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**COLLAPSE ARRESTORS FOR DEEPWATER PIPELINES: FINITE ELEMENT MODELS AND
EXPERIMENTAL VALIDATIONS FOR DIFFERENT CROSS-OVER MECHANISMS**

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ABSTRACT

Using finite element models it is possible to determine the cross-over external pressure of different pipeline arrestor designs. In this paper these finite element models are discussed and validated by comparing their results with experimental determinations. The flipping and flattening cross-over mechanisms are considered in the experimental validation of the numerical models.

INTRODUCTION

Deepwater pipelines are normally subjected to external pressure and bending. They fail due to structural collapse when the external loading exceeds the pipes collapse limit surface. For seamless steel pipes, the influence on this limit surface of manufacturing imperfections has been thoroughly studied using finite element models that have been validated via laboratory full-scale tests [1-6].

If by accident the collapse is initiated at a certain location, the collapse is either restrained to the collapse initiation section or it propagates along the pipeline, being this second alternative the most detrimental one for the pipeline integrity [7]. Since the external collapse propagation pressure is usually quite low in comparison with the external collapse pressure, it is necessary to build in the pipeline spaced reinforcements, usually steel rings, to act as arrestors for the collapse propagation.

Two different buckle arrestor cross-over mechanisms were identified in the literature: flattening and flipping. The occurrence of either cross-over mechanism is determined by the geometry of the pipes and of the arrestors [8]. In this paper we develop finite element models to analyze the collapse pressure, collapse propagation pressure and cross-over pressure of pipelines and we present an experimental validation for these models.

**EXPERIMENTAL RESULTS USING SEAMLESS STEEL
PIPES**

Few experimental results are available in the literature for the cross-over of integral ring buckle arrestors under external pressure on large diameter carbon steel pipes [9, 10]. Most of the available experimental results correspond to stainless steel and small diameter steel pipes [8, 11-14]. Therefore this paper adds to the available technical literature in a range where more information can be useful.

The purpose of our laboratory tests was to determine the equilibrium path for the assembly (pipe + arrestor + pipe) under external pressure; and from it determine the collapse pressure, and the cross-over pressure. Fig. 1 shows the sample configuration.

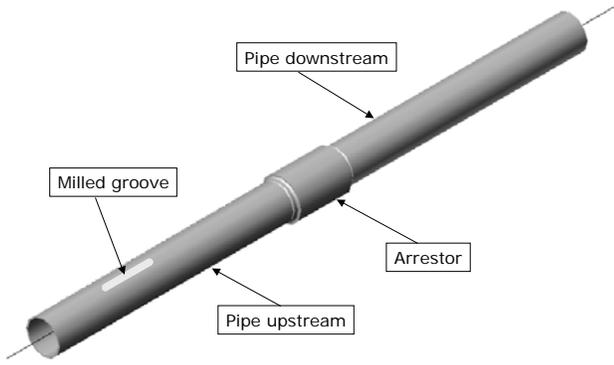


Figure 1. Sample configuration

To localize the buckle initiation we milled a groove in one of the pipes (upstream pipe). In Fig. 2 we present a detail of the arrestors:

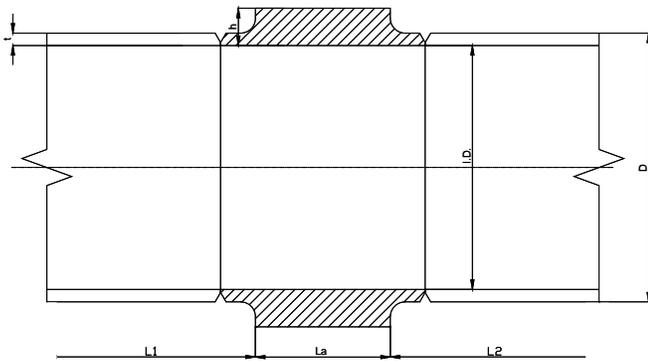


Figure 2. Arrestor geometry

Table 1 provides the data for the tested samples:

Sample	Pipe OD [mm]	Pipe thickness (t) [mm]	Pipe steel grade	Arrestor (h/t)	Arrestor (La/D)	Arrestor steel grade	Sample length [mm]	Expected cross-over mechanism
1	141.3	6.55	X42	2.0	0.50	6 (ASTM A-333)	2250	Flattening
2	141.3	6.55	X42	2.5	0.50	X42	2250	Flattening
3	141.3	6.55	X42	3.0	0.75	X42	2274	Flipping
4	141.3	6.55	X42	3.0	1.00	X42	2330	Flipping

Table 1. Data for tested samples

Geometrical Characterization of the Tested Samples

The outer surface of the samples was mapped using the *shapemeter* [1]; the corresponding Fourier decomposition of one of the tested samples is shown in Fig. 3. The zone with high amplitude corresponds to the milled groove, whereas the zone with low amplitude belongs to the arrestor, which was machined in a lathe.

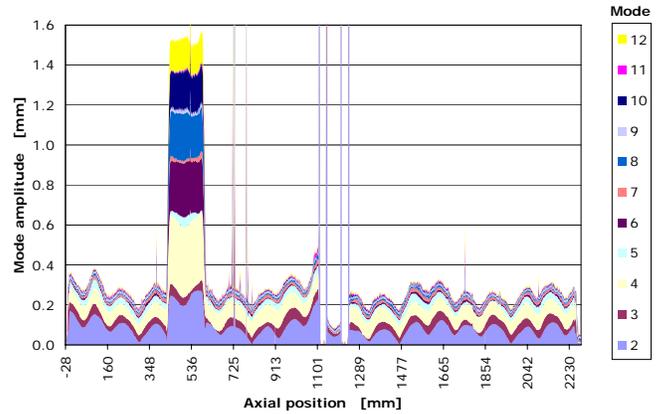
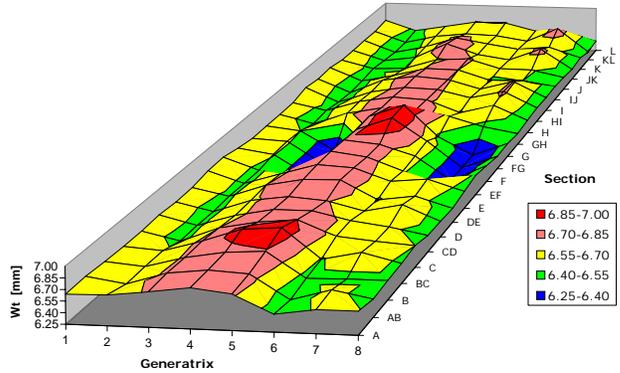


Figure 3. OD Fourier analysis of the first sample

The thickness of the samples was also mapped using a standard ultrasonic gauge; the corresponding thickness map of the first sample is shown in Fig. 4.

Sample 1 - Upstream pipe - OD : 5 9/16" Wt : 6.55 mm



Sample 1 - Downstream pipe - OD : 5 9/16" Wt : 6.55 mm

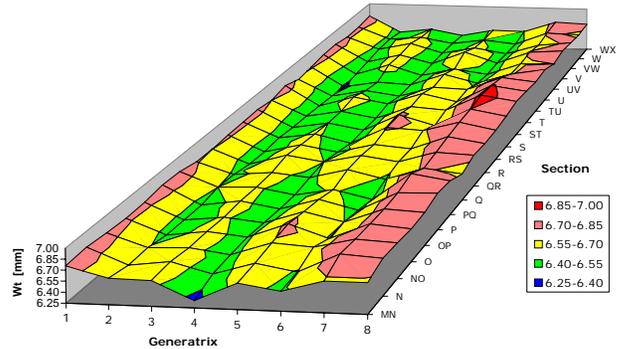


Figure 4. Thickness distribution for the first sample

Mechanical Characterization of the Tested Samples

For all the pipe and arrestor materials we determined:

- True stress – true strain curves (longitudinal tensile tests since the thickness of the pipes was too small for hoop samples)
- Hoop residual stresses (evaluated using slit ring tests)

Sample	Max. residual stress / yield stress
1	0.39
2	0.47
3	0.47
4	0.49

Table 2. Measured residual stresses

Experimental facility

In Fig. 5 we present a scheme of the experimental set-up. In order to measure the internal volume variation perforated end-caps were welded to the pipes. Each specimen was completely filled with water before the beginning of the test. From the hole in one of the end caps the water was directed to a container connected to a load cell. The load variation in the load cell is proportional to the displaced water.

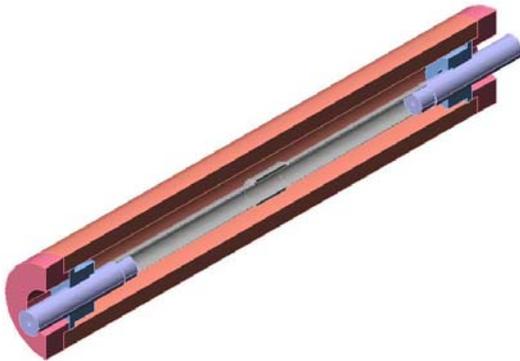
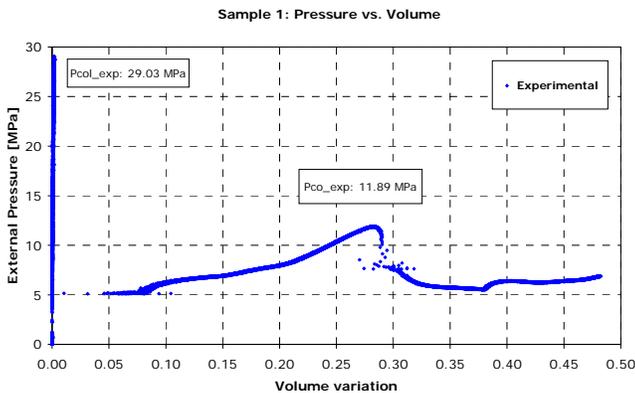


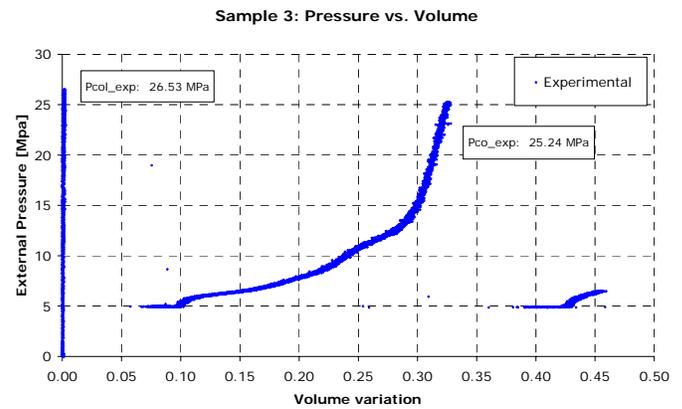
Figure 5. Experimental set-up

Experimental results

Typical experimental results are shown in Fig. 6.



(a) First sample: Flattening mode



(b) Third sample: Flipping mode
Figure 6. Experimentally determined p-V curves

We use:

$$Volume\ variation = \frac{\Delta inside\ volume}{Original\ inside\ volume} \quad (1)$$

THE FINITE ELEMENT MODELS

For the numerical simulation of the crossing of an integral ring arrestor by a quasi-statically propagating buckle, we developed a finite element model using the MITC4 shell element in the ADINA general-purpose code [15 -16].

The numerical model was developed using a material and geometrical nonlinear formulation, taking into account large displacements/rotations but small strains [17] and it incorporates the following features:

- Geometry as described by the O.D. mapping and by the thickness distribution that was acquired for each sample as reported above.
- Von Mises elasto plastic material model with isotropic multilinear hardening.
- Hoop residual stresses.
- Contact elements on the pipe inner surface in order to prevent its inter-penetration in the post collapse and propagation regime.
- Nonlinear equilibrium path tracing via the algorithm developed in Ref. [18].
- Residual stresses modeled with the technique discussed in [1].

Identifying the different cross-over mechanisms

In Figures 7 and 8 we present the finite element predicted deformed shapes for a (pipes – arrestor) system exhibiting a flattening cross-over mechanism and in Figs. 9 and 10 we show the predicted deformed shapes for a system presenting a flipping cross-over mechanism.

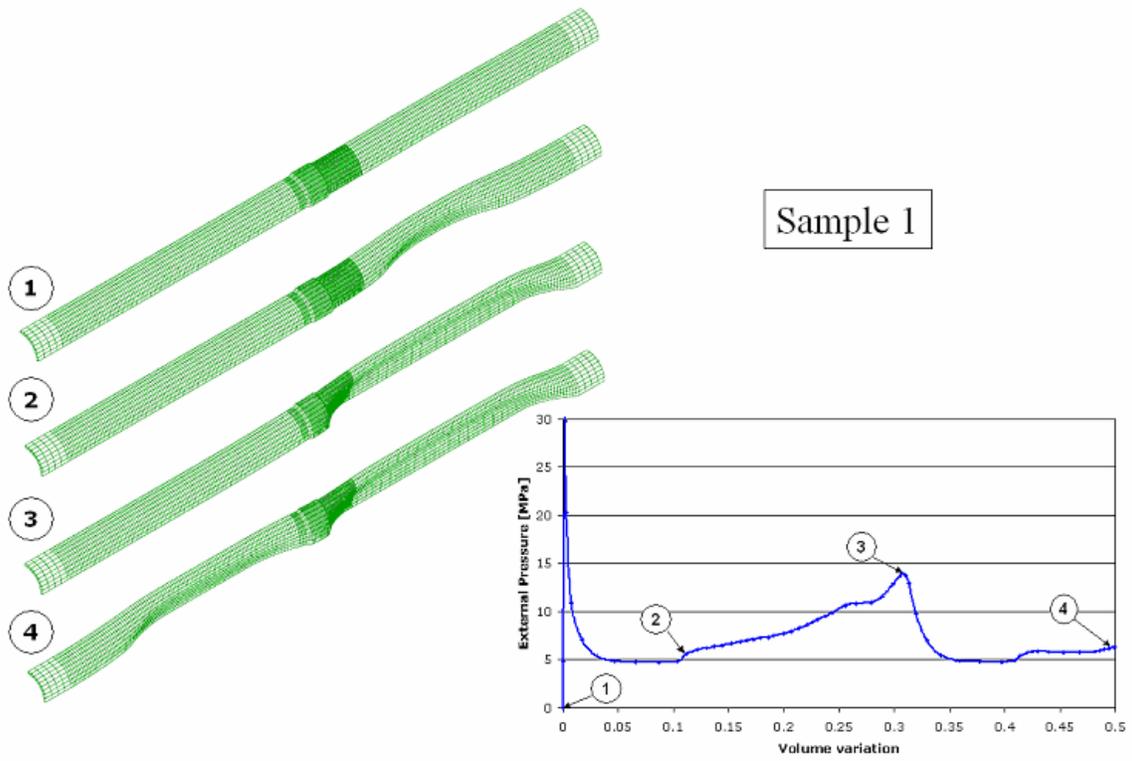


Figure 7. Sample 1: Flattening cross-over mechanism

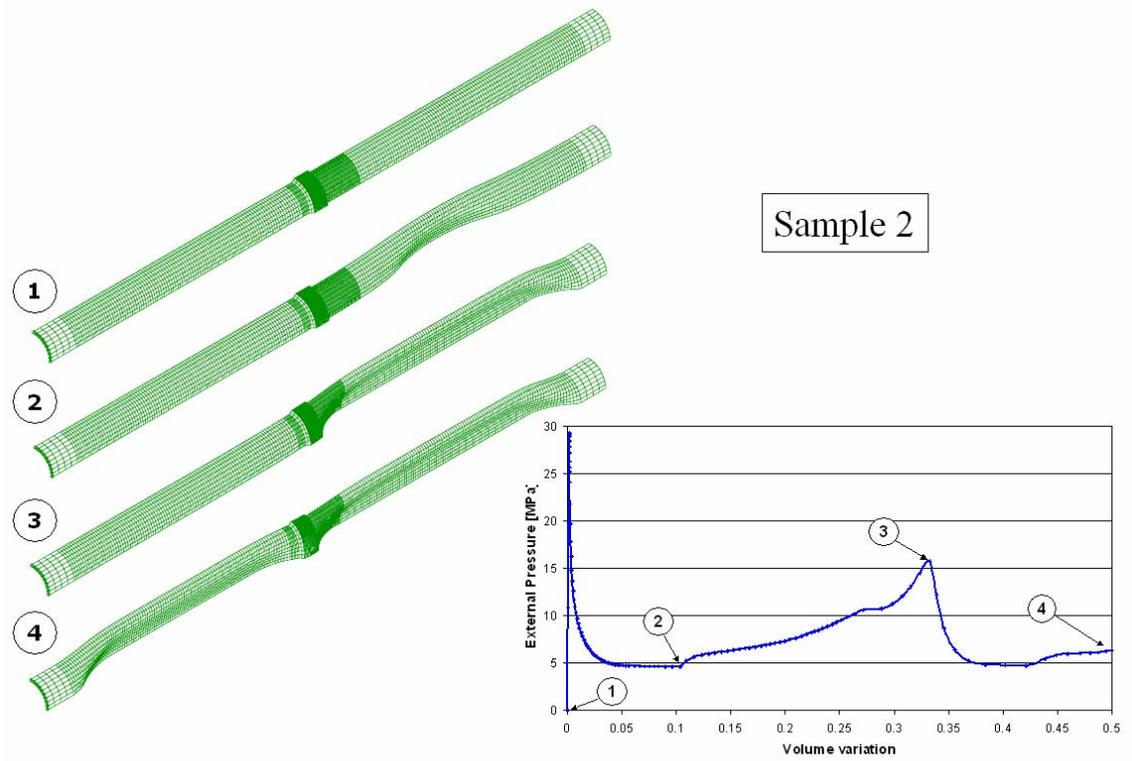


Figure 8. Sample 2: Flattening cross-over mechanism

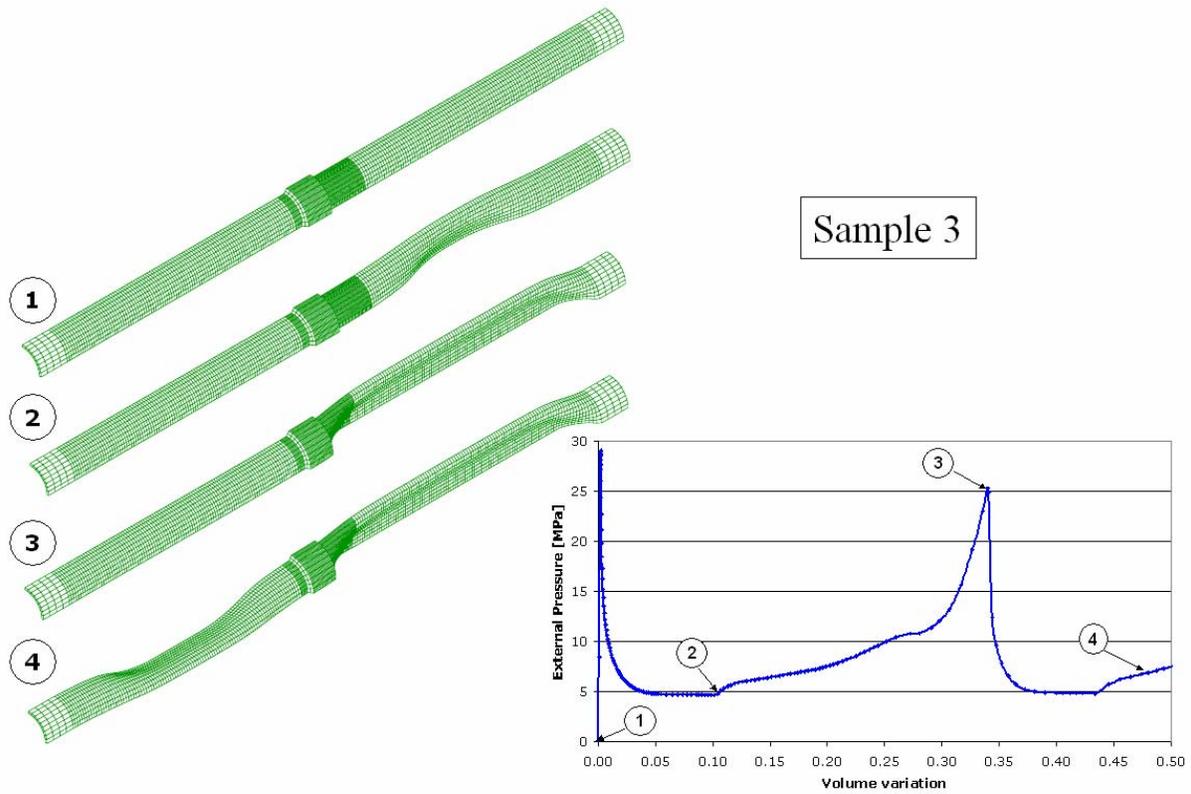


Figure 9. Sample 3: Flipping cross-over mechanism

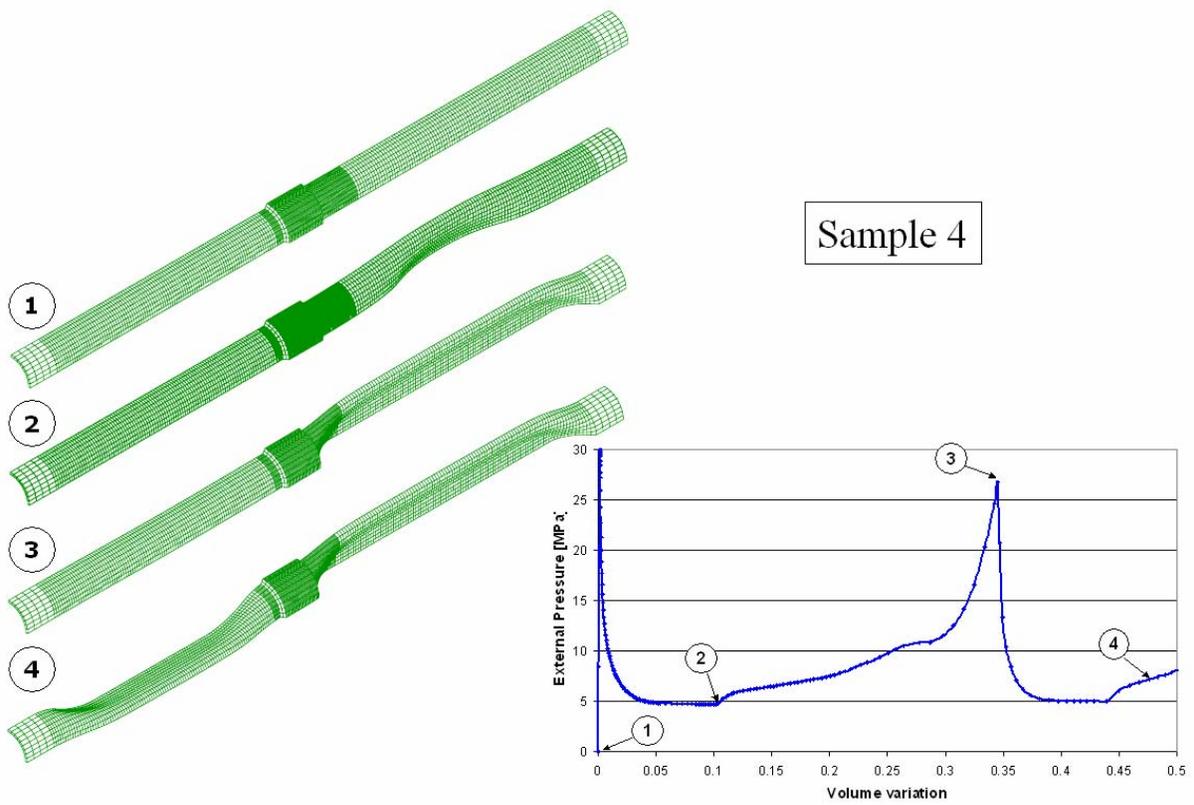


Figure 10. Sample 4: Flipping cross-over mechanism

Validation of the Finite Element Results Using the Experimental Results

Table 3 compares the FEA results with the experimental ones:

Sample	Collapse pressure: FEA/lab	Cross-over pressure: FEA/lab
1	0.921	1.006
2	0.923	0.967
3	0.953	0.927
4	0.859	0.910

Table 3. FEA vs. Experimental results

It is important to point out that the finite element results indicated in the previous table were obtained considering that the residual stresses in the two pipe sections are the residual stresses measured in the full length pipe. The modifications in residual stresses induced by the pipe cutting, the welding and groove machining were not considered in the model, this results in numerically predicted collapse pressures lower than the actual ones.

In Figures 11 and 12 we compare, for Samples 1 and 2 (flattening), the experimentally determined and FEA predicted equilibrium paths. During the laboratory determination for Sample 1, some water was spilled out of the measurement system, a fact that explains the shifting observed in Figure 11, in the horizontal axis, between the FEA and experimental results.

In Figures 13 and 14 we present the same comparison for the cases in Figs. 9 and 10 (flipping). Finally in Fig. 15 we compare the experimentally observed and FEA predicted shapes of two collapsed pipes after cross-over.

CONCLUSIONS

A 3D finite element model was developed in order to be able to analyze the behavior of an integral ring buckle arrestor crossed over by a propagating buckle. The model was validated by comparing the numerical predictions with experimental determinations.

The model is able to simulate both, the flipping and the flattening [8] cross-over mechanisms.

The agreement between the finite element predictions and the laboratory observations, both for the collapse and cross-over pressure, is very good; hence, finite element models can be used as a reliable engineering tool to assess the performance of integral ring buckle arrestors for steel pipes.

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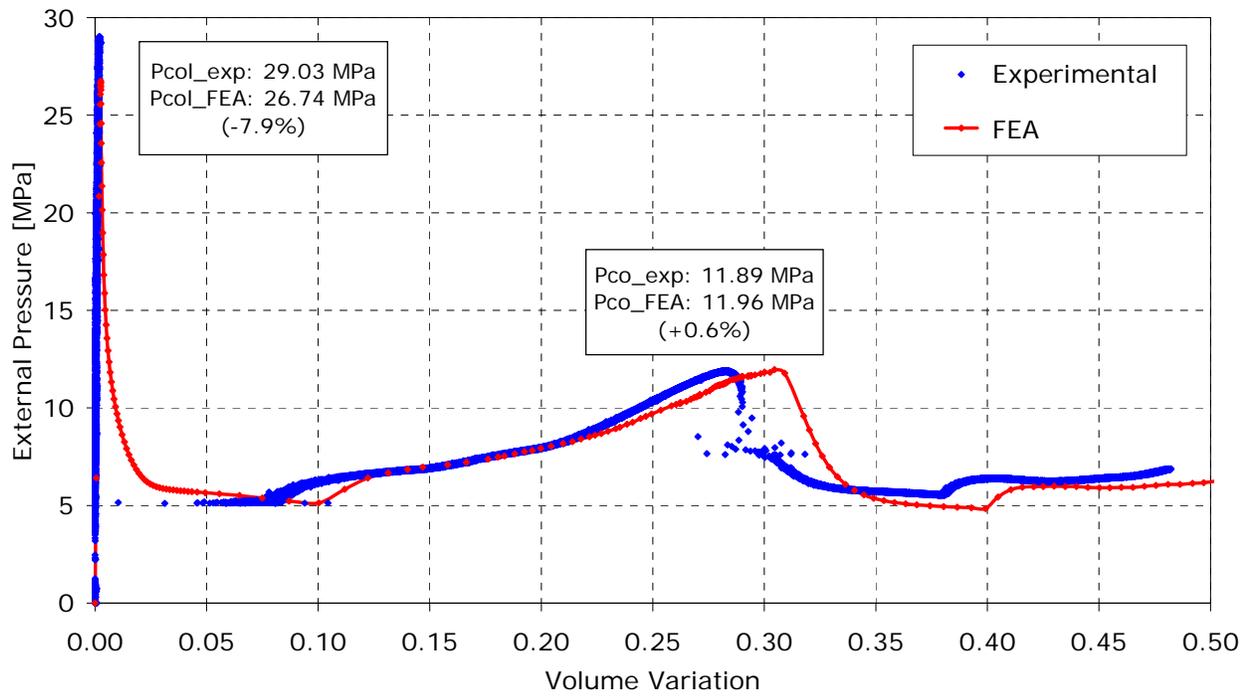


Figure 11. FEA vs. experimental results: flattening (Sample 1)

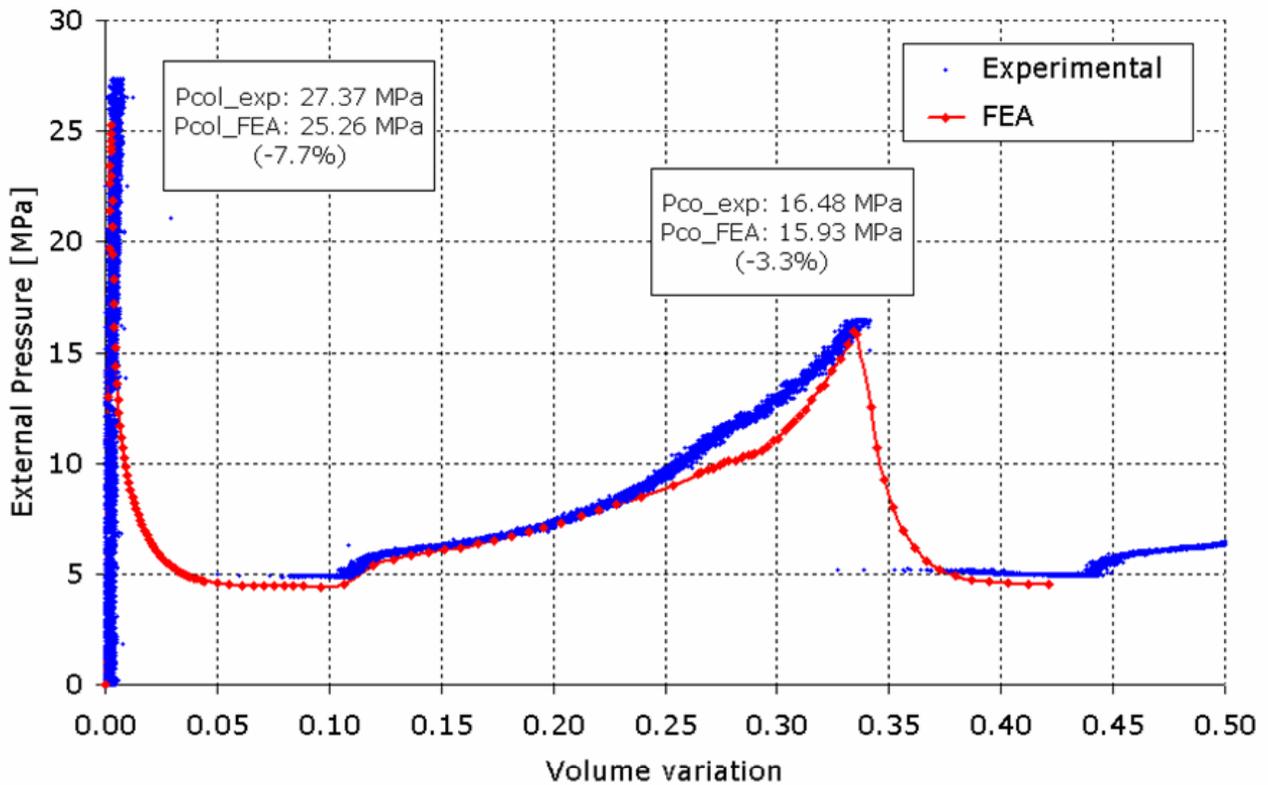


Figure 12. FEA vs. experimental results: flattening (Sample 2)

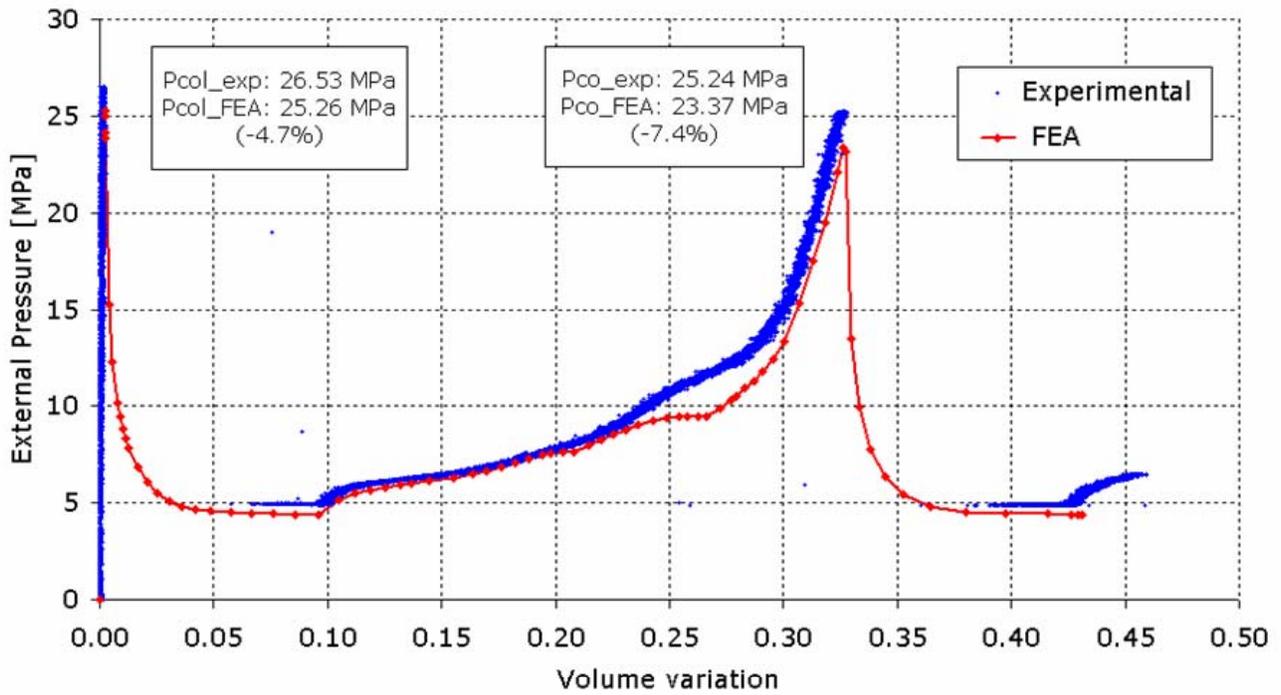


Figure 13. FEA vs. experimental results: flipping (Sample 3)

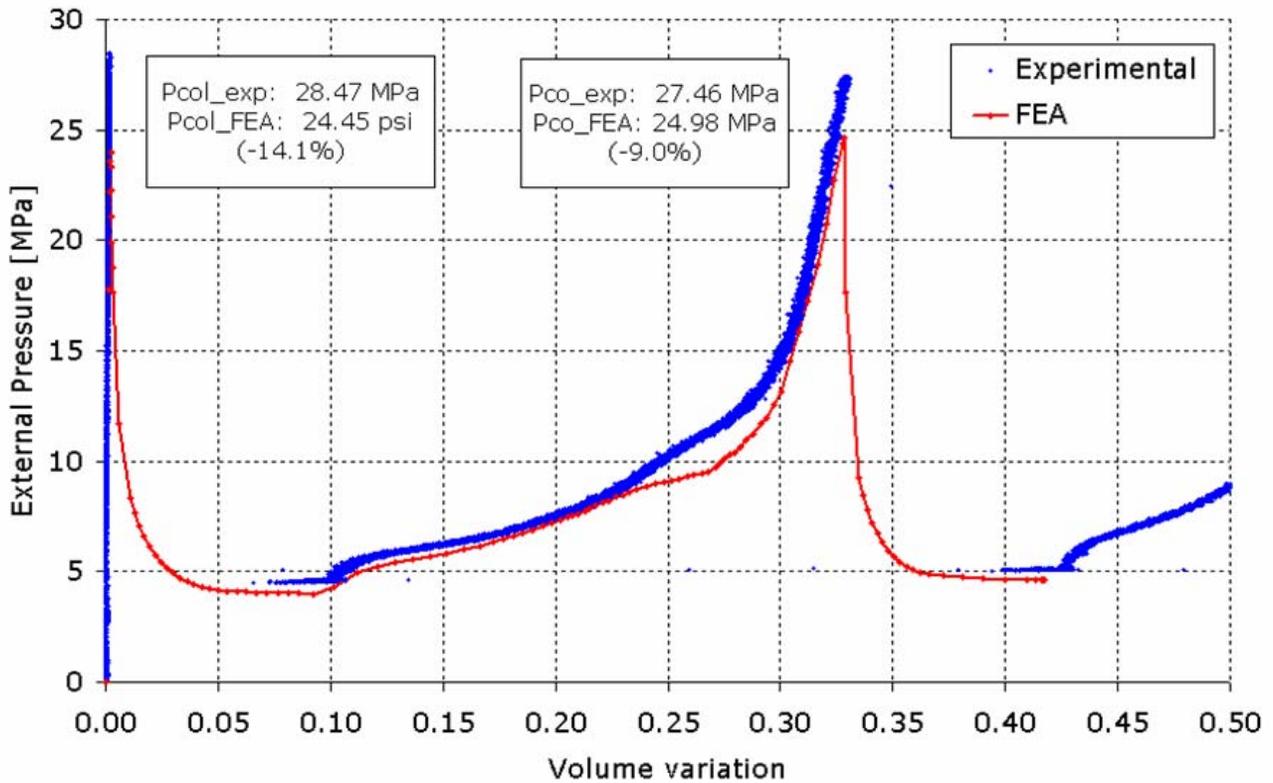
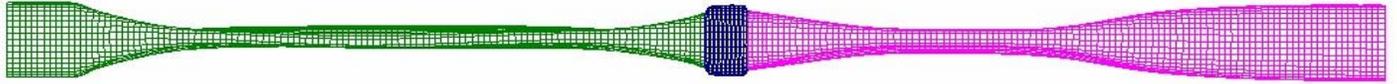
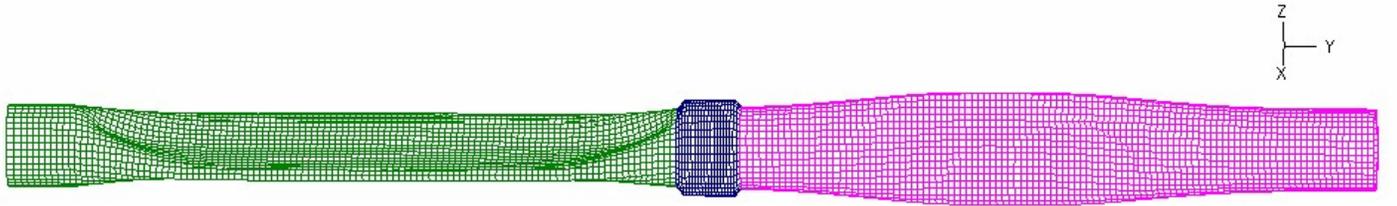


Figure 14. FEA vs. experimental results: flipping (Sample 4)



(a) Sample 2 – flattening



(b) Sample 3 - flipping

Figure 15. Experimentally observed and FEA predicted shapes of collapsed pipes after cross-over.