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## DRAFT: FEA OF A LAMINATE INTERNAL BUCKLE ARRESTOR FOR DEEP WATER PIPE-IN-PIPE FLOWLINES

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### ABSTRACT

Development of deepwater oil reservoirs has been undertaken in the Gulf of Mexico (GoM) where flowlines are installed in water depths in the vicinity of 2,740m (9,000ft). Preventing the propagation of local collapse/buckle failures is one of the key engineering design limit states that is defined in the industry codes to ensure the pipeline integrity. Deep-water buckle propagation is almost unavoidable as the wall thickness selection cannot be directly driven by the buckle propagation limit state. Field data indicates that once a buckle happens, the flowline could collapse for many kilometers instantly. Buckle propagation could cause substantial economic impact if left uncontrolled. For Pipe-in-Pipe (PIP) flowline, due to lack of pressure differential, the jacket pipe is a fragile component in terms of buckle propagation. It is crucial to prevent any possible local buckling during the flowline installation and during the entire operational lifetime. One way to stop buckle propagation is to utilize buckle arrestors of various types. Successfully designed buckle arrestors can contain such disasters to a limited pipeline section. Internal buckle arrestors are a relatively new solution for PIP systems being investigated by the industry. As it is installed in the annulus of PIP, it becomes a preferred choice since it fits all types of installation methods. The objective of this paper is to present the design and finite element analysis (FEA) of a laminate type internal buckle arrestor, and to investigate the effectiveness of this innovative buckle arrestor design for deepwater flowline. Sensitivities of key design parameters are explored with the purpose of guiding detailed mechanical design.

### INTRODUCTION

Oil and gas development starts moving to deep water in the Gulf of Mexico region. Among the many limit states in the design of deepwater steel pipelines, determining the appropriate wall thickness (WT), pressure containment, local buckling, collapse, and buckle propagation are the fundamentals. It is often uneconomical to select a wall

thickness with sufficient strength to prevent buckle propagation since the collapse pressure is much higher than the propagation pressure. However, buckle propagation could cause substantial economic impact if left uncontrolled. Field data indicates that once a buckle happens many kilometers of flowline could collapse instantly. Evaluation of the propagation pressure and design of a suitable buckle arresting system is as important as avoiding any local buckling that is caused by the external pressure combined with the compressive effective axial force, as well as the bending moment [1]. Generally, the spacing of buckle arrestors is driven by the cost of repair, the availability of spare pipe, and the likelihood of a local buckling occurring. For PIP flowline, due to lack of pressure differential, the outer pipe becomes a fragile component in terms of buckle propagation. If the annulus is breached, the flowline thermal performance will be affected and the inner pipe will be exposed to a threat of buckle propagation during operational shut-down periods.

Buckle arrestors prevent the buckle crossover under a comparative lower external pressure by strengthening the pipe section. The design of buckle arrestors normally affects the magnitude of the crossover pressure. Three types of buckle arrestors are commonly used. Thick wall pipe joint buckle arrestors and integral ring buckle arrestors directly increase the pipe wall strength by welding the integral ring with thicker wall or a thick pipe section to the pipe respectively. They are used in S-lay or J-lay. J-lay collars can serve as buckle arrestors of these types. They have to be designed to meet the requirements for buckle arrestor function, and one collar is assumed to be installed every quad joint. A slip-on or grouted sleeve buckle arrestor is a steel ring slid over the end of selected pipe joints and grouted in place thus removing the welding process. A clamp-on buckle arrestor [2] is a type of slip-on buckle arrestor composed of upper-half clamp and lower-half clamp that are assembled together by high torque bolts. It has two advantages compared with the regular slip-on buckle arrestor. It eliminates

the built-in clearance thereby improving the arresting efficiency, and it can be used for reel-lay installation.

The presence of an annulus between two pipes of pipe-in-pipe (PIP) system offers additional buckle arrestor design alternatives. This kind of internal buckle arrestor [3,4] can be installed before laying the PIP system and is free of any additional work during the offshore operation on the lay barge. The thermal insulation of the PIP system can also be maintained by using materials other than steel with good thermal insulation properties, but the rigidity and the strength of these materials need to be considered. Therefore, the laminated internal buckle arrestor is considered to provide thermal protection while maintaining material strength.

This paper presents cross checks of propagation pressure for single pipe and PIP utilizing the finite element method. The effectiveness of a laminated internal buckle arrestor is investigated for deepwater flowlines.

**NOMENCLATURE**

- PIP Pipe-in-Pipe
- API American Petroleum Institute
- DNV Det Norske Veritas
- RP Recommended Practice
- OS Offshore Standard
- WD Water Depth
- OD Outside Diameter
- ID Inside Diameter
- WT Wall Thickness
- SMYS Specified Minimum Yield Strength

**PIPE BUCKLE PROPAGATION**

**Single-Pipe Buckle Propagation**

Buckle propagation is considered as a limit state in the design of pipelines. Typical design codes and study work are summarized in Table 1. Proper safety factors need to be included in these equations during the design code check.

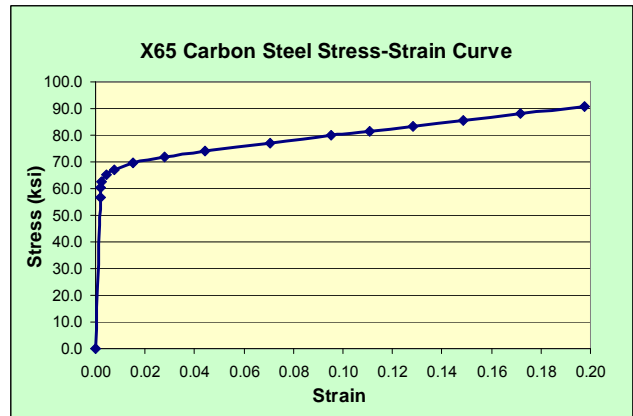
**Table 1. Equations to Determine Allowable Propagation Pressure**

Design Code or Published Work	Expression
API RP 1111 [1]	$P_p = 24 \sigma_y \left[ \frac{t}{D} \right]^{2.4}$
DNV OS-F 101 [5]	$P_p = 35 \cdot \sigma_y \cdot \alpha_{fab} \cdot \left( \frac{t}{D} \right)^{2.5}$
KYRIAKIDES [6,7]	$P_p = A \sigma_y \left( \frac{t}{D} \right)^\beta$
$P_p$ = propagation pressure; $\sigma_y$ = specified minimum yield strength; $D$ = nominal outside diameter of pipe; $t$ = minimum nominal wall thickness including corrosion allowance; $\alpha_{fab}$ = maximum fabrication factor, taken from 0.85 to 1.0; $A$ = 39.25; $\beta$ = 2.5.	

A single wall pipe with OD of 11.81" and WT of 0.56" is studied in this section. Table 2 lists the properties of the API-X65 (SMYS=65ksi) steel used in the model. An elastic-plastic stress-strain curve for X65 steel is plotted in Figure 1.

**Table 2. Material Properties of Carbon Steel X65**

Material Properties	Values	Unit
Young's Modulus	30,000	ksi
Poisson Ratio	0.3	-



**Figure 1. Stress-Strain Curve for API X65 Carbon Steel**

Table 3 presents the results of hand calculations from the equations listed in Table 1 and the results from FEA of this work for the propagation pressure of a single pipe with outside diameter (OD) of 11.81" and the thickness of 0.56". The equivalent water depths are also given. The water density ( $\rho_{sw}$ ) utilized was 64.2lb/ft<sup>3</sup>. The FEA results match with the upper-bound of the DNV-OS-F101 [2] results. Figure 2 illustrates the buckled pipe.

**Table 3. Propagation Pressure Calculated via FEA and Different Codes**

Equations	Propagation Pressure (psi)	Equivalent Water Depth (ft)
API RP 1111 [1]	1036	2320
DNV OS-F 101 [5]	947 - 1114	2120 - 2500
KYRIAKIDES [6,7]	1249	2800
FEA	1112	2490

The minimal water depth to safely prevent buckle propagation can be derived per API RP 1111 [1] as,

$$D_{X\_Min} = WD * 1.25 \tag{1}$$

where, WD is the design water depth.  $D_{X\_Min}$  is defined as minimum buckle arrestor crossover depth.

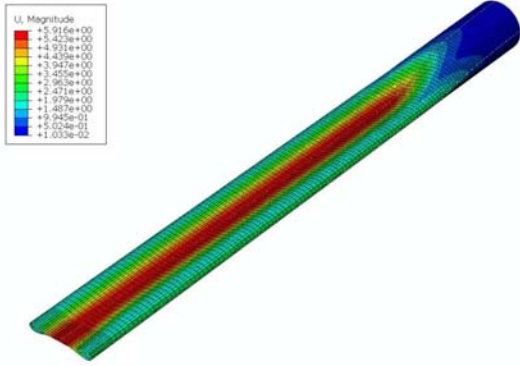


Figure 2. Fully Buckled and Propagated Pipe (11.81" x 0.56")

### Pipe-in-Pipe Buckle Propagation

The pressure to collapse a PIP relies on many parameters and becomes quite complicated. Based on numerous test data, Kyriakides [4] recommended following relationship with caution,

$$\frac{P_{p2}}{P_p} = 1 + 1.095 \left( \frac{\sigma_i}{\sigma_o} \right)^{0.4} \left( \frac{D_i}{D} \right) \left( \frac{t_i}{t} \right)^2 \quad (2)$$

where,

- $P_{p2}$  = Propagation pressure of the PIP;
- $P_p$  = Propagation pressure of the outer pipe;
- $\sigma_i$  = Specified minimum yield strength of inner pipe;
- $\sigma_o$  = Specified minimum yield strength of outer pipe;
- $D_i$  = OD of the inner pipe;
- $D$  = OD of the outer pipe;
- $t_i$  = Wall thickness of the inner pipe;
- $t$  = Wall thickness of the outer pipe.

This expression takes into account the full resistance of the inner pipe, and forms the upper bound of propagation pressure. For most of PIP design, the primary limit state is pressure containment that results in a thicker wall for the inner pipe compared to the outer pipe. In combination with the smaller OD, this causes the inner pipe to have a much higher propagation pressure (refer to Table 1). This is demonstrated by many tests and field results that have shown buckle propagation of the outer pipe, while the inner pipe was still intact. For this reason, the following equation is very practical, although it might be conservative;

$$\frac{P_{PS}}{P_p} = 1 + B \left( \frac{D_s}{D} \right)^\gamma \quad (3)$$

where,  $P_{PS}$  stands for a pressure that could cause a buckled pipe to propagate on a solid rod.  $D_s$  is the OD of solid rod.  $B = 2.116$  and  $\gamma = 2.677$  provide the best least square fit to the test [7].

Table 5 presents a side-by-side comparison of the calculations of propagation pressure using the analytical

equations (2) and (3) and the FEA model (Figure 4) for this PIP geometry:

- Inner Pipe, 7.69" x 1.28";
- Outer Pipe, 11.81" x 0.56".

Two different grades of steel were considered for PIP. The material for outer pipe was API X65 steel; the material for the inner pipe was API X70 steel (with SMYS of 70ksi). Table 4 lists the properties of API-X70 used in the model. An elastic-plastic stress-strain curve for X70 steel is plotted in Figure 3.

Table 4. Material Properties of Carbon Steel X70

Material Properties	Values	Unit
Poisson Ratio	0.3	-
Compressive Modulus	1,300	ksi
Compressive Strength	24	ksi
Thermal Conductivity	2.10	BTU-in/ft <sup>2</sup> -hr-°F
Maximum Operating Temperature	450	°F

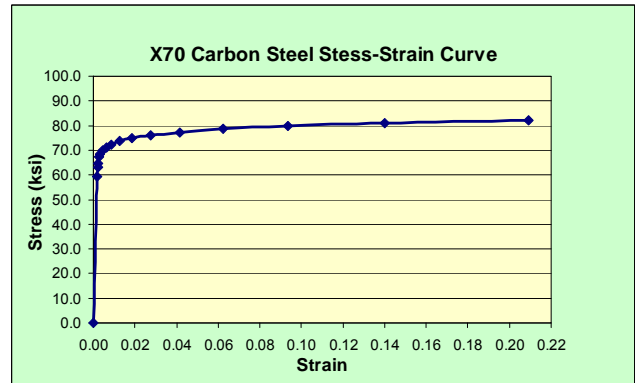
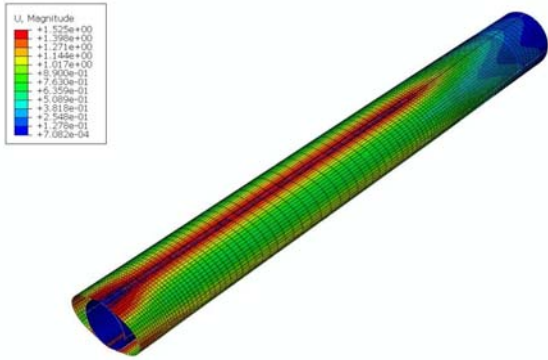


Figure 3. Stress-Strain Curve for API X70 Carbon Steel

Table 5. Propagation pressure of a PIP calculated via the analytical equations and FEA

Sources	Propagation Pressure of PIP(psi)	
KYRIAKIDES [4]	$P_{ps}$	2,090
	$P_{p2}$	5,010
FEA	$P_{ps}$	2,590
	PIP Outer-Pipe Buckled	2,040



**Figure 4. Buckle Propagation of a PIP System**

It was noticed that there was a large gap between the  $P_{ps}$  and  $P_{p2}$ . This seems reasonable since the relatively thicker inner pipe serves more likely as a solid rod. The outer pipe was buckled and fully propagated along the OD of the inner pipe. The pressure required for full buckle and propagation of PIP is very large compared to the partially buckle propagation. Due to the thickness of the inner pipe, the partial propagation pressure for outer pipe is close to the  $P_{ps}$ .

This practice indicates that FEA results are consistent with the works by Kyriakides [4]. It provides a reliable source to determine the lower bound of propagation pressure of a (partially) buckled PIP.

FEA also indicated that different from the single pipe, the propagation pressure of PIP was not a constant value due to the different levels of involvement of the inner pipe during the propagation process.

**LAMINATED INTERNAL BUCKLE ARRESTOR**

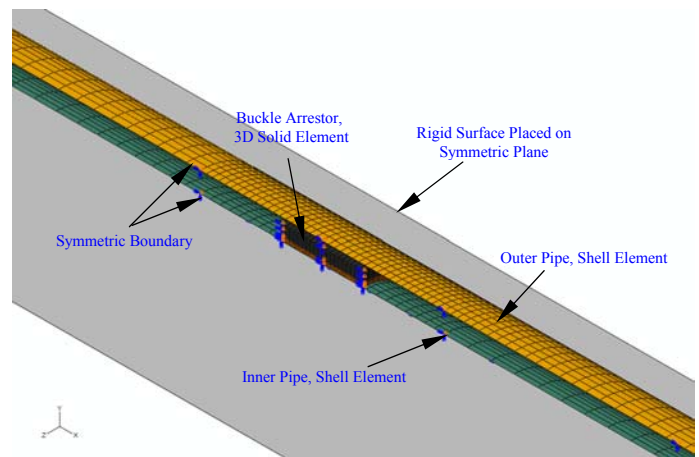
Typically, the annulus between two pipes of PIP system in deepwater applications contains non-structural insulation material to provide a good thermal protection for inner pipe. Although an internal buckle arrestor may not have a big impact on the thermal insulation capability of the entire flowline due to its relatively short length, materials with lower thermal conductivity than steel such as polymer or composites have been seen used in field applications to provide more thermal protection. However, the lower strength of the alternative material may affect the crossover pressure. One possible solution to this would be the design of a laminated internal buckle arrestor.

In this section, an FE model of an 18ft long PIP flowline section with a laminated internal buckle arrestor installed ( as shown in Figure 5) is presented. The model was developed in ABAQUS 6.8 with shell element, S4R (4-node doubly curved general-purpose shell, reduced integration, hourglass control, finite membrane strains), and 3D stress element (8-node linear brick, reduced integration, hourglass control). Due to symmetry, only a quarter of the pipe and buckle arrestor were modeled. Higher density meshing was assigned in the regions where interaction is crucial. Surface to surface contact was

assigned between the buckle arrestor and OD of the outer pipe. The interaction between the two components was simulated by the given static friction coefficient of 0.3. A rigid surface was placed along one of the symmetric plane to simulate the self contact of the pipe ID during the collapse and propagation. The pipe coating was neglected.

The PIP uses the same geometry and materials as described in previous section. The laminated buckle arrestor uses the same material as the outer pipe (X65 steel) for the outer layer. The inner layer was made of a typical thermal plastic material with the material properties listed in

Table 6. The geometries of the internal buckle arrestor are listed in Table 7, in which the ID is equal to the OD of the inner pipe. There is a small clearance between the OD of the buckle arrestor and the ID of outer pipe. The internal buckle arrestor was made as a laminated type, with an outer layer steel ring providing rigidity and strength as well as an inner layer of PPS polymer preventing heat loss from inner pipe. This type of internal buckle arrestor can be easily installed by sliding over the internal pipe or being clamped on using high torque bolts.



**Figure 5. Finite Element Model of a PIP with Laminated Internal Buckle Arrestor Installed**

**Table 6. Material Properties of a Typical Thermal Plastic Material used in FEA**

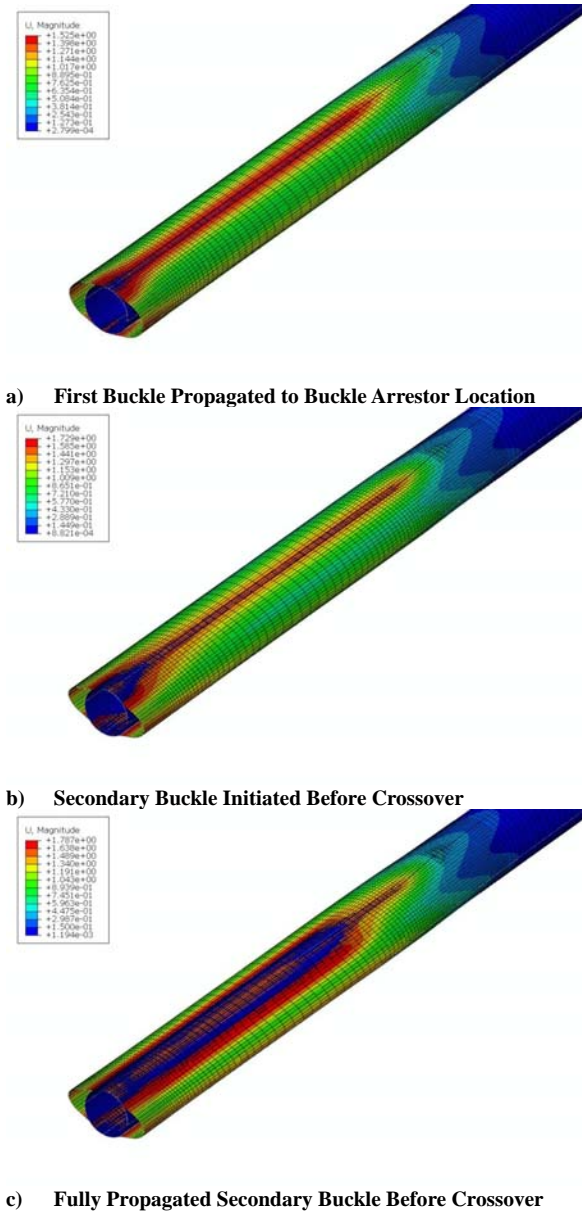
Material Properties	Values	Unit
Young's Modulus	30,000	psi
Poisson Ratio	0.5	-

**Table 7. Geometry of a Laminated Internal Buckle Arrestor**

Length (inches)	Thickness (Steel/ PPS, inches)	Clearance with Outer Pipe ID (inches)
6	0.8 / 0.255	0.445

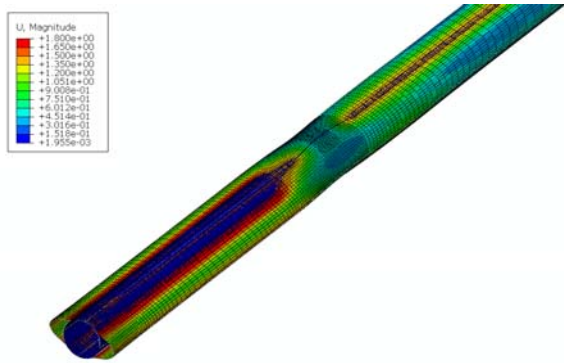
As expected, a consistent buckle propagation pressure has been obtained from the FEA results for all six cases. The values comply with the PIP outer pipe buckle propagation pressure in

Table 5. If the external pressure continues increasing after the buckle reaches the internal buckle arrestor, a secondary buckle at the same section of pipe was noticed before buckle crossed over the arrestor as shown in Figure 6.



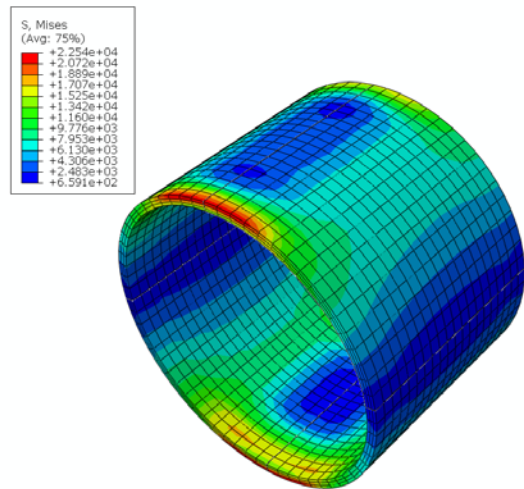
**Figure 6. Secondary Buckle Before Crossover**

The secondary buckle pressure was 3,380 psi according to FEA. After fully propagating, the buckle of the outer jacket pipe crossed over the internal buckle arrestor, as shown in Figure 7.



**Figure 7. Buckle Cross Over Internal Arrestor for PIP System**

When the buckle crossed over the buckle arrestor, the internal arrestor was bearing the maximum compressive load. The lower strength of the plastic layer was of the most concern while designing the buckle arrestor. As shown in Figure 8, the maximum stress of the plastic ring was around 22.5ksi, which is lower than the material’s compressive strength of 24ksi. Considering that the local high-stress area was limited to a small area, the overall strength of the laminated buckle arrestor met the design requirement with enough safety margin.



**Figure 8. Stress Results in the Plastic Layer When Buckle Crossed Over the Laminated Buckle Arrestor**

**GEOMETRIC SENSITIVITY OF LAMINATED BUCKLE ARRESTOR**

In order to address the key design parameters in the laminated internal buckle arrestor design, a series of buckle arrestors (Table 8) were selected to study their efficiency.

**Table 8. Geometries of Laminated Internal Buckle Arrestors**

Length (inches)	Thickness (Steel/ PPS, inches)	Clearance with Outer Pipe ID (inches)
2.5	0.8 / 0.35	0.35
	0.8 / 0.255	0.445
4	0.8 / 0.35	0.35
	0.8 / 0.255	0.445
6	0.8 / 0.35	0.35
	0.8 / 0.255	0.445

The FEA results indicated that a length of 4" is enough for preventing the buckle from crossing over at relatively low pressure. No major difference in terms of the crossover pressure was observed from the analysis of arrestors with different lengths. The crossover pressures for two cases analyzed with 0.445" clearance were lower.

For the proposed PIP geometry with thick wall inner pipe, it was observed that once the whole length of the thin wall outer pipe had collapsed, the pressure kept increasing and a new quasi-steady state collapse was initiated. The pressure that caused the secondary buckle and further crossover was still insufficient to collapse the thick wall inner pipe. This means the crossover pressure was still lower than  $P_{p2}$  because of the buckling resistance of the inner pipe.

Buckle arrestor design can be evaluated by calculating the arresting efficiency ( $\eta$ ) [3], which is expressed as,

$$\eta = \frac{P_x - P_p}{P_{co} - P_p} \quad (6)$$

where,  $P_{co}$  is the collapse pressure of a pipe, and  $P_x$  is quasi-static crossover pressure.

To design an internal buckle arrestor, the criterion is that equivalent buckle arrestor crossover water depth needs to exceed the minimum buckle arrestor crossover depth ( $D_{X\_Min}$ ). This equivalent value is calculated by the buckle arrestor crossover pressure ( $P_x$ ) over the density of seawater ( $\rho_{sw}$ ),

$$D_{Eqv} = P_x / \rho_{sw} \quad (4)$$

The minimum crossover depth is the safety factored design water depth. The ratio of this depth over the equivalent crossover depth defines the design requirement (as  $\leq 1$ ),

$$UC = D_{X\_Min} / D_{Eqv} \quad (5)$$

## CONCLUSION REMARKS

This paper investigated the pipeline buckle propagation phenomena using a finite element approach. The FEA simulation agreed with the results from available empirical equations from industry codes and the research studies for both single pipe and PIP systems. Emerging use of plastic/composite materials during design of buckle arrestors in field application,

due to the thermal conductivity consideration, was noticed and a laminated internal buckle arrestor was proposed in this paper. FEA simulations were performed for buckle propagation of the jacket pipe of a PIP system with internal buckle arrestor installed. The buckle behaviors of PIP before and after reaching the buckle arrestor were investigated. A secondary quasi-steady state buckle propagation was observed before external pressure was increased enough for buckle to crossover. FEA also indicated that the plastic layer met the strength requirement for the buckle arrestor.

Detailed studies were carried out using different geometries and configurations for the laminated buckle arrestor. These showed the mechanical effectiveness of this type of buckle arrestor. The minimum design requirements were also specified.

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