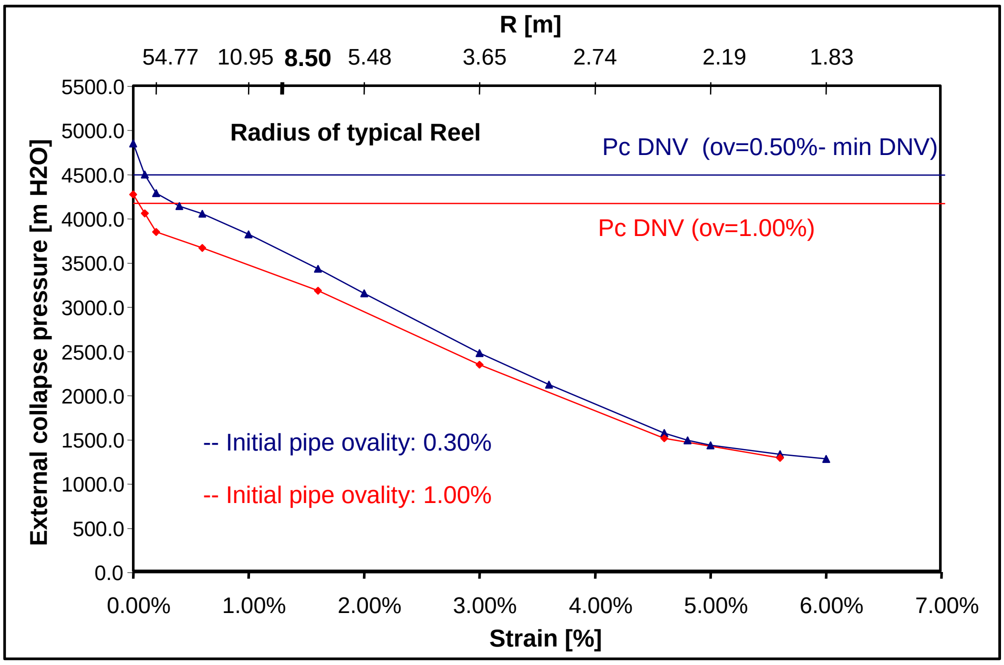


Figure 5. Ovality effect on the collapse pressure. 8 5/8" x 12.7 mm X-60 pipe

Finally, to compare the predictions using 2D elements and shell elements we considered the case described in Table I. We compared the plane strain result obtained using the QMITC element with the shell model result developed imposing zero axial displacements. The difference between both models was only 1.2%.

2.4 Shell elements: 3D finite element model of finite pipes

The 3D finite element models of finite pipes were developed to overcome the limitations of the simpler models described previously.

It is important to take into account that when the sample is long enough (L/D>10) the end conditions have only a very small influence on the collapse pressure (Fowler, Klementich and Chappell, 1983).

Following with the example described in Table 1, we compared the results obtained using the two different shell models,

- Short model with no axial displacements (shell under plane strain conditions)
- (L/D=10) model with the ends restrained to remain on a plane via constraint equations (welded end cups)

The results summarized in Table 2 indicate the equivalence of both models. For cases with (L/D<10) we may expect the end conditions to play a more significant role.

Short model under plane strain conditions	$\frac{[p_{cr}]_{theoretical}}{[p_{cr}]_{shell\_PS}} = 0.980$
Long model; (L/D)=10	$\frac{[p_{cr}]_{theoretical}}{[p_{cr}]_{shell\_long}} = 0.978$

Table 2: long shell model compared with plane strain shell model

2.5 Nonlinearities

In this subsection we analyze the nonlinearities that we must include in our finite element models to be able to predict the collapse of steel pipes under external pressure and to track their post-collapse behavior (Palmer and Martin, 1975).

Since we need to predict collapse, we have to use a geometrically nonlinear analysis considering large displacements/rotations, that is to say we have to fulfill the equilibrium equations in the deformed configuration (Bathe, 1996). However, as seen in Fig. 6, used for the validation of the model that predicts the post-collapse behavior of a pipe with collapse arrestors, even if very high strains are developed at localized points, the general behavior of the post-collapse response can be determined without including in the analyses finite strain models.

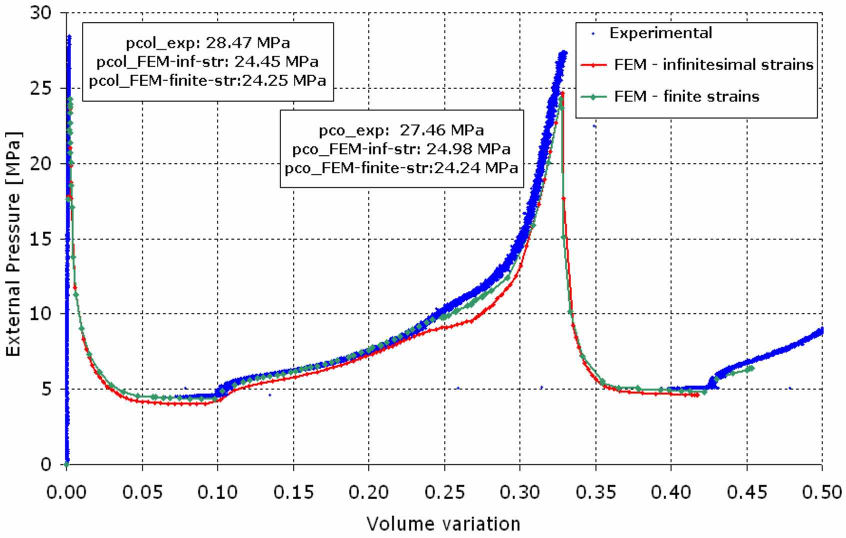


Figure 6. Infinitesimal or finite strains (flipping mode)

In the range of (D/t) values that are within our scope, the collapse is an elastic-plastic collapse, that is to say plasticity is developed before and after collapse; hence the material nonlinearity has to be included in the analysis.

In Fig. 7 (Toscano, Mantovano, Amenta, Charreau, Johnson, Assanelli and Dvorkin, 2008), we sketched the equilibrium path of a typical post-collapse response for a [pipes-arrestor] system. To track this response we use an algorithm that iterates in the load-displacement space (Bathe and Dvorkin, 1983).

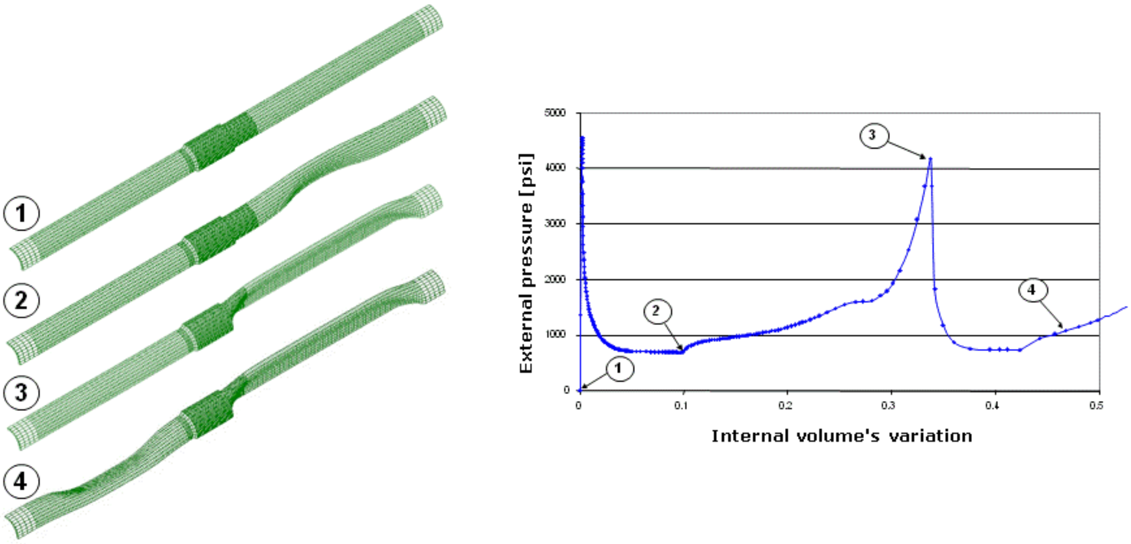


Figure 7. Post-collapse equilibrium path for a [pipes -arrestor] system

Considering the [external pressure-internal volume’s variation] curve (Fig. 7) we observe,

- The test starts at point "1".
- After point “2” a contact algorithm (Bathe, 1996) is required because opposite points located on the inner surface of the upstream pipe establish contact and afterwards, while the contact area extends, the external equilibrium pressure increases.
- At point "3" ("cross-over pressure") the collapse buckle crosses the arrestor and the downstream pipe collapses.
- Afterwards the collapse buckle propagates (Palmer and Martin, 1975) through the downstream pipe.

2.6 Follower loads

As discussed in (Brush and Almroth, 1975) it is important to consider follower loads to model the effect of the external hydrostatic pressure, since the consideration of fixed-direction loads results in important errors when predicting collapse pressures.

2.7 Material modeling

In our models we use von Mises associated elasto-plastic material models with isotropic hardening. We model the hardening using bi-linear or multi-lineal models. Even though it is clear that more sophisticated hardening models can be used, this very simple model has been very successful in the prediction of collapse and post collapse pipe behaviors, as it was demonstrated in Refs. (Assanelli, Toscano, Johnson and Dvorkin, 2000; Toscano, Amenta and Dvorkin, 2002; Toscano, Mantovano, Amenta, Charreau, Johnson, Assanelli and Dvorkin, 2008; Toscano, Timms, Dvorkin and DeGeer, 2003; Toscano, Gonzalez and Dvorkin, 2003) (see Fig. 6, 8 and the verification section, Figs. 10-12).

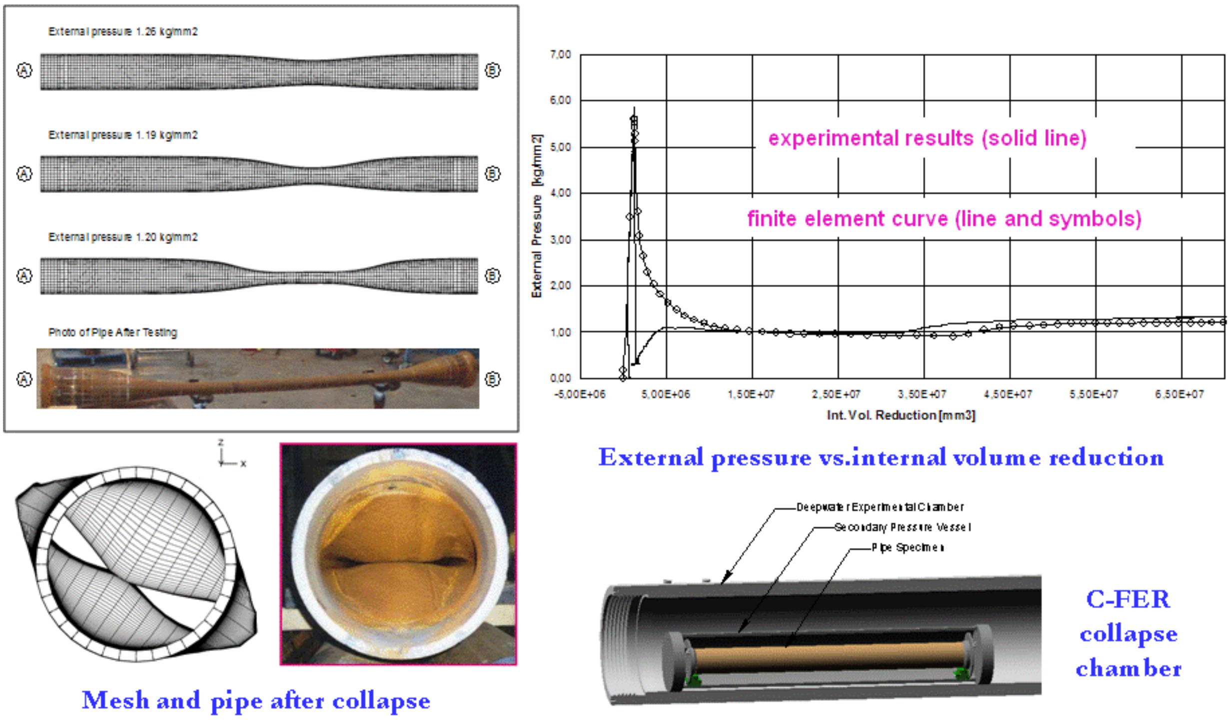


Figure 8. FEM vs. experimental results

2.8 Modeling of residual stresses

In most of our analyses we considered a linear residual stresses distribution across the pipe wall thickness. In (Assanelli, Toscano, Johnson and Dvorkin, 2000) we checked the modeling of the residual stresses distribution by modeling a slit ring test using the ADINA "element birth and death" feature. In the slit-ring tests the samples are cut and slit open by machining.

To determine the residual stresses, the measured openings are post-processed according to the following formulas,

$$\sigma_R = \frac{a \cdot t \cdot E}{4\pi \cdot R^2 \cdot (1-\upsilon^2)} \quad \text{(long sample)} \qquad (3)$$

$$\sigma_R = \frac{a \cdot t \cdot E}{4\pi \cdot R^2} \quad \text{(short sample)} \qquad (4)$$

Where,

- a: opening of the slit ring sample
- t: average thickness
- E: Young's modulus
- R: mean pipe radious

The meshes before and after slitting are shown in Fig. 9, while Table 2 summarizes the obtained results.

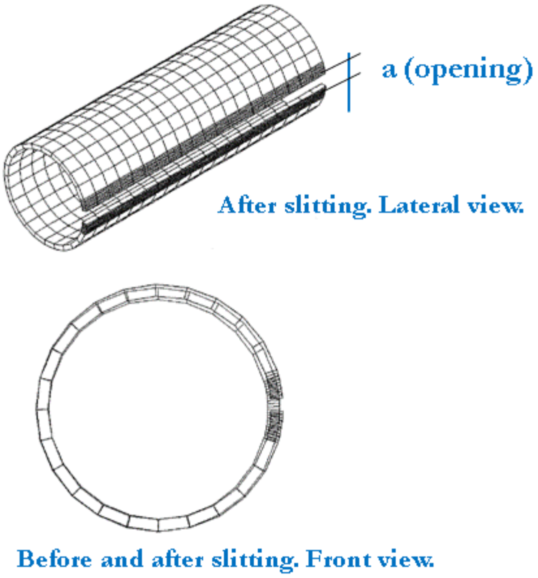


Figure 9. Residual stresses measurement: meshes before and after slitting (slit ring tests)

Sample length	$a_{FEA} / a_{analytical}$
25 mm	1.02
3 OD	0.99

Table 2. Residual stresses: numerical vs. analytical results

3 CODE VERIFICATION AND MODEL VALIDATION

In the verification process we have to prove that we are solving the equations right, and therefore this is a mathematical step (Roache, 1998). In this step we have to show that our numerical scheme is convergent and stable.

It is important to notice that the verification process is not only related to a numerical procedure but also to its actual implementation in software (either commercial software or an in-house one) (Roache, 1998).

In the validation process we have to prove that we are solving the right equations, and therefore it is an engineering step (Roache, 1998).

We do validate neither a formulation nor software: we validate the usage of verified software when used by a design analyst in the simulation of a given process. We have to validate the complete procedure.

In (Toscano, Timms, Dvorkin and DeGeer, 2003; Toscano, Gonzalez and Dvorkin, 2003) we present the results of a full-scale test program and finite element analyses performed on seamless steel line pipe samples under external pressure only and external pressure plus bending. These laboratory tests were carried out in order to obtain experimental results to be used in the validation of the numerical models. In those references we described the experimental program, compared the experimental vs. numerical results and evaluated the sensitivity of the numerical results to small variations in the model data.

Regarding arrestors, to validate our numerical results on buckling arresting and cross-over mechanisms, we performed a series of laboratory tests on medium-size carbon steel pipes (Toscano, Mantovano, Amenta, Charreau, Johnson, Assanelli and Dvorkin, 2008).

3.1 Finite element model of buckle arrestors for deepwater linepipes

In (Toscano, Mantovano, Amenta, Charreau, Johnson, Assanelli and Dvorkin, 2008) we developed a complete validation of the collapse and post-collapse analyses of pipes with collapse arrestors. We can observe the flattening (Figs. 10 and 11) and flipping modes (Fig 6 and 12) described in the literature (Park and Kyriakides, 1997).

The comparison between the experimentally and numerically determined, pressure vs. volume variation curves and post-collapse shapes indicate that the models developed using the above discussed methodology were very successful in simulating the collapse and post-collapse behavior of steel pipes.

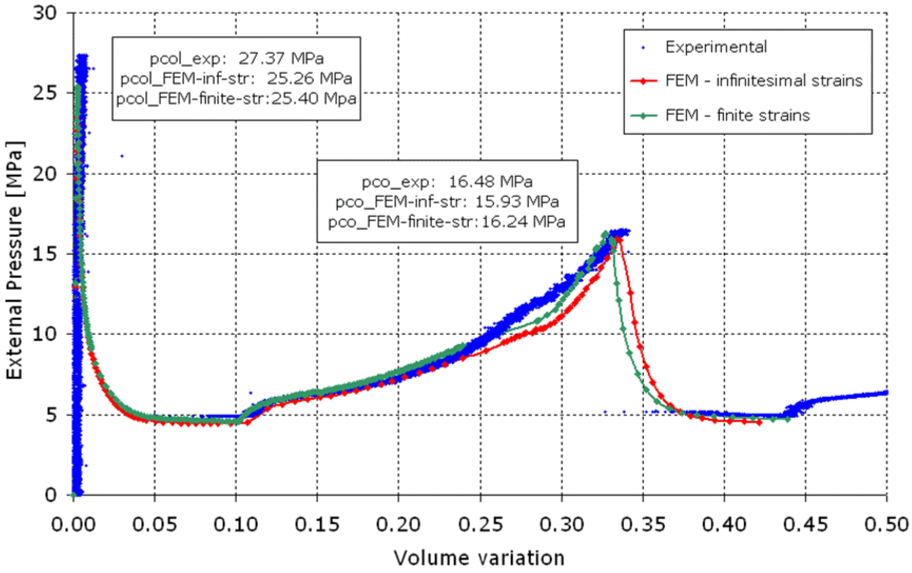


Figure 10. FEM vs. experimental results for a flattening cross-over

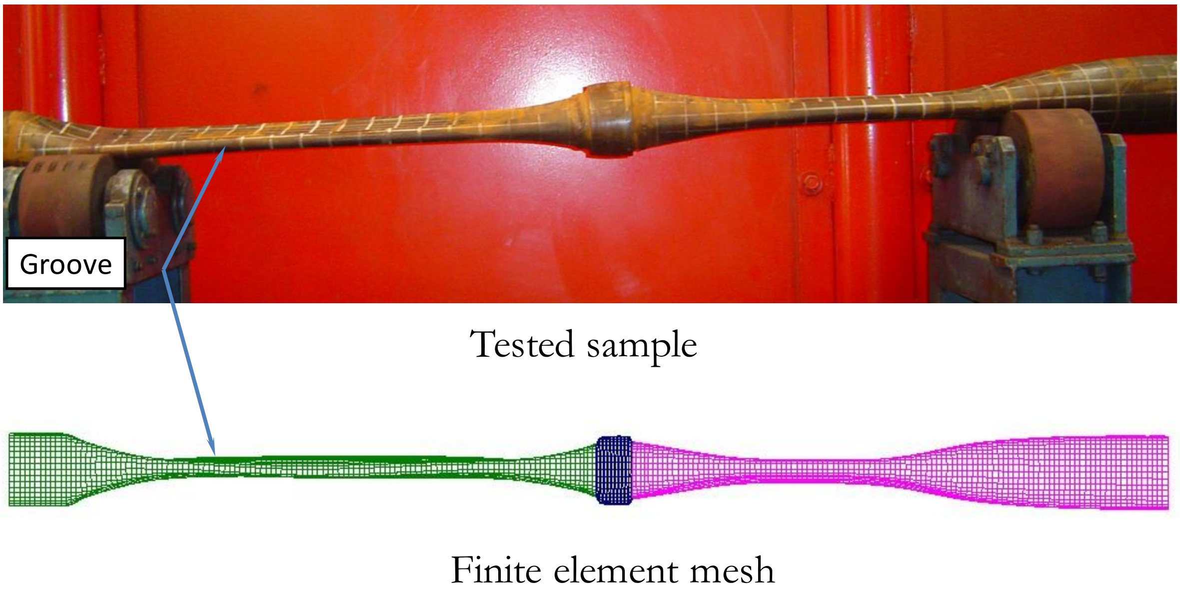


Figure 11. Experimentally observed and FEM predicted shapes of collapsed pipes after a flattening cross-over

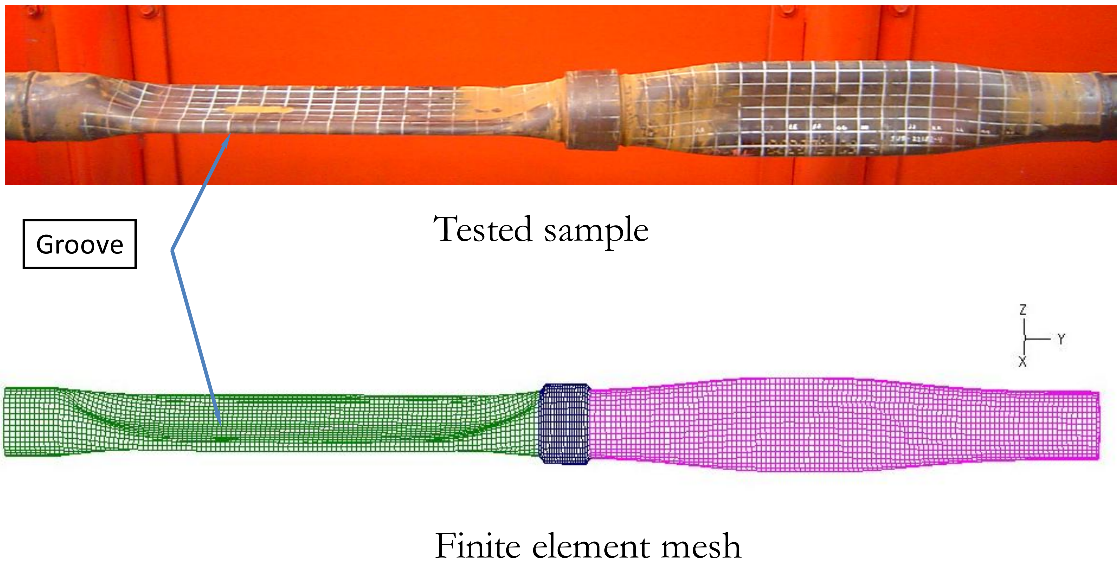
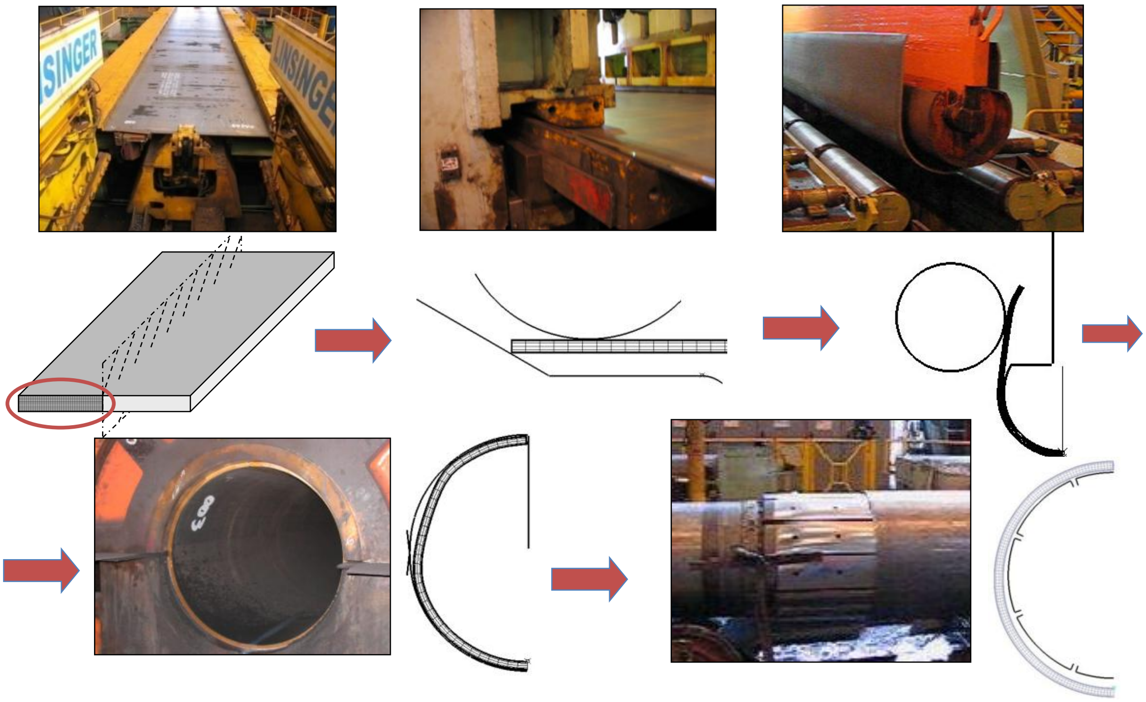


Figure 12. Experimentally observed and FEM predicted shapes of collapsed pipes after a flipping cross-**over**

4 THE UOE PROCESS

Using a 2D finite element model developed with ADINA we simulated the UOE pipes forming process.

The UOE process introduces accumulated plastic strains and residual stresses; to evaluate their effect on the result of the forming model we modeled a collapse test (Fig. 13).



(Tenaris Confab-Brazil)

Figure 13. UOE pipe manufacturing process

Details of these models were provided in (Toscano, Raffo, Fritz, Silva, Hines and Timms, 2008).

As an example, Figure 14 presents the evolution, along the UOE process, of the accumulated plastic strains of a 16” x 0.5” WT X60 pipe.

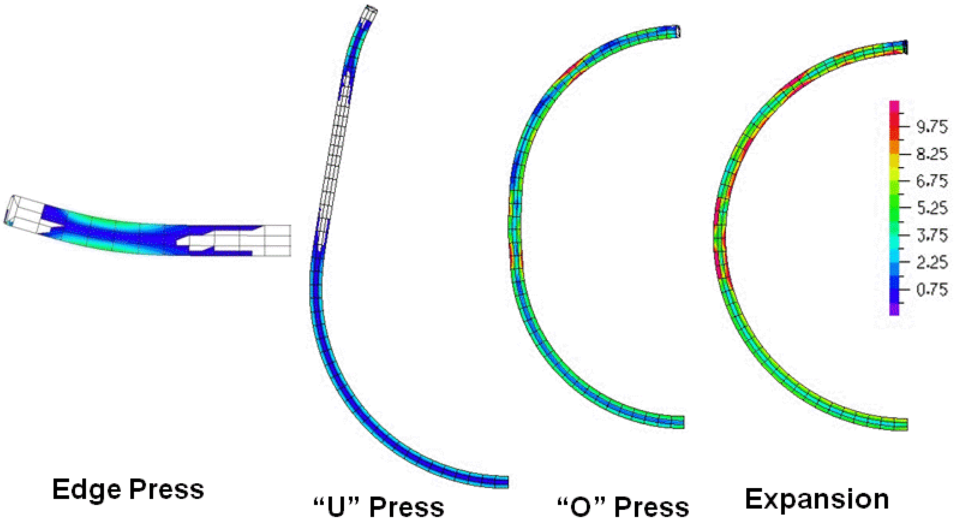


Figure 14. Accumulated effective plastic strains evolution [%]

Fort the same pipe, the results of a parametric analysis performed with the composed model are shown in Fig. 15, where TC is total compression in the “O” press.

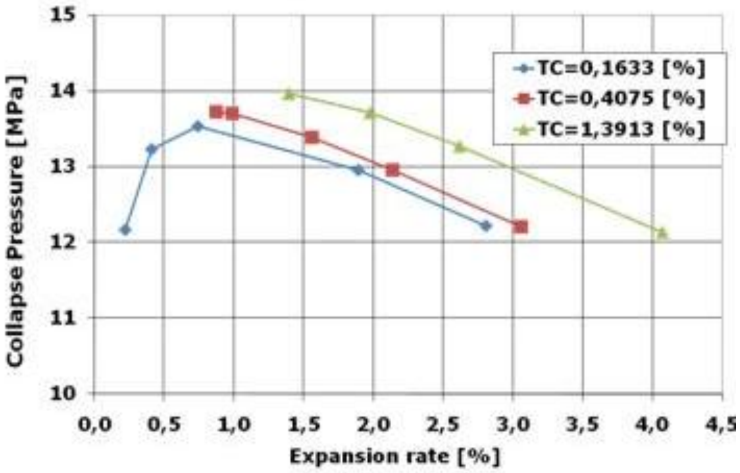


Figure 15. Results of the forming+collapse models.

It is clear that, controlling the compression rate in the “O” press and the expansion rate, the collapse behavior can be optimized.

5 THREADED CONNECTIONS

We analyzed the structural and functional behavior of threaded connections using bi-dimensional models and QMITC elements. In previous publications (Assanelli and Dvorkin, 1998; Assanelli and Dvorkin, 1993) we showed the validation and verification of those numerical models.

It is well known that if during the connection make-up, too much dope is used either in the seal area or in the thread area, the extra dope gets trapped and develops a high pressure that can damage the connection. Of course, different connection designs have more or less capability for avoiding the dope trapping.

A connection similar to the one shown in Fig. 16 was made-up with extra dope; the dope pressure values were measured during the make-up.

In Fig. 17 we compare the strains measured experimentally with the numerical results obtained with and without the inclusion of the dope pressure; it is obvious that when the dope pressure distribution determined in the full-scale test was included in the finite element model, the numerical results showed a very good agreement with the experimental ones.

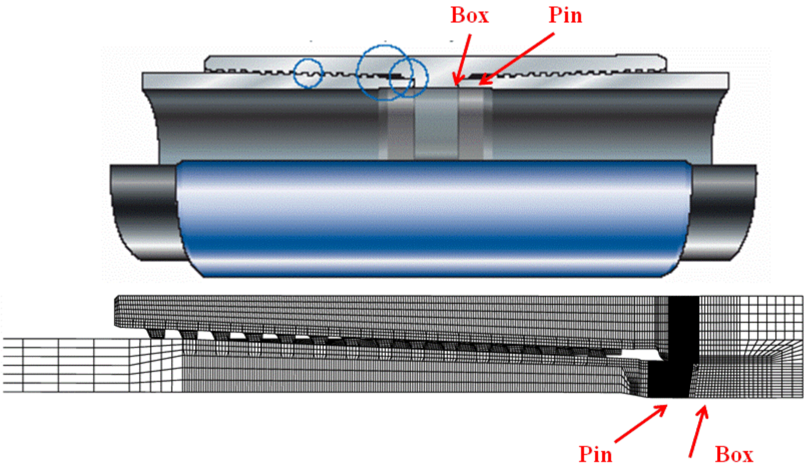


Figure 16. Threaded&coupled connection. 2D mesh.

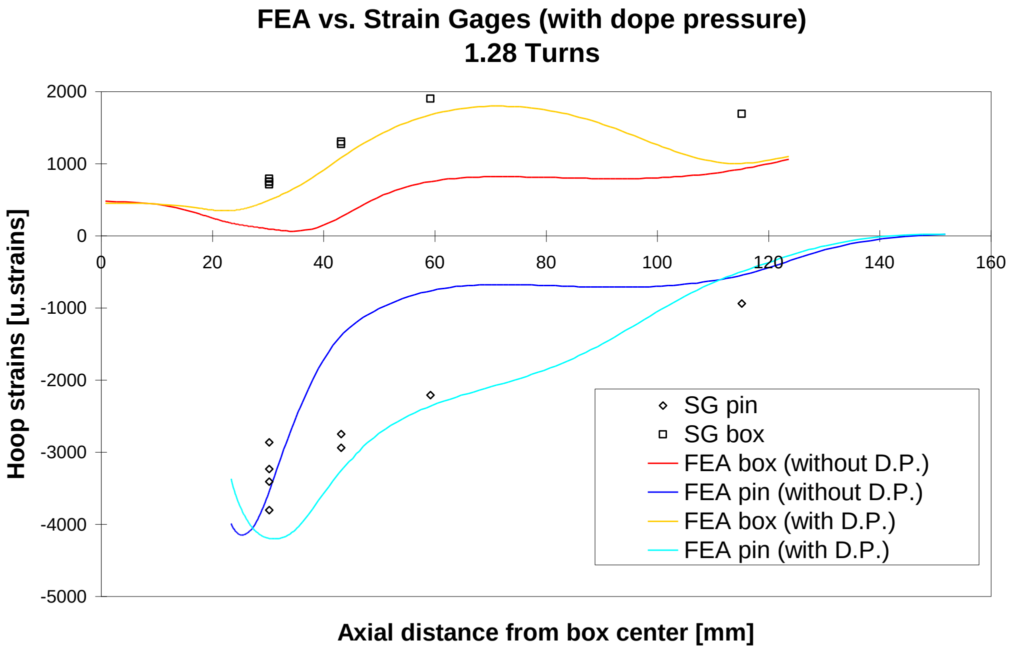


Figure 17. Strains comparison considering dope pressure in an over-doped connection

6 CONCLUSIONS

A methodology for using the finite element method as a robust engineering tool for analyzing the effect of steel pipes manufacturing tolerances on their collapse and post-collapse behavior was discussed.

It was shown that 2D models can only be used for performing general parametric analyses and not for predicting the collapse and post-collapse behavior of a specific pipe.

For including bending and material/geometrical variations along the pipes length, 3D models should be used. We showed that using the MITC4 shell element for developing these 3D models is a successful procedure.

Even though we have to introduce geometrical nonlinearities for the simulation of the collapse and post-collapse behavior, the use of finite strain models is only necessary if the local strains/stresses are sought, but their consideration can be avoided if only the equilibrium path is sought.

The use of very simple bilinear elasto-plastic models provided an excellent agreement between the numerical and experimental results.

Regarding the link between production process and manufacturing tolerances, we present some results obtained with the UOE process model as well as the threaded connections model. The modeling of the UOE process produced specific indications for optimizing the pipes collapse pressure working on the process parameters, while the results obtained including the dope pressure as a load in the connections model was a definitive demonstration of the high importance of designing the connections with the objective of avoiding the dope entrapment.

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