ON THE EFFECTIVENESS OF COLLARS AS BUCKLE ARRESTORS FOR OFFSHORE PIPELINES

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Abstract. *Collars are devices similar to thick-walled rings which are welded to two adjacent strings of pipe during installation through the J-lay method. They are designed to support the suspended portion of the pipeline between the seafloor and the laugthing tower while the downstream segment of pipe is welded to the line. Because they locally increase the rigidity of the line, these devices also have the potential to arrest an eventual propagating buckle and thus, in such event, limit the damage to a small portion of the line. In this paper, the effectiveness of this type of local reinforcement as a buckle arrestor is studied through a nonlinear finite element model capable to reproduce the buckle propagation in pipes and its engagement to collars. The model is based on finite deformation kinematics and properly treats the contact that develops in the collapsed pipe behind the propagating buckle. Pipe and collar materials are modeled as J_2 flow theory solids with isotropic hardening. Numerical procedure and results are summarized here and then used to propose a simplified method to evaluate the effectiveness of collars as buckle arrestors.*

Keywords*. oil exploitation, offshore pipeline, buckle propagation, J-lay collars, buckle arrestors.*

1. Introduction

Deepwater pipelines are designed to withstand the ambient external pressure in order to avoid local collapse when combined with other loads such as bending and tension. Unfortunately, this is not always sufficient because off-design events such as local buckles induced by excessive bending during installation or impact of the line by a foreign body can deteriorate the integrity of the line and induce local collapse. This, in turn, can initiate a running buckle that has the potential to destroy the whole structure (Kyriakides and Babcock, 1979, Kyriakides and Netto, 2000). The propagation pressure (P_P) is the minimum pressure at which a buckle will propagate. It is approximately 15% of the collapse pressure (P_{CO}) of the intact pipe (Dyau and Kyriakides, 1993). In order to guarantee that the propagation pressure is higher then the ambient pressure, an increase in the thickness of the pipeline could be suggested, insuring that any local collapse will never propagate. This, however, may not be feasible due to prohibitive increases in the cost of the material and of the installation process. A more attractive alternative is the periodic placement of buckle arrestors such that, in the event of a propagating buckle, the damage is restricted to the portion of the line between two arrestors.

Buckle arrestors are devices that locally increase the circumferential bending rigidity of the pipe and thus provide an obstacle in the path of a propagating buckle. Figure (1) illustrates several design alternatives for buckle arrestors. Of these, the integral arrestor has been preferred for pipelines installed in moderately deep and ultra-deep waters. It consists of a heavier section of pipe with the same internal diameter as the pipeline, welded between two strings of pipe (Netto and Estefen, 1996, Park and Kyriakides, 1997)

In some installation methods such as the J-lay, pipe sections are welded on the vessel as the line is laid on the sea floor. In this case, the suspended portion of the line is supported on the launching tower by collars that are welded between two pipe strings. A typical collar is shown in Figure (2). The geometrical similarity between collars and integral buckle arrestors prompted this study to evaluate the efficiency of collars in stopping an eventual propagating buckle. That is, given the geometric and material parameters of the pipeline, the aim is to verify whether the collar will arrest a propagating buckle initiated at the maximum project water depth, making unnecessary the use of specific devices for this purpose.

A numerical model capable to reproduce the quasi-static propagation of buckles in pipelines and arrest by collars was developed within the framework of the finite element code ABAQUS. Pipe and collar materials are assumed to be J_2-type elasto-plastic, finitely deforming solids, with isotropic hardening. The model is first used to evaluate the performance of a specific collar geometry and material previously used in the installation of a pipeline in the Campus Basin, Brazil. Subsequently, an extensive parametric study on the arresting efficiency of different pipe-collar geometric configurations is performed. These numerical results are then used to develop a simplified procedure to assess the arresting performance of these devices in the preliminary stages of design.

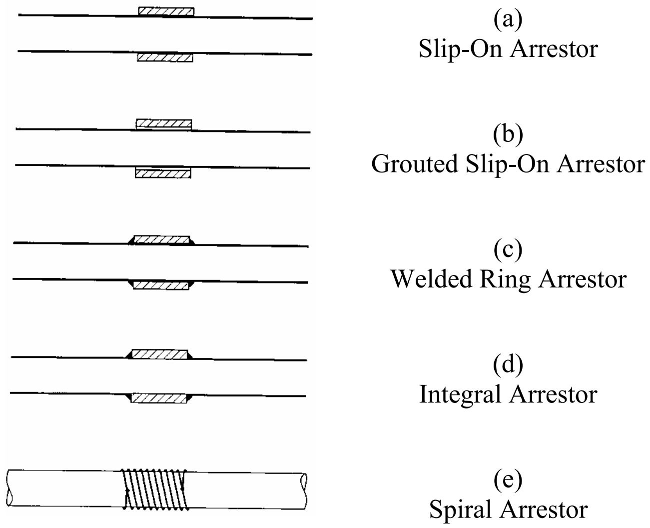


Figure 1 – Different conceptions of buckle arrestors.

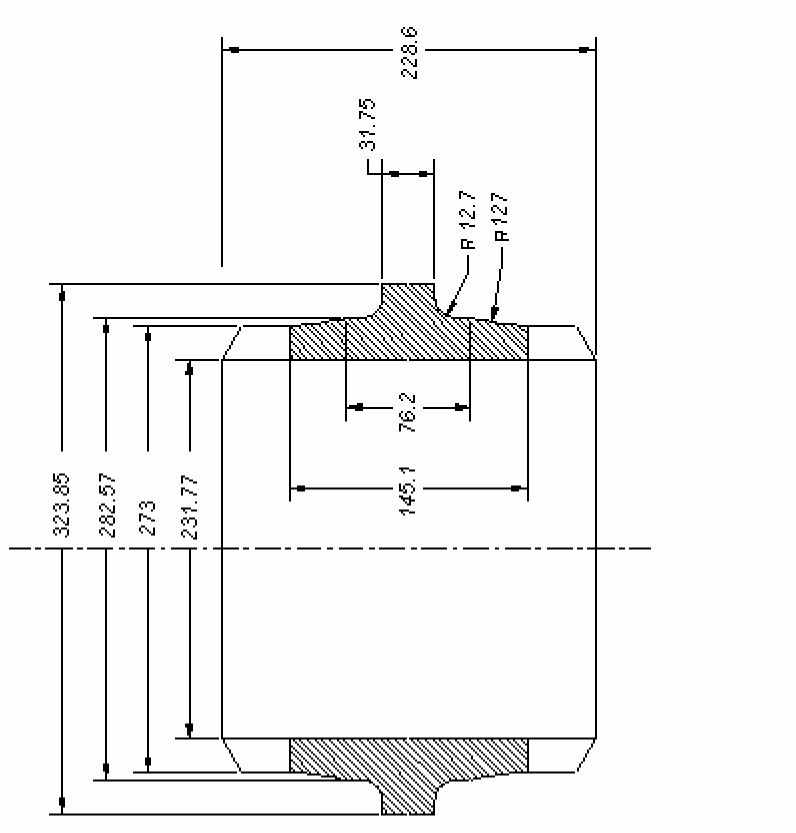


Figure 2 – Longitudinal cut of a typical collar.

2. Pipe-collar configurations

The most appropriate measure of the effectiveness of buckle arrestors is the arresting efficiency, η, defined in Kyriakides and Badcock (1980) as:

$$\eta = \frac{P_X - P_P}{P_{CO} - P_P}, \; 0 \leq \eta \leq 1 \qquad (1)$$

That is, a maximum efficiency (η = 1) is attained when the pressure at which the buckle crosses the arrestor (denominated crossover pressure, P_X) is equal to the collapse pressure (P_{CO}) of the intact pipe. By contrast, a crossover pressure (P_X) equal to the propagation pressure of the pipe (P_P) implies that η = 0.

Kyriakides et.al. (1998) recently performed a parametric study on integral buckle arrestors in which efficiencies between 0.2 and 1.0 were obtained for different combinations of arrestor lengths (L_a) and heights (h). These values were varied between $0.25 \le L_a/D \le 2.5$, and $1.5 \le h/t \le 7.5$, where D and t are pipe diameter and thickness, respectively. They established important dimensional bounds for the arrestor thickness and length and also developed an empirical design formula for such devices. Based on these results, and on typical commercial collar geometries, collar lengths and heights were here selected within $0.1 \le L_a/D \le 1$, and $.2 \le h/t \le 5$. Two pipes with diameter to thickness ratio (D/t) equal to 13 and 23, Table (1), were analyzed in conjunction with each collar geometry. Pipe and collar material were both assumed to be API X-60. Figure (3) shows the stress-strain engineering curve for both the pipe and the collar.

Table 1 – Geometric and material parameters of pipes analyzed.

D (mm)	t (mm)	D/t	Material	E (kN/mm^2)	σ_p (N/mm^2)	σ_o (N/mm^2)
273	21	13	X-60	207	310.3	413.7
219	9.5	23	X-60	207	310.3	413.7

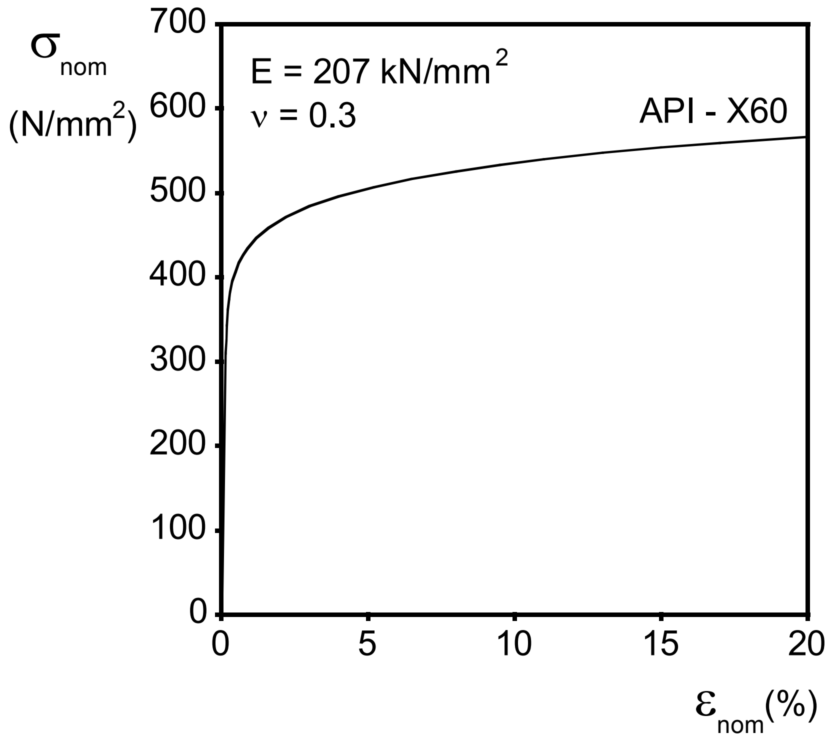


Figure 3 – Engineering stress-strain curve from steel API-X60.

3. Numerical Model

A nonlinear finite element model was developed within the framework of the commercial software ABAQUS (2003). Computational routines to generate specific meshes were used to discretize the problem in which buckle propagation in pipes and its engagement to collars are simulated. Due to the similarity of the structures analyzed, the numerical model adopted here is analogous in many aspects to the one developed by Park and Kyriakides (1997) for simulation of quasi-static propagation of buckles in pipes and their arrest by integral buckle arrestors.

The problem geometry is shown in Figure (4a). It consists of an upstream pipe section of length L_1, a collar of length L_a, and a downstream section of pipe of length L_2. Planes 1-2, 1-3 and 2-3 are assumed to be planes of symmetry, as indicated in the figure. The end nodes ($x_1 = L_1 + L_a + L_2$) are restricted in the 2-3 directions.

In the neighborhood of $x_1 = 0$, it was prescribed an initial imperfection to the pipe in the form of ovality, defined as:

$$\frac{w_o(\theta)}{D} = -\frac{\Delta_o}{2}\exp\left[-\beta\left(\frac{x_1}{D}\right)^2\right]\cos 2\theta \quad (2)$$

Where w_o is the imperfection in the radial direction, β is a parameter that affects the longitudinal extent of the imperfect region, and

$$\Delta_o = \frac{D_{max} - D_{min}}{D_{max} + D_{min}} \quad (3)$$

is the maximum ovality at x_1=0. The values adopted in this study were β = 1 and Δ_o =1%.

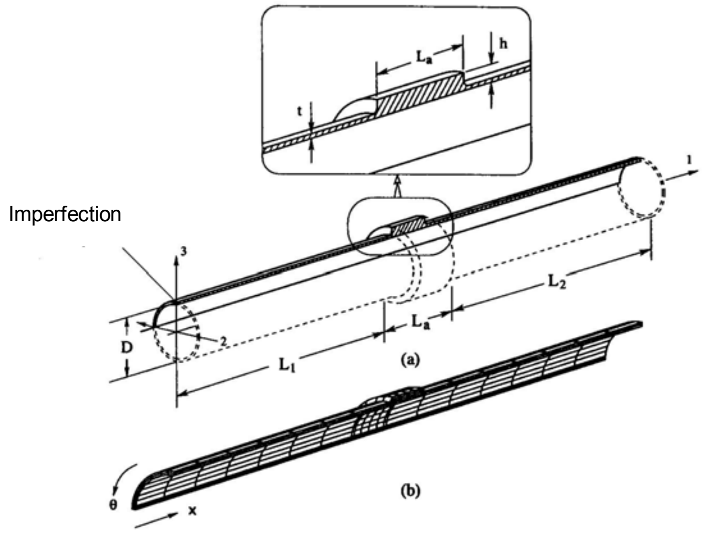


Figure 4 – (a) Geometry of pipe/ collar assembly analyzed.
(b) Typical finite element mesh used in the analyses.

Figure (4b) illustrates a typical finite element mesh used in the analyses. Pipe and collar were discretized with three-dimensional quadratic elements with 27 nodes (C3D27). For the sake of simplicity, the transition between collar and pipe were approximated by triangular prisms with the same material volume as the original shape. Prismatic quadratic elements with 15 nodes (C3D15V) were used in these regions. Figure (5) depicts the transition region of the commercial collar previously shown in Figure (2). The exact shape and its simplified modeling are respectively drawn on the left and right hand side of the collar.

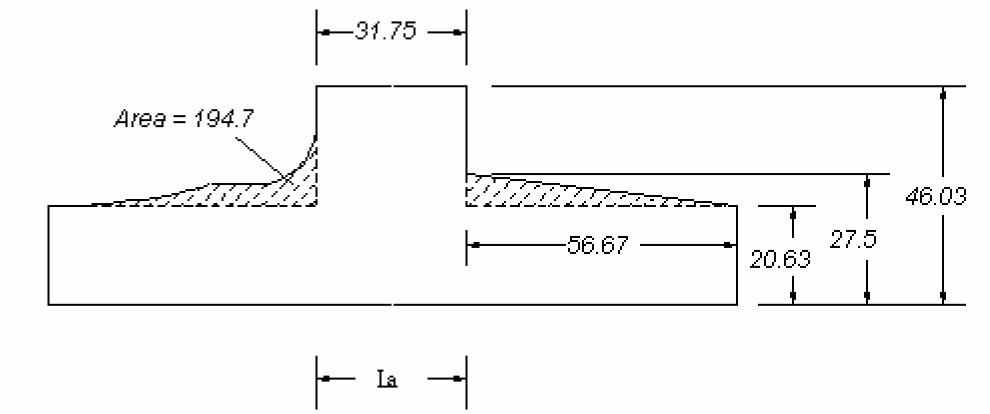


Figure 5 – Exact transition (left side) and approximate transition between the collar and the pipe (dimensions in inches).

The mesh refinement suggested after an extensive sensitivity study in Park and Kyriakides (1997) and Netto (1998) was adopted here. In the circumferential direction, the 90 ° section was discretized with 10 elements. The following angular spacements were used (beginning on axis 3): 10°-10° -15° -15° -10° -10° -7.5° -7.5° -2.5° -2.5°. Through the wall thickness of the pipe, two elements were used and, three to five for the collar depending on *h*. Figure (6) shows in detail a typical mesh used for the collar and transition region. Since only one quarter of the cross-section was analyzed, an imaginary rigid surface was placed along plane 1-2 using rigid elements to simulate contact of the inner surface of the pipe wall during buckle propagation.

Finally, the materials of the pipes and collars were assumed to be J_2-type, elastoplastic, finitely deforming solids which harden isotropically.

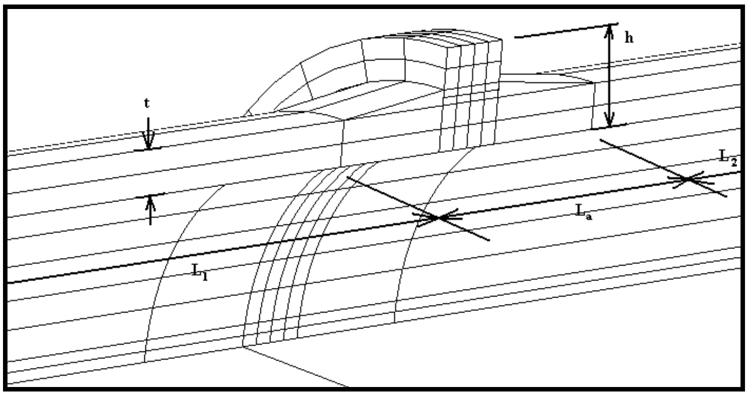


Figure 6 – Finite element mesh at the collar section.

4. Numerical Procedure

The numerical procedure to determine the crossover pressure (P_X) of the different configurations of pipe-collar will be following described. Hydrostatic pressure is applied on the external surface of the pipe-collar structure with the aid of three-dimensional hydrostatic elements (F3D3, F3D4) available in the ABAQUS library. These elements allow prescription of the change in volume inside a control region defined around the structure, which is an equivalent method of volume control. The pressure becomes an additional unknown while the volume change is enforced as a constraint via the Langrange multiplier's method.

Figure 7 shows the calculated pressure-variation of internal volume response obtained from the numerical analysis of the collar from Figure (2) along with a pipe with D = 273 mm and t = 21 mm (V_0 is the initial internal volume of the structure). External pressure is applied on the pipe-collar external surface until local collapse of the imperfect region (in the neighborhood of $x_1 = 0$). Pressure ceases to drop when contact between the collapsing walls of the pipe first occurs. The subsequent stable response is followed by a pressure plateau corresponding to buckle propagation at P_P = 22.8 N/mm^2. When the buckle reaches the collar, the pressure increases again and, as a consequence, collar and downstream pipe start to ovalize. Eventually, the external pressure and the ovalization reach a critical combination and the downstream pipe collapses. This second pressure maximum determines the quasi-static crossover pressure (in this case, P_X = 37.10 N/mm^2). For completeness, the exact shape of the transition region was also modeled and the results compared with the approximate model. The crossover pressures obtained from both analyses (red and black curves in Figure (7)) were almost identical (0.32% difference), confirming the suitability of the simplified model. The deformed configuration of the actual collar-pipe geometry immediately after collapse of the downstream pipe is illustrated in Figure 8.

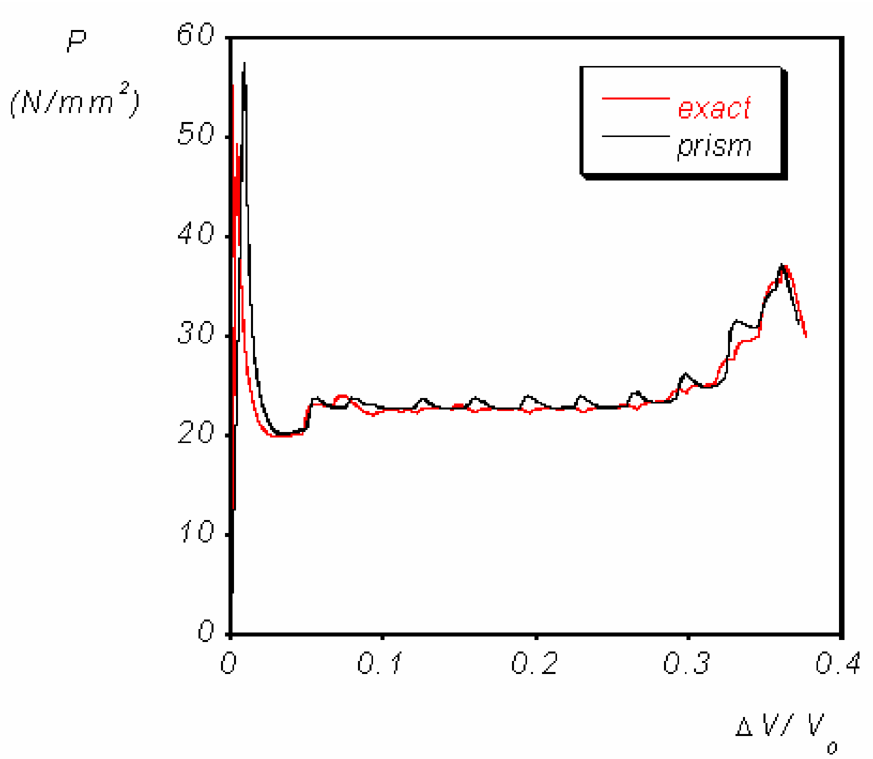


Figure 7 – Calculated pressure-variation of volume response for the pipe-collar configuration shown in Figure (2).

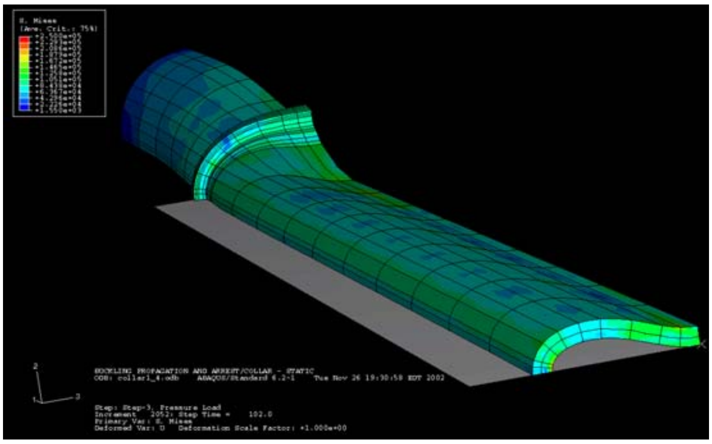


Figure 8 – Deformed configuration showing buckle crossover.

5. Parametric study

In order to determine the efficiency η of the different pipe-collar configurations, the collapse pressure (P_{CO}), the propagation (P_P) and the pressure of both pipes in Table (1) were determined using a numerical model described in the previous section, Table (2) (an initial ovality of 2% was used in the calculation of the collapse pressure). The model was then used to calculate the crossover pressure (and thus the efficiency) of sixteen different configurations in which the parameters *D/t*, *h/t* and L_a/D were varied. The results are summarized in Table (3).

Table 2 – Collapse and propagation pressures for API X-60 pipes with *D/t* = 13 and 23.

D/t	Numerical	
	P_{CO} *(N/mm2)*	P_P *(N/mm2)*
13	63.8	22.9
23	27	5.4

Table 3 – Summary of the parametric study.

D/t	*h/t*	L_a/D	P_X *(N/mm²)*	*η*	Transposition modes
13	2	0.1	34.8	0.29	flattering
13	2	0.2	39.6	0.41	flattering
13	2	0.5	52.7	0.73	flattering
13	2	0.75	58.3	0.86	flattering
13	2	1	62.2	0.96	flipping
13	3	0.2	56.4	0.82	flattering
13	3.5	0.2	62.3	0.96	flipping
13	4	0.2	61.0	0.93	flipping
13	5	0.2	61.1	0.93	flipping
23	2	0.1	8.7	0.15	flattering
23	2	0.2	9.7	0.2	flattering
23	2	0.5	13.2	0.36	flattering
23	2	1	17.5	0.56	flipping
23	3	0.2	14.0	0.4	flattering
23	4	0.2	21.4	0.74	flipping
23	5	0.2	21.5	0.74	flipping

5.1 – Crossover modes

Corroborating Park and Kyriakides (1997), buckles were found to cross the collars in two different modes, depending on their geometry. Higher efficiency arrestors exhibited the flipping mode as a result of the ovalization induced to the downstream pipe that is orthogonal to the mode of collapse of the upstream pipe. Example of this crossover mode is shown in Figure (9) obtained from experimental tests by Netto (1998). As it can be seen in Tab. (3), collars with efficiencies greater than 0.7 exhibited the flipped mode of crossover. By contrast, thinner collars exhibited the flattening mode, Figure (10), in which the incoming buckle causes the collar and downstream pipe to deform in a similar fashion as the collapsed pipe. More on these two mechanisms of crossover can be found in Park and Kyriakides (1997).

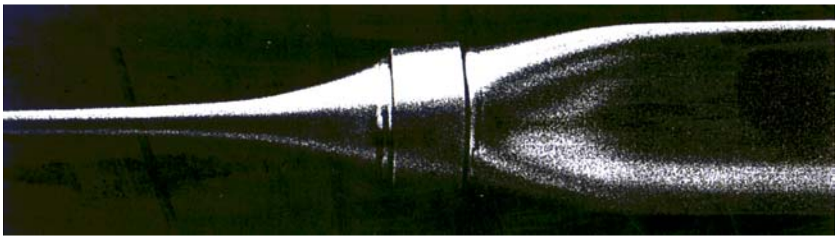


Figure 9 – Example of the flipping mode of crossover (Netto, 1998).

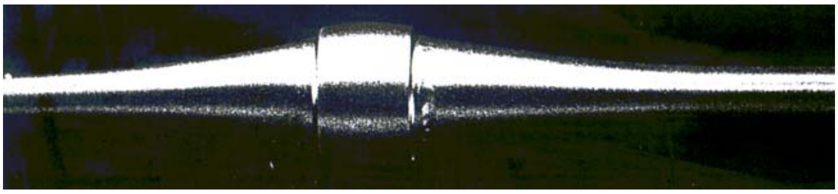
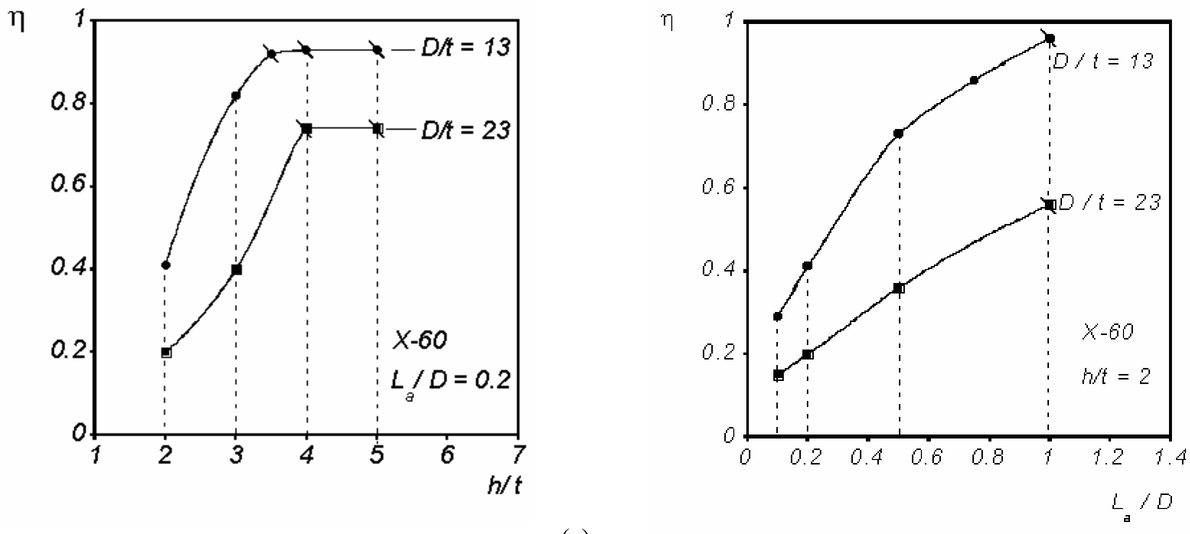


Figure 10 – Example of the flattering mode of crossover (Netto, 1998).

5.2. Efficiency as a function of collar height and length

The pipe geometry was first fixed at *D/t* = 13 while the collar thickness and length were extensively varied. In the first series of analyses, L_a/D was varied from 0.1 to 1 for a fixed value of *h/t* = 2. As the collar length approached the value of one diameter (i.e., L_a/D = 1), the efficiency tended to 1, as shown in Figure (11a). Subsequently, L_a/D was set equal 0.2, while *h/t* ranged from 2 to 5. Maximum efficiencies were obtained for *h/t* values greater than 3.5, as indicated in Figure (11b). In addition, it can be noticed that in the region where the crossover mode switches from flattering to flipping, the efficiency does not increase monotonically with the increment of *h/t* (see *h/t* = 3.5 and 4, L_a/D = 0.2, *D/t* = 13, Table (3)). Interestingly, Kyriakides *et. al*. (1997) made the same observation in their study on integral arrestors.

Qualitatively similar results were obtained for pipes with *D/t* = 23. Nevertheless, the maximum efficiencies obtained in the two series of calculations were 0.56 and 0.74 (i.e., fixing *h/t* = 2 and then L_a/D = 0.2, Figures (11) and (12)). These values are much lower than the maximum efficiency obtained for *D/t* = 23 with the same collar geometries. Therefore, for the same geometric parameters, efficiencies for the pipe with *D/t* = 13 is always greater then for *D/t* = 23.



(a) (b)

Figure 11 – Collar efficiency as a function of (a) L_a/D and (b) *h/t*.

6. Simplified method for evaluating the collar efficiency

Clearly, a full-scale finite element calculation of the type described above remains a viable option. However, such an effort is computationally expensive and may not be the best option in the early stages design. Approximate design formulae can then be very useful when evaluating different solutions for a given scenario.

Similar procedures were successfully developed for integral (Kyriakides et.al., 1998), slip-on (Kyriakides and Babcock, 1980), and spiral buckle arrestors (Kyriakides and Babcock, 1982). from numerical and experimental results. In the quasi-static setting considered in this study, the crossover pressure (P_X) will depend on the propagation pressure (P_P) and the main geometric and material parameters, i.e.:

$$P_X = f(P_P, E, \sigma_o, D, t, L_a, h) \qquad (4)$$

From Buckinghsm's Π theorem, this can be express as the following series:

$$\frac{P_X}{P_P} = F\left(\frac{\sigma_o}{E}, \frac{D}{t}, \frac{L_a}{t}, \frac{h}{t}\right). \qquad (5)$$

We assume that this can be expressed as the following series:

$$\frac{P_X}{P_P} = \sum_{n=0}^{\infty} A_n \left[\left(\frac{\sigma_o}{E}\right)^{\alpha_1}\left(\frac{D}{t}\right)^{\alpha_2}\left(\frac{L_a}{t}\right)^{\alpha_3}\left(\frac{h}{t}\right)^{\alpha_4}\right]^n \qquad (6)$$

Since $P_x / P_p \geq 1$, we deduce that $A_o = 1$. In an effort to produce the simplest possible relationship we first neglect terms with powers n > 1 and consider the approximate relationship:

$$\frac{P_X}{P_P} \approx 1 + A_1\left(\frac{\sigma_o}{E}\right)^{\alpha_1}\left(\frac{D}{t}\right)^{\alpha_2}\left(\frac{L_a}{t}\right)^{\alpha_3}\left(\frac{h}{t}\right)^{\alpha_4} \qquad (7)$$

The collar efficiency can now be deduced from Eq. (1),

$$\eta \approx A_1 \frac{\left(\frac{\sigma_o}{E}\right)^{\alpha_1}\left(\frac{D}{t}\right)^{\alpha_2}\left(\frac{L_a}{t}\right)^{\alpha_3}\left(\frac{h}{t}\right)^{\alpha_4}}{\left(\frac{P_{CO}}{P_P} - 1\right)}, \qquad (8)$$

where parameters α_1, α_2, α_3, α_4 are determined through the least square method in order to produce the best correlation between all available data.

The data was found to exhibit a bimodal trend with $\eta = 0.7$ as the turning point. Collars with efficiency lower than 0.7 showed a correlation coefficient higher than 0.98 (all collars in this range exhibited the flattering mode of crossover). However, it was not possible to achieve a good correlation for collars with efficiency higher than 0.7. For integral buckle arrestors Kyriakides *et. al.* (1997) observed the same bimodal trend. In the interest of simplicity, it was decided to accept this bimodal trend, proceeding to select α_i, in a way to pursue the best correlation for $\eta \leq 0.7$. This methodology yielded $\alpha_1 = 1$, $\alpha_2 = 0.3$, $\alpha_3 = 0.63$, $\alpha_4 = 1.79$, with the coefficient $A_1 = 123.35$, i.e.:

$$\eta \approx 123.35 \frac{\left(\frac{\sigma_0}{E}\right)\left(\frac{t}{D}\right)^{0.3}\left(\frac{L_a}{t}\right)^{0.63}\left(\frac{h}{t}\right)^{1.79}}{\left(\frac{P_{CO}}{P_P} - 1\right)}. \qquad (9)$$

All the data are plotted against the parameter

$$\xi = \frac{\left(\frac{\sigma_0}{E}\right)\left(\frac{t}{D}\right)^{0.3}\left(\frac{L_a}{t}\right)^{0.63}\left(\frac{h}{t}\right)^{1.79}}{\left(\frac{P_{CO}}{P_P} - 1\right)} \qquad (10)$$

in Fig. (12). A good correlation was obtained for values of $\eta \leq 0.7$. We can see that the data nicely coalesce to a straight line in this range. Nevertheless, for higher values of η, equation (9) is not valid. For this range, the lower bound indicated in Figure (12) by a dashed line is suggested. In other words, a conservative approach is recommended when designing high efficiency collars.

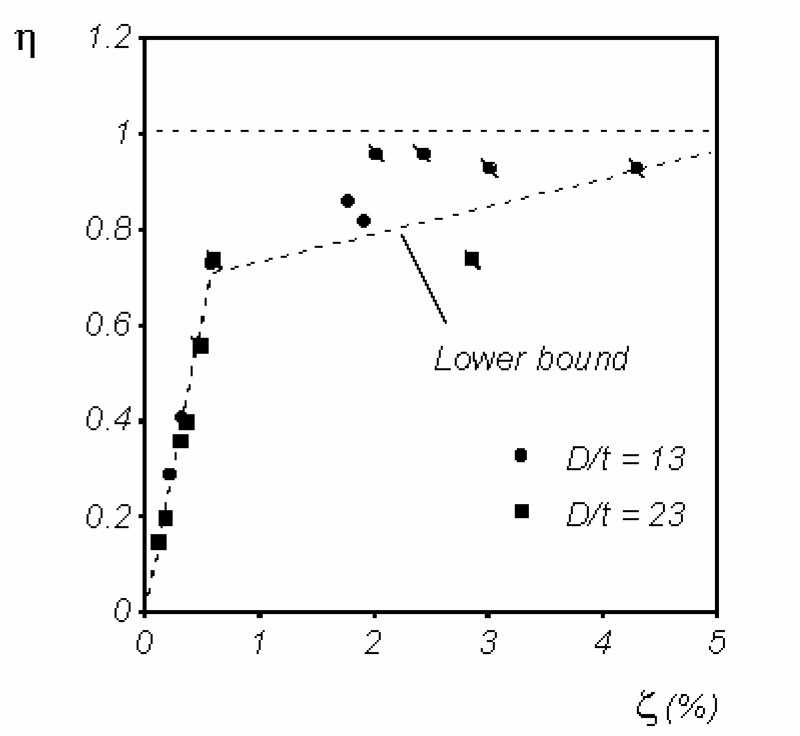


Figure 12 – Collar efficiency versus empirical function of parameters and lower bound for design.

7. Conclusions and recommendations

A three-dimensional finite element model was developed to simulate buckle propagation in pipes and its arrest by collars. The model incorporates nonlinear kinematics and plasticity. It was initially used to calculate the crossover pressure of a typical pipe-collar configuration for offshore applications. Subsequently, sixteen different configurations were analyzed and the calculated crossover pressures were then used to produce a simplified method for evaluating the arresting efficiency of collars. In summary, the following methodology for assessing the efficiency of collars in arresting propagating buckles is suggested:

- Calculate the collapse and propagation pressure of the pipeline.
- Calculate the parameter ξ for the material and geometrical configuration of pipe-collar.
- Depending on the value of ξ, obtain an estimative of the efficiency using Eq. (9) or through the graphic in Figure (12).
- Calculate the corresponding crossover pressure and compare it with the operational pressure. The crossover pressure should be higher than the equivalent water depth multiplied by a safety factor.
- Test your design by a dependable numerical model like the one discussed here, or by a full-scale test of the pipe-collar considered for the application.

It should be noted that the procedure described above is only valid for similar geometries and materials as used in this study. If the problem parameters deviate significantly from those of the present work, new dependable data must be added to it and, if necessary, a new fit should be attempted before such empirical formula is used directly.

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