IBP1021_05

COLLAPSE ARRESTORS FOR DEEP WATER PIPELINES: IDENTIFICATION OF CROSSOVER MECHANISMS

Rita G. Toscano[1], Luciano Mantovano[2], Andrea Assanelli[3], Pablo Amenta[4], Daniel Johnson[5], Roberto Charreau[6] and Eduardo Dvorkin[7]

Abstract

Deepwater pipelines, normally subjected to external pressure and bending, fail due to structural collapse when the external loading exceeds the pipes collapse limit surface. For steel pipes, the influence on this limit surface of manufacturing imperfections has been thoroughly studied by CINI using finite element models that have been validated via laboratory full-scale tests.
After a steel pipeline collapses, the collapse is restrained to the collapse initiation section or it propagates along the pipeline, being this second alternative the most detrimental one for the pipeline integrity. Therefore, it is necessary to build in the pipeline periodic reinforcements, to act as arrestors for the collapse propagation.
Using finite element models, we study the crossover of collapse arrestors by the propagating collapse. The occurrence of different crossover mechanisms is determined by the geometry of the pipes and of the arrestors.
Laboratory tests were carried out at CINI in order to obtain experimental results that could be used to validate the numerical models. In this paper, we compare the numerical and experimental results for external pressure load.

1. Introduction

Deepwater pipelines are normally subjected to external pressure and bending. They fail due to structural collapse when the external loading exceeds the pipe 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 test [1-6].

After a steel pipeline collapses, 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 quite low in comparison with the external collapse pressure, it is necessary to build in the pipeline periodic reinforcements, usually steel rings, to act as arrestors for the collapse propagation.

Two different buckle arrestor crossover mechanisms were identified in the literature: flattening and flipping. The occurrence of either crossover 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 crossover pressure of pipelines and we also present an experimental validation for these models.

2. Experimental Results Using Steel Pipes

Few experimental results are available in the literature on the crossover of integral ring buckle arrestors under external pressure on large diameter steel pipes [9, 10], most of them correspond to stainless steel and small diameter steel pipes [8, 11-14].

[1] Master, Civil Engineer - TENARIS – Center for Industrial Research (CINI)
[2] Mechanical Engineer - TENARIS – Center for Industrial Research (CINI)
[3] Civil Engineer - TENARIS – Center for Industrial Research (CINI)
[4] M.Sc. in Naval Engineer - TENARIS – Center for Industrial Research (CINI)
[5] Mechanical Engineer - TENARIS – Center for Industrial Research (CINI)
[6] Mechanical Engineer - TENARIS – Center for Industrial Research (CINI)
[7] Ph.D. in Mechanical Engineer - TENARIS – Center for Industrial Research (CINI)

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, the propagation pressure and the crossover pressure. Figure 1 shows the experimental assembly.

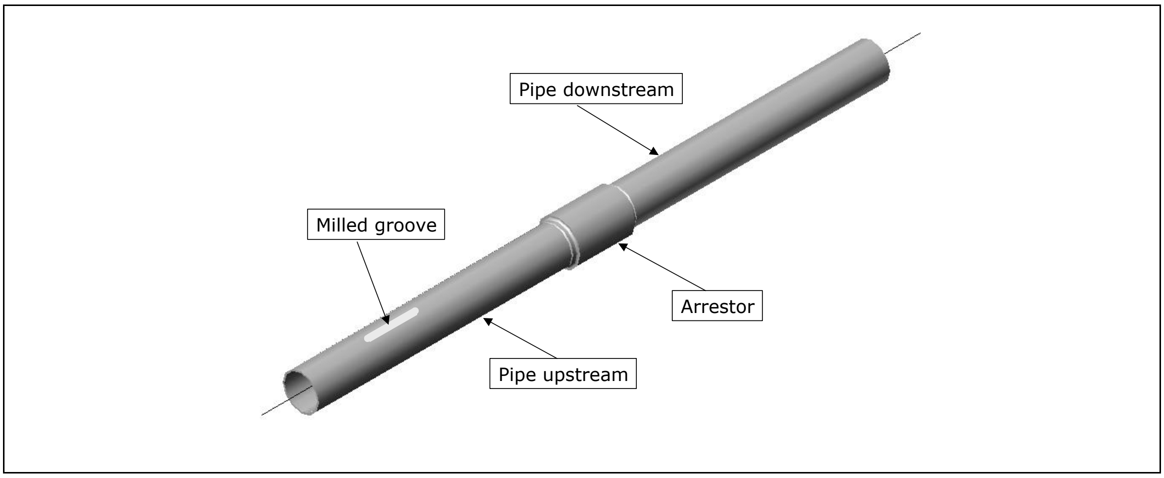

Figure 1. Experimental set-up

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

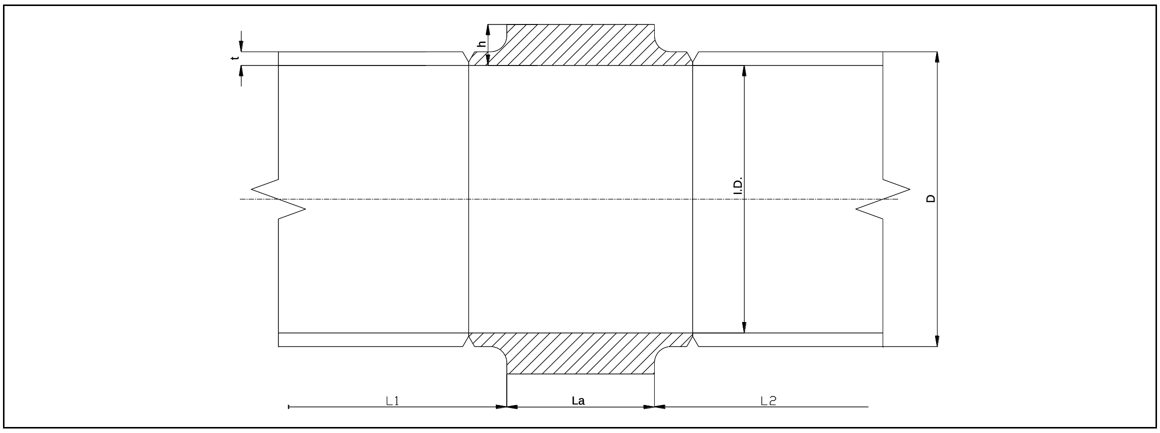

Figure 2. Arrestors geometry

Table 1 provides data on the tested samples:

Table 1. Data for the tested samples

Sample	**Pipe**			**Arrestor**			**Total length [mm]**
	D [mm]	**t [mm]**	**Grade**	**h/t**	**La/D**	**Grade**	
1	141.3	6.55	X-42	3.0	1.50	6 (ASTM A-333)	2300
2	141.3	6.55	X-42	2.0	0.50	6 (ASTM A-333)	2250
3	141.3	6.55	X-42	3.0	0.50	6 (ASTM A-333)	2240

2.1. Geometrical Characterization of the Three Tested Samples

The outer surface of the samples was mapped using the *shapemeter* [1]; the corresponding Fourier decompositions of the first sample is shown in Figure 3. The zone with high amplitude corresponds to the milled groove, whereas the zone with low amplitude belongs to the arrestor, which was machined.

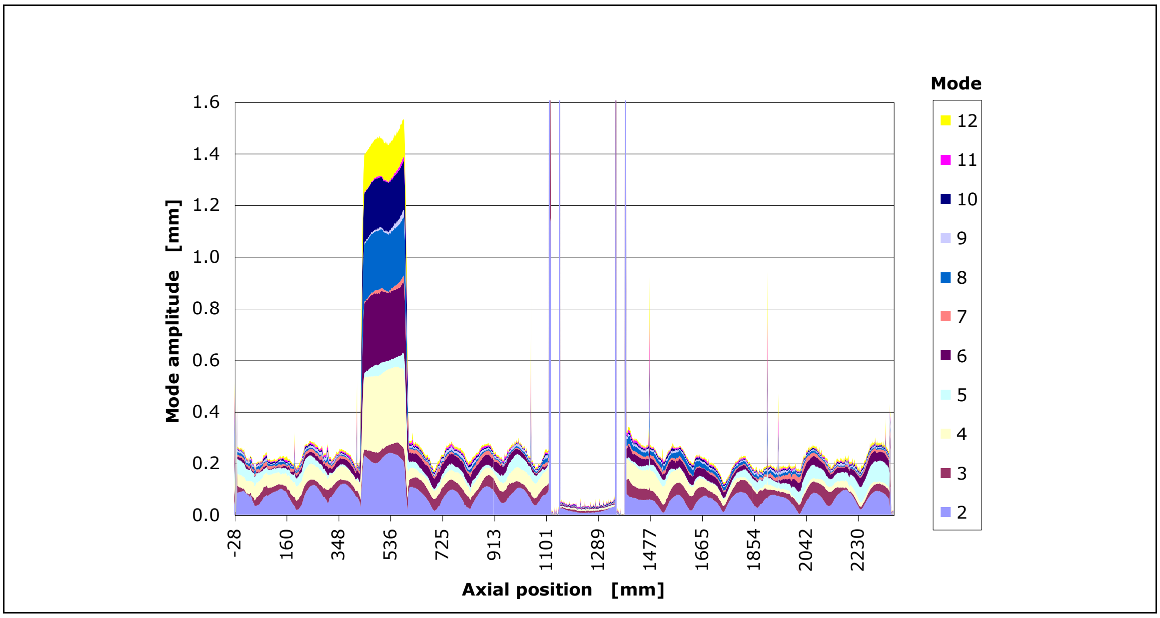

Figure 3. Typical geometry analysis for the samples OD

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

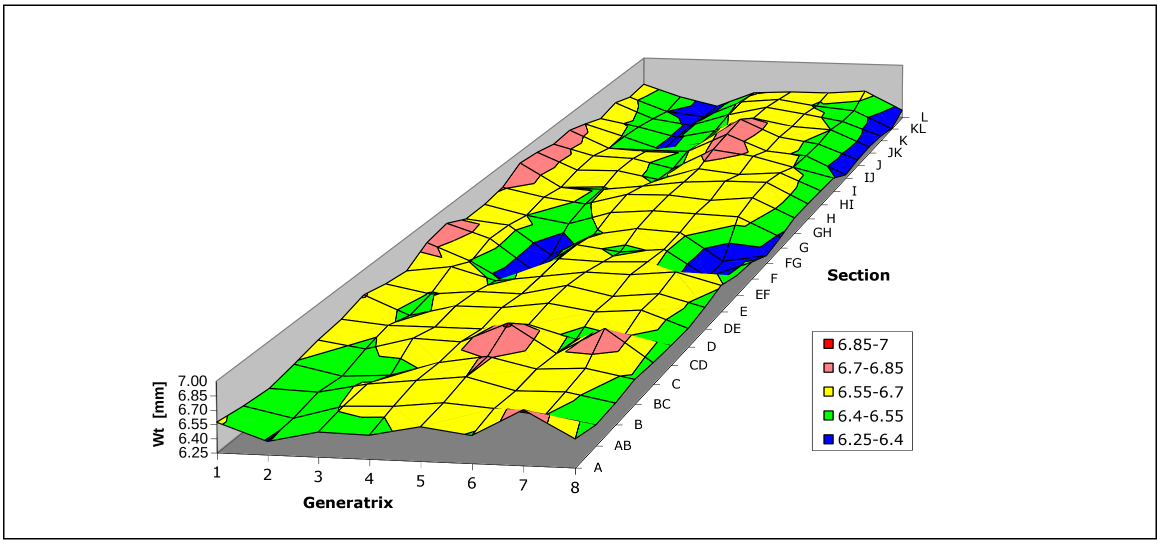

Figure 4. Typical thickness distribution

2.2. Mechanical Characterization of the Samples

The yield stress and hoop residual stresses were measured for all the pipes and arrestors.

2.3. Experimental Facility

In Figure 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 test started. 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.

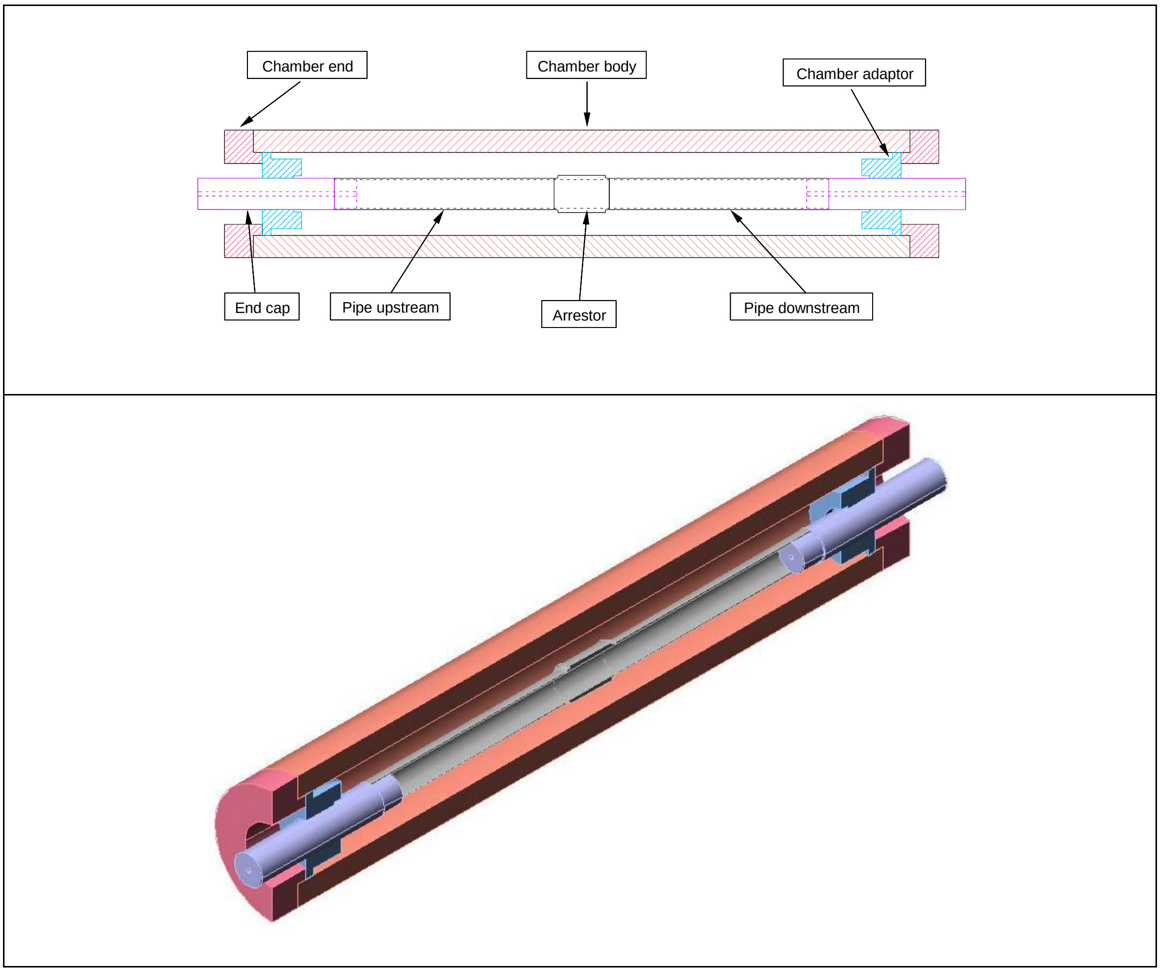

Figure 5. Experimental set-up

2.4. Experimental Results

A typical experimental result is shown in Figure 6. Table 2 summarizes the experimental results for the three samples.

Table 2. Experimental results

Sample	**Collapse pressure [psi]**	**Crossover pressure [psi]**
1	4279	Not reached
2	4210	1725
3	4064	3071

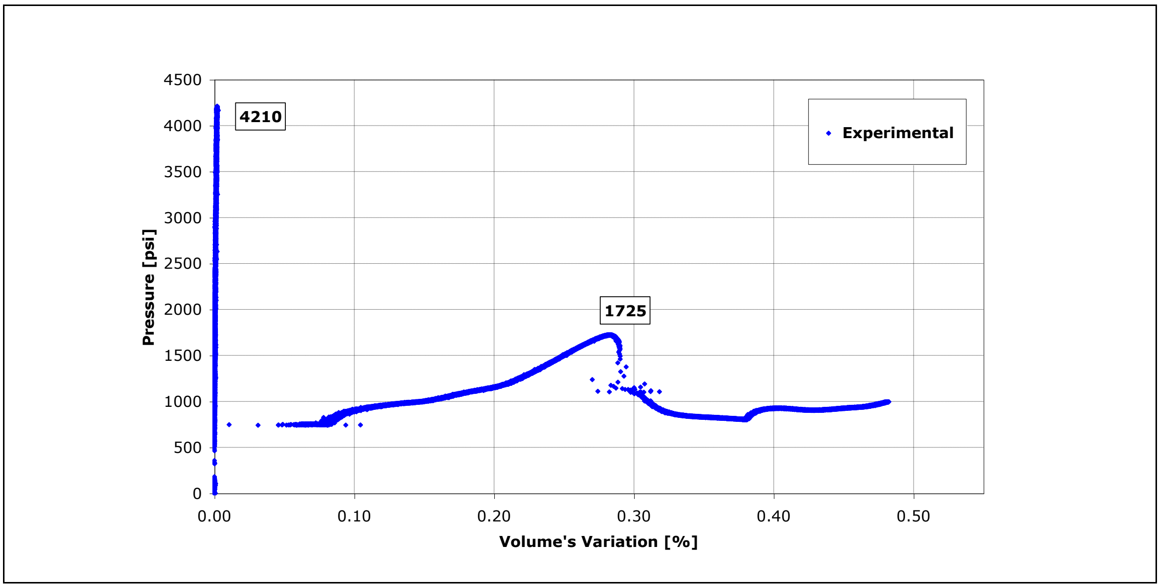

Figure 6. Typical experimental result

3. 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 for each sample was acquired as reported above.
- Von Mises elasto plastic material model with 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 was traced using the algorithm developed in Ref. [18]

3.1. Identifying the Different Crossover Mechanisms

In Figure 7 we present the finite element predicted deformed shapes for a (pipes – arrestor) system presenting a flattening crossover mechanism and in Figure 8 we show the predicted deformed shapes for a system presenting a flipping crossover mechanism.

3.2. Validation of the Finite Element Results Using the Experimental Results

Table 3 compares the FEA results with the experimental ones:

Table 3. FEA vs. Experimental results

Sample	Collapse pressure: FEA/Experimental	Crossover pressure: FEA/Experimental
1	0.915	Not reached
2	0.921	1.006
3	0.969	1.105

The two cases where the crossover pressure was experimentally reached correspond to the flattening crossover mechanism.

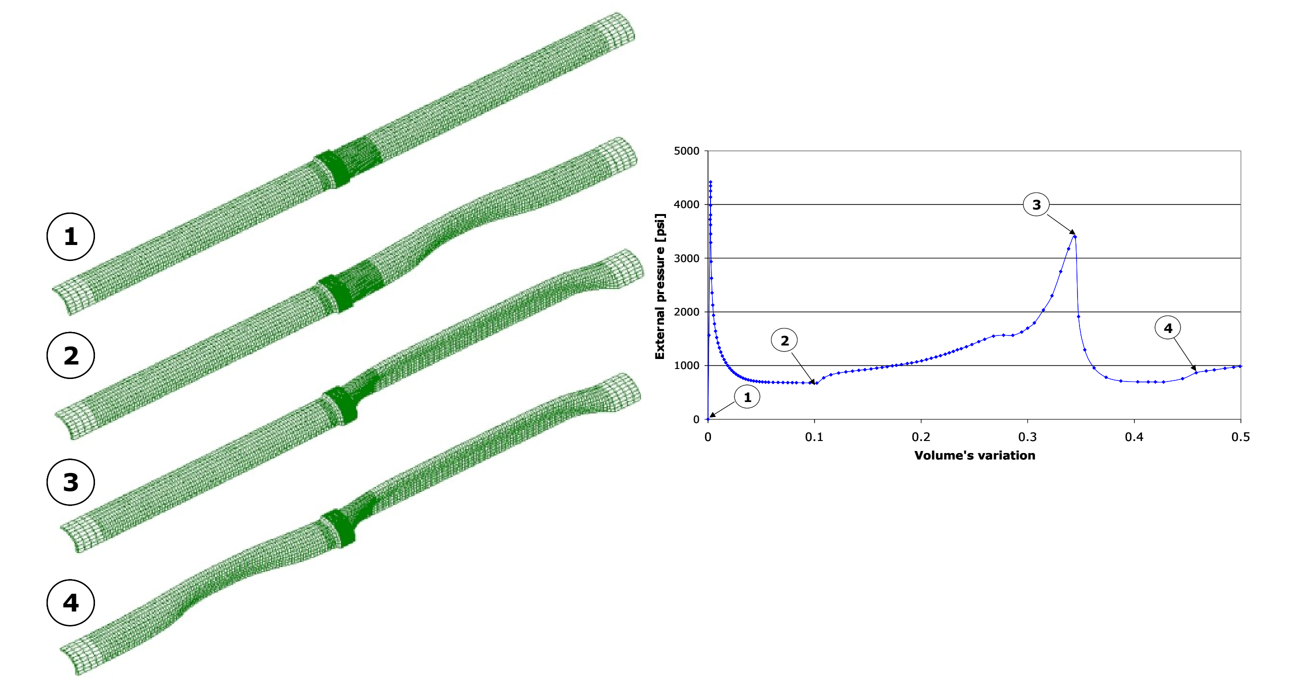

Figure 7. Flattening crossover mechanism

In Figure 9 we compare, for the case in Figure 6, the experimentally determined and FEA predicted equilibrium paths. Finally, in Figure 10 we show the final collapsed shapes after crossover of an experimental sample and of its finite element model.

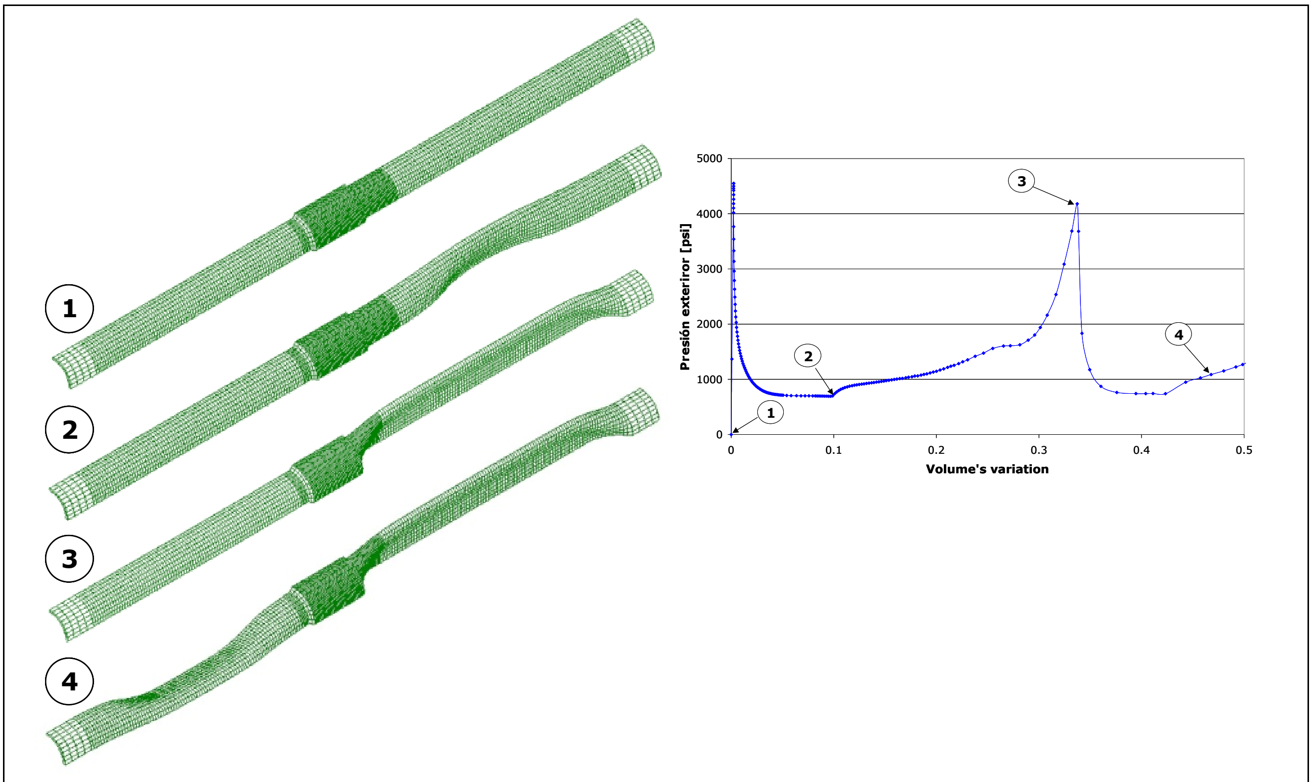

Figure 8. Flipping crossover mechanism

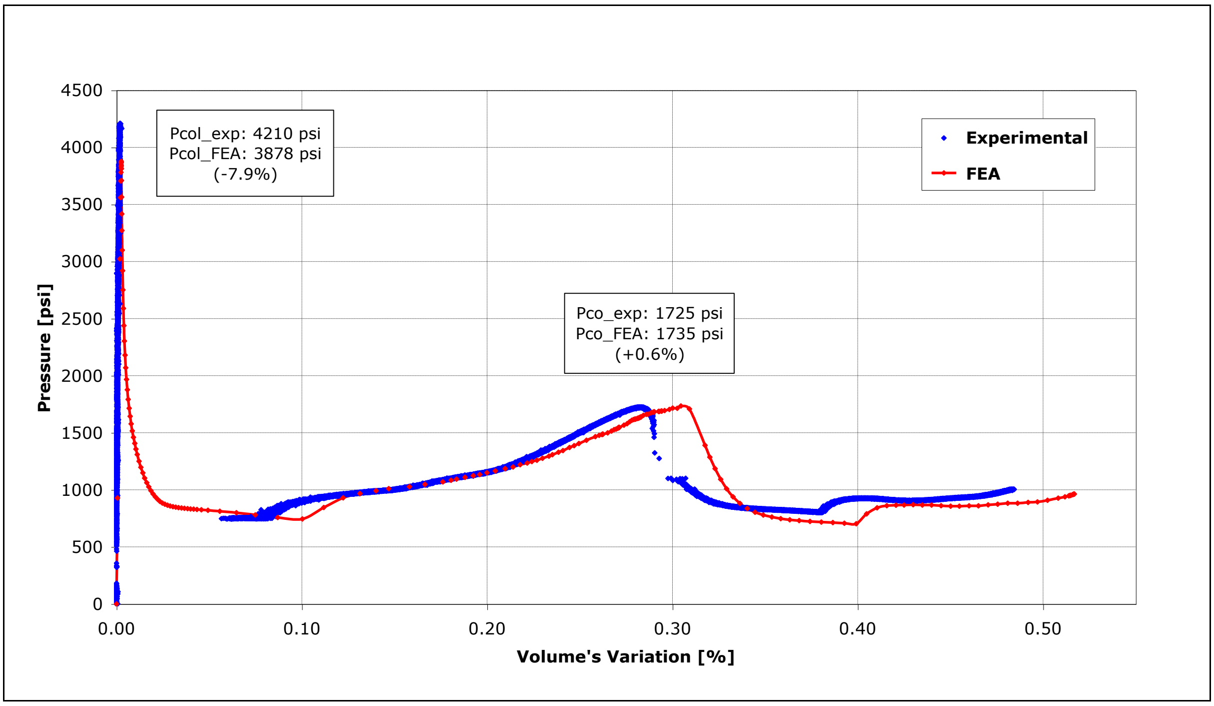

Figure 9. FEA vs. experimental results

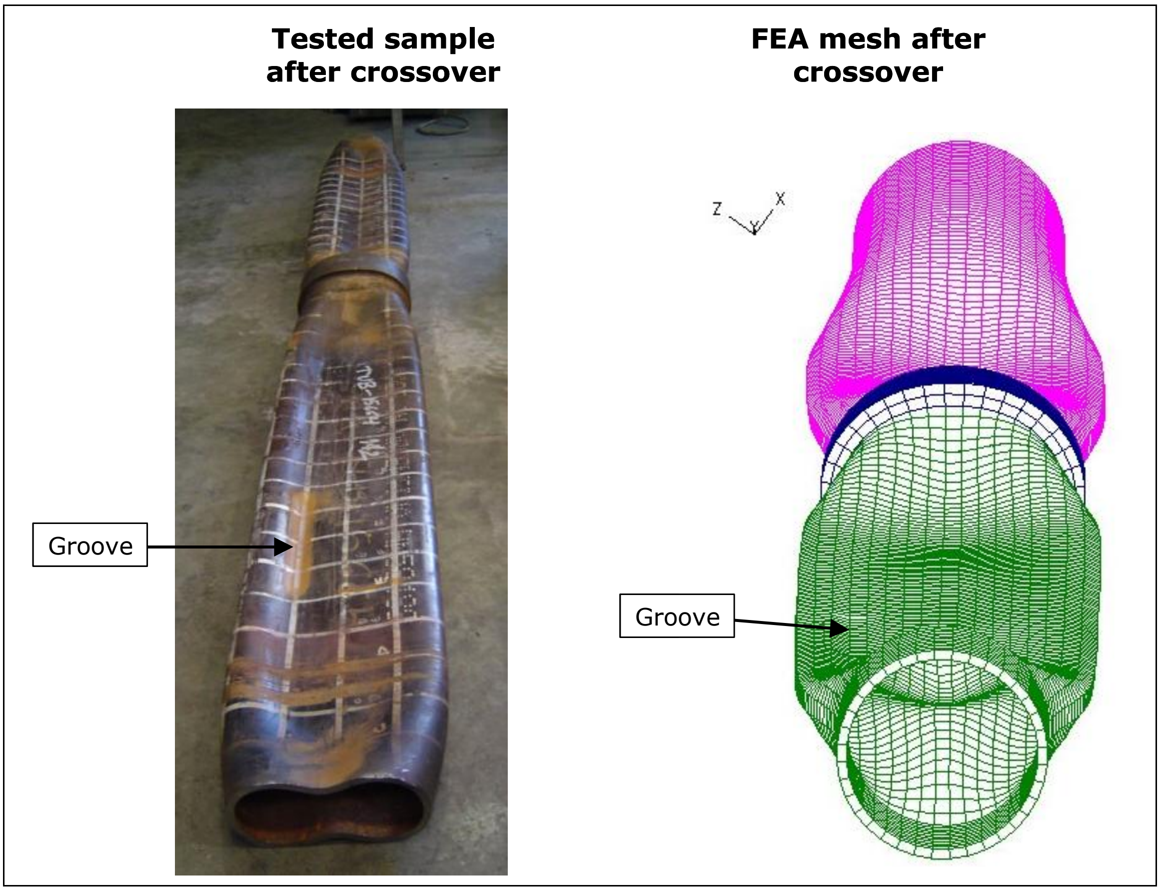

Figure 10. Experimental sample and its finite element model after crossover.

4. Conclusions

A 3D finite element model to analyze the behavior of an integral ring buckle arrestor crossed over by a propagating buckle was developed and validated by comparing with experimental results.

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

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

In the near future we will continue the numerical / experimental analyses to also validate the finite element model for the flipping crossover mechanism. Afterwards we will use the model to analyze the effect of bending on the crossover pressures.

5. References

1. A.P. Assanelli, R.G. Toscano, D.H. Johnson and E.N. Dvorkin, “Experimental / numerical analysis of the collapse behavior of steel pipes”, *Engng. Computations,* **17**, pp.459-486, 2000.
2. R.G. Toscano, P.M. Amenta and E.N. Dvorkin, “Enhancement of the collapse resistance of tubular products for deep-water pipeline applications”, *Proceedings 25th. Offshore Pipeline Technology Conference*, IBC, Amsterdam, The Netherlands, 2002.
3. R.G. Toscano, M. Gonzalez and E.N. Dvorkin, "Validation of a finite element model that simulates the behavior of steel pipes under external pressure", *The Journal of Pipeline Integrity,* **2**, pp.74-84, 2003.
4. R.G. Toscano, C. Timms, E.N. Dvorkin and D. DeGeer, "Determination of the collapse and propagation pressure of ultra-deepwater pipelines", *Proceedings OMAE 2003 - 22nd. International Conference on Offshore Mechanics and Artic Engineering,* Cancun, Mexico, 2003
5. R.G. Toscano, M. Gonzalez and E.N. Dvorkin, “Experimental validation of a finite element model that simulates the collapse and post-collapse behavior of steel pipes”, *Proceedings Second MIT Conference on Computational Fluid and Solid Mechanics*, (Ed. K.-J. Bathe), Elsevier, 2003.
6. R.G. Toscano, L. Mantovano and E.N. Dvorkin, “On the numerical calculation of collapse and collapse propagation pressure of steel deep water pipelines under external pressure and bending: Experimental verification of the finite element results”, *Proceedings 4th. International Conference On Pipeline Technology*, pp. 1417-1428, Ostend, Belgium, 2004.
7. A.C. Palmer and J.H. Martin, “Buckle propagation in submarine pipelines”, *Nature*, **254**, pp. 46-48, 1975.
8. T.D. Park and S. Kyriakides, "On the performance of Integral Buckle Arrestors for Offshore Pipelines", *International Journal of Mechanical Sciences*, **39** pp.643-669, 1997.
9. T.G. Johns, R.E. Mesloh and J.E. Sorenson, “Propagating buckle arrestors for offshore pipelines”. *ASME Journal of Pressure Vessel Technology*, **100**, pp. 206-214, 1978.
10. C.G. Langer, “Buckle arrestors for Deepwater Pipelines”, *Proceedings of the Offshore Technology Conference*, OTC 10711, Houston, TX, U.S.A., 1999.
11. S. Kyriakides, T.D. Park and T.A. Netto, "On the design of Integral Buckle Arrestors for Offshore Pipelines", *International Journal of Applied Ocean Research*, **20** pp.95-104, 1998.
12. T.A. Netto and S. Kyriakides, “Dynamic performance of integral buckle arrestors for offshore pipelines. Part I: Experiments”, *International Journal of Mechanical Sciences*, **42** pp.1405-1423, 2000
13. T.A. Netto and S. Kyriakides, “Dynamic performance of integral buckle arrestors for offshore pipelines. Part II: Analysis”, *International Journal of Mechanical Sciences*, **42** pp.1425-1452, 2000
14. T.A. Netto and S.F. Estefen, “Buckle Arrestors for Deepwater Pipelines”, *International Journal of Marine Structures*, **9** pp.873-883, 1996
15. E.N.Dvorkin and K.J.Bathe, “A continuum mechanics based four-node shell element for general nonlinear analysis”, *Engng. Computations*, **1**, pp. 77-88, 1984.
16. The ADINA SYSTEM, ADINA R&D, Watertown, MA, U.S.A.
17. K.J. Bathe, *Finite Element Procedures*, Prentice Hall, NJ, 1996.
18. K.J. Bathe and E.N. Dvorkin, “On the automatic solution of nonlinear finite element equations”, *Computers & Structures*, **17**, pp.871-879, 1983.