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## **Report**

Sensitivity analysis of Clock Spring repair to Hydrogen gas-Effect on burst pressure

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## 1. CONTEXT

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The gas transmission pipelines have to convey gas under high pressure between the source and the delivery points. Different kinds of defects (construction defects, corrosion and mechanical damages like gouges, dents) can have an impact on the safety of pipelines and the financial aspect. From a mechanical point of view, the main consequences of defect failures on a pipeline are a leak or a rupture by burst, sometimes after Fatigue propagation. To avoid these consequences when a defect is identified, operators must ask:

- Is the defect acceptable without repair? If yes, the defect is harmless and can be left as it was;
- If not acceptable, is the defect repairable? And what is the more adapted repair technique? If not repairable, the extreme decision to replace the damaging pipe or segment is taken requiring an interruption of gas transit and so a loss of earnings.

Clock Spring is one of repair techniques which is widely used since more than 15 years by gas operators due to its implementation (limited workforce) and its wide application range. In this context, a numerical study of sensitivity has estimated the ability of this technique to repair defects which could become severe when hydrogen is transported in pressurized pipelines.

## 2. OBJECTIVE

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The Clock Spring technique was validated by Gaz de France to repair natural gas transmission pipelines damaged by internal or external corrosions. Within the framework of the Naturalhy project, we study the applicability of Clock Spring for transmission pipelines which could be weakened by the hydrogen gas. The steel embrittlement could happen by hydrogen interaction with the plastic area developed around the defect. To validate a repair criterion by Clock Spring, Gaz de France has developed a numerical model to simulate the damaged pipe behaviour repaired by Clock Spring. This model is used to estimate the hydrogen effect on this repair criterion applied to metal loss defect like corrosion. This study only considers the failure by burst, not by fatigue. The main steps are the following:

- Description of Repair Method by Clock Spring;
- Steel Interaction with hydrogen gas;
- Burst test of a pipe damaged by a metal loss and repaired by Clock-Spring;
- Numerical model to simulate the burst of a pipe damaged by a metal loss and repaired by Clock Spring;
- Sensitivity numerical study :Hydrogen effect on the Clock Spring repair criterion.

With the result of these analysis, we could conclude on the Clock Spring as a candidate repair method for hydrogen transmission pipelines.

## 3. DESCRIPTION OF REPAIR METHOD BY CLOCK SPRING

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During the last years, many efforts have been devoted to the development of composite sleeves like Clock spring for the permanent repair of damaged pipelines. Notably, the GRI (Gas research Institute) contributed with a large effort during the 1990s [1], [2]. The main advantage of these techniques is that they allow the permanent repair of corrosion or indented defects on operating pipelines, without the need of welding on the pipeline. The main functions of these composite sleeves are the following:

- Restoring the full strength of a damaged pipeline,
- Increasing the stiffness of the repaired section of pipe, and then reducing the local strain induced by internal pressure on the defect area,
- Favouring leak before rupture failure modes, and arresting crack propagation,
- Inhibiting external corrosion phenomenon, the composite acting as an external coating.

Among these functions, the first two govern the design of a composite sleeve repair. Then, the implementation of a composite sleeve repair allows:

- To increase the thickness of the section submitted to the hoop stress induced by internal pressure,
- To introduce a second material having other mechanical properties (yield and ultimate strength) than the pipeline material properties. The thickness of the composite wrap and

his mechanical strength determines the reinforcement provided to the pipe under internal pressure.

After the implementation of a composite repair, the reinforcement mechanism can be described in the following steps :

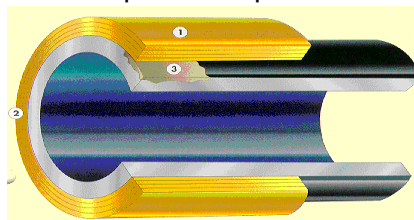
- The pipe and the composite wrap are strained as the internal pressure increases, the higher stress being exerted on the stiffer element (generally the Clock Spring),
- As plastic strain occurs in the damaged section of the pipe, its relative stiffness decreases. The reinforcement provided by the composite is then activated, as a load transfer occurs from the pipe to the wrap. The mechanical strength of the repaired structure is then governed by the mechanical strength of the wrap,
- After that stage, the ultimate strength of the repaired structure is governed by the relative strengths of the damaged pipe and the reinforcement.

A key point in the design of composite wraps stands in their durability: composite materials are ageing, resulting in a decrease of their mechanical performances with time. This decrease of mechanical performance has to be taken into account for the qualification of a composite wrap as a permanent repair, a lifetime of at least 50 years being a standard specification like the CSA Z662 [3] such a repair. Ageing kinetics depends, for buried pipelines, mainly on environmental parameters such as soil humidity, temperature, pH of the soil, the ageing process being mainly thermo-hydrolytic. The manufacturing of the composite, mainly the curing of the matrix or the adhesives used, plays also a great role in the intrinsic ageing of the material. Polymer resins used for the manufacturing of such wraps have to be selected for their stability in time, but also for their impermeability, water absorption accelerates the ageing of composite materials by inducing fibre/matrix disbandment and chemical ageing of the composite elements (fibres and matrix).

The Clock Spring is a flexible and effective method of pipelines repair, bringing a durable consolidation of the structure corroded or mechanically damaged, comprising at least 20% of thickness. To ensure the safety, the installation of the sleeve must cover at least 50 cm healthy pipe at each end.

This product is distributed by Clock-Spring Co. [4], under license of NCF Industries Inc. The system consists in composite material with a polyester matrix and a type E glass fibres reinforcement, pre-fitted and pre-streined in a cylindrical coil of 8 layers (cf. figure 1). So, for a given diameter, the Clock Spring thickness is always the same. Fibres are continuous in the wrap and oriented circumferentially, in order to strengthen the wrap in the hoop direction. The implementation of a Clock-Spring wrap requires three different components:

- A composite coil, pre-fitted to the pipe diameter,
- A methacrylate adhesive, allowing to bond the composite to the pipe, and the successive layers of the coil one to another,
- A high stiffness filling resin, allowing the load transfer between the defect to be repaired and the composite wrap.



- ① Glass fiber
- ② Bi- component high strength adhesives
- ③ Filler: high compressive strength bi-component resin

NOTE: for internal defect, no filler.

Figure 1: Clock Spring description

#### Advantages of Clock Spring

- Widely used since the 90's
- Broad application range (internal and external metal losses , large range of diameters)

#### Drawbacks of Clock Spring

- Toxic to apply – Caution for workman – Protection required (gas mask,...)

- Not easy to apply for complex shape components (elbow,...)
- Can not be applied to repair bends (though a different version of the product, consisting in a juxtaposition of narrow wraps, can be used for the repair of cold bends) and ovalization sections
- Do not provide axial reinforcement of the damaged section.

## 4. HYDROGEN EMBRITTLEMENT

Figure 2 illustrates the origin of the term ‘hydrogen embrittlement’. When a tensile test is conducted on a steel specimen at room temperature in air, the strain at fracture is slightly dependent of strain rate, while the cold temperatures have a significant effect on the embrittlement. This is not the case when the specimen is immersed in a hydrogen-containing environment (such as a gaseous medium containing molecular hydrogen gas) [5]. In hydrogen tests, the ductility decreases when the strain rate diminishes. Hydrogen embrittlement steel is also shown by the fracture surface. Unfortunately, the worse case which promotes the brittleness happens at room temperature and low strain which are the conditions of pipelines in service.

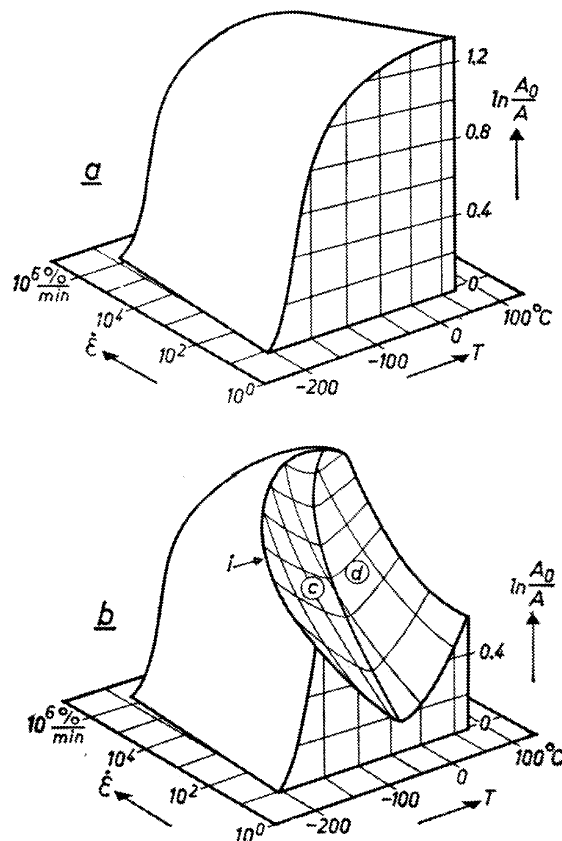


Fig. 2 True tensile strain at fracture  $\ln A_0/A$  versus temperature  $T$  and strain rate  $\dot{\epsilon}$ , for steel  
a) annealed, b) charged cathodically for 1 h in 4 % sulphuric acid (blisters were observed).

So, how is affected the Clock Spring repair criterion when the steel is weakened by the hydrogen gas ?

<sup>1</sup> Toh, T., Baldwin, W.M., Ductility of steel with varying concentrations of hydrogen, Stress Corrosion Cracking and Embrittlement, ed. W.D. Robertson, Wiley New York (1956) 176-186

## 5. BURST TEST OF A PIPE DAMAGED BY AN INTERNAL METAL LOSS AND REPAIRED BY CLOCK SPRING

Before to analyse by numerical simulation the hydrogen effect on the Clock spring repair criterion, an experimental case has been tested consisting of a pipe damaged by an internal loss and repaired by Clock spring. It has been burst with water pressure to check the relevance of the numerical model.

### 5.1. Pipe and defect geometries

An internal metal loss has been machined in a 203° angle of the circumference of a 24" (609.6mm) diameter pipe. Pipe and defect geometries are given in tables 1 and 2

DIAMETER (mm)	609.6
THICKNESS (mm)	9
GRADE	X52
TYPE OF MANUFACTURE	Longitudinal welding
YEAR	unknown

Table 1 : Pipe geometry

Type of defect	Internal metal loss
Length (mm)	1090 mm
Width (mm)	1050 mm
Depth (mm)	maximum : 76 % average: 72 %

Table 2 : Defect geometry

The capacity is composed of the portion of pipe with the defect (an internal metal loss), and of 2 cuffs reinforce comprising dished bottoms. The tube and the cuffs are welded; the thickened tube is machined to ensure a progressive transition to the level from the welding in the thickness. Figure 3 shows the view of the internal metal loss in the pipe and the Clock Spring



Figure 3 : Internal metal loss and Clock Spring

Figure 4 represents a longitudinal cut of the capacity with the defect and the Clockspring

The defect was machined by a millstone to obtain a uniform internal metal loss.

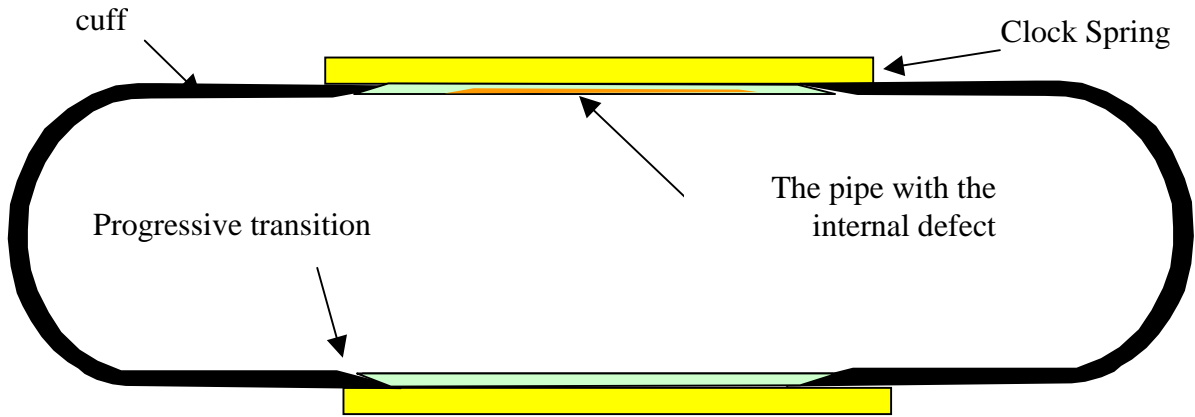


Figure 4 : Longitudinal length of the test capacity

## 5.2. Steel properties

The tensile properties and the mechanical behaviour of the pipe steel are given in Table 3 and Figure 4 :

Young's modulus (MPa)	210 000
Yield strength (MPa)	390
Ultimate Strength (MPa)	509
Average elongation of rupture	23%

Table 3 : Mechanical properties

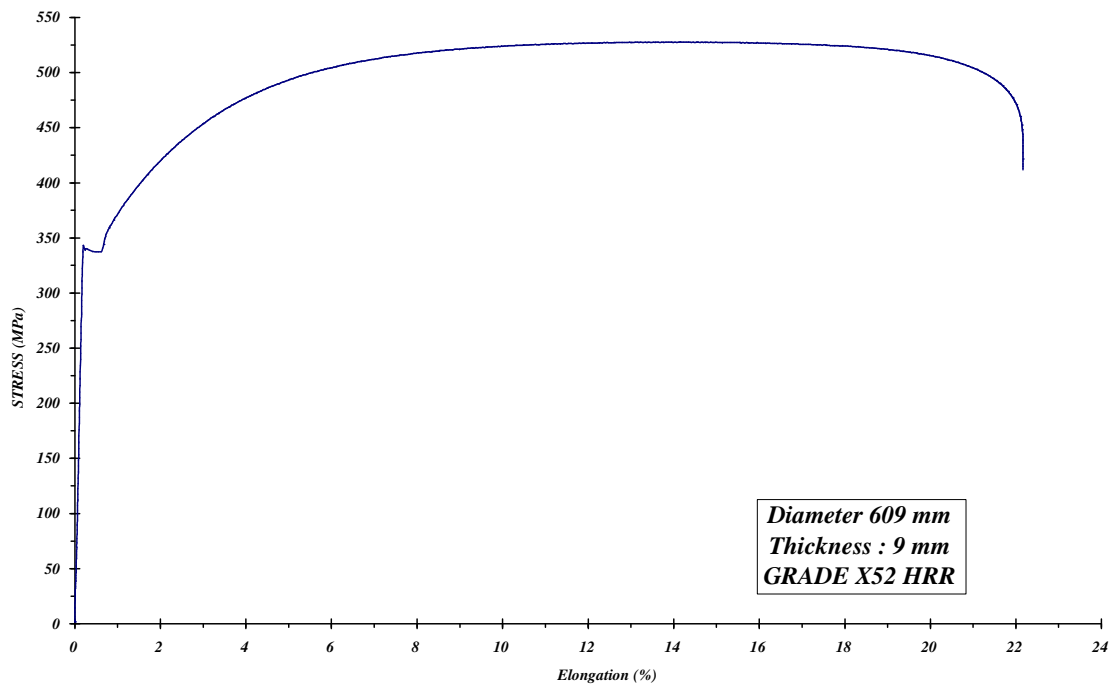


Figure 5 : Conventional tensile curve

### 5.3. Instrumentation

To record the strains during the pressure test, circumferential and longitudinal gauges are stuck in different places:

- on steel in the defect generally in weak zones (fillets, under-thickness), (C1, Ci1, Ci3). C1 is on external steel surface under the Clock-Spring, Ci1 and Ci3 on internal surface defect
- on steel and under the Clock-Spring at the opposite to the defect, (C2)
- on Clock Spring at the opposite defect. (CE2)

A displacement sensor (LVDT) is placed on the defect.

The gauges positions are showed in figure 6 and the displacement sensor in figure 7.

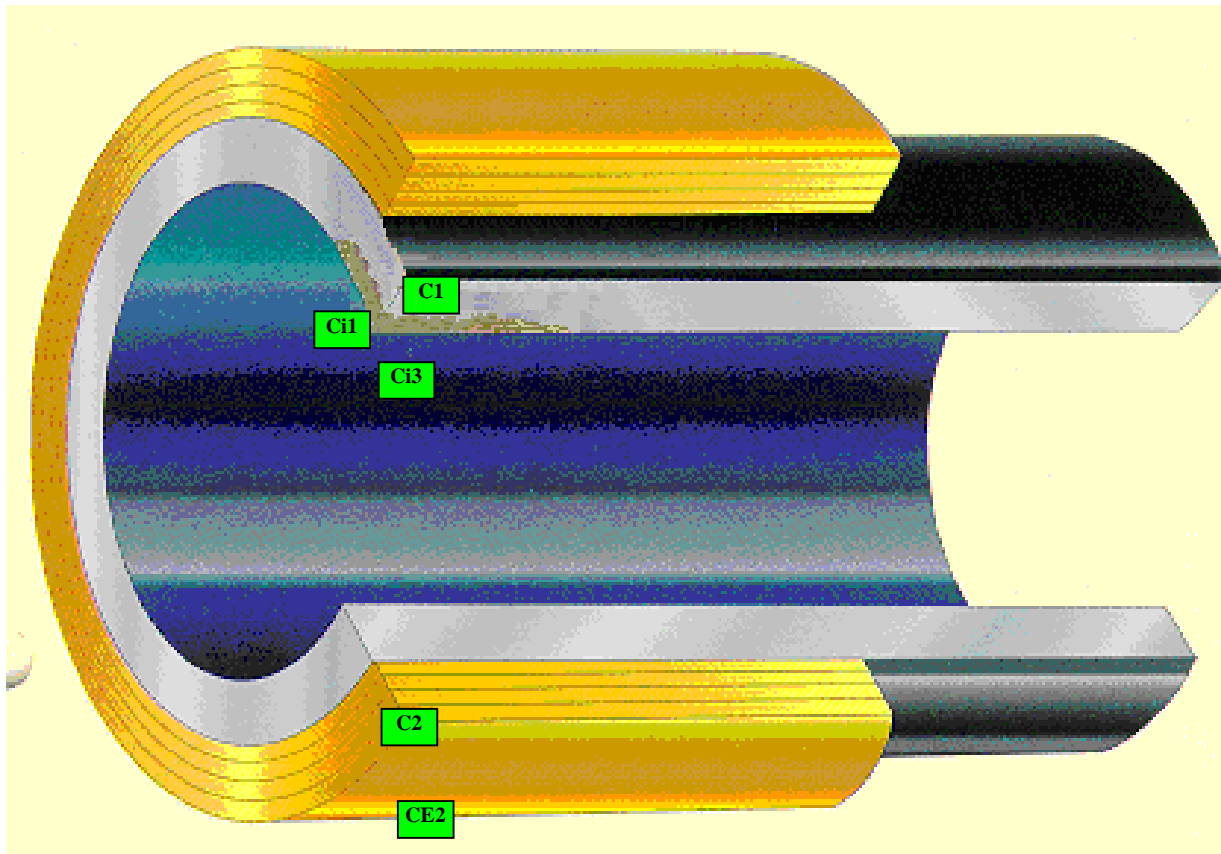


Figure 6: Emplacement of the gauges

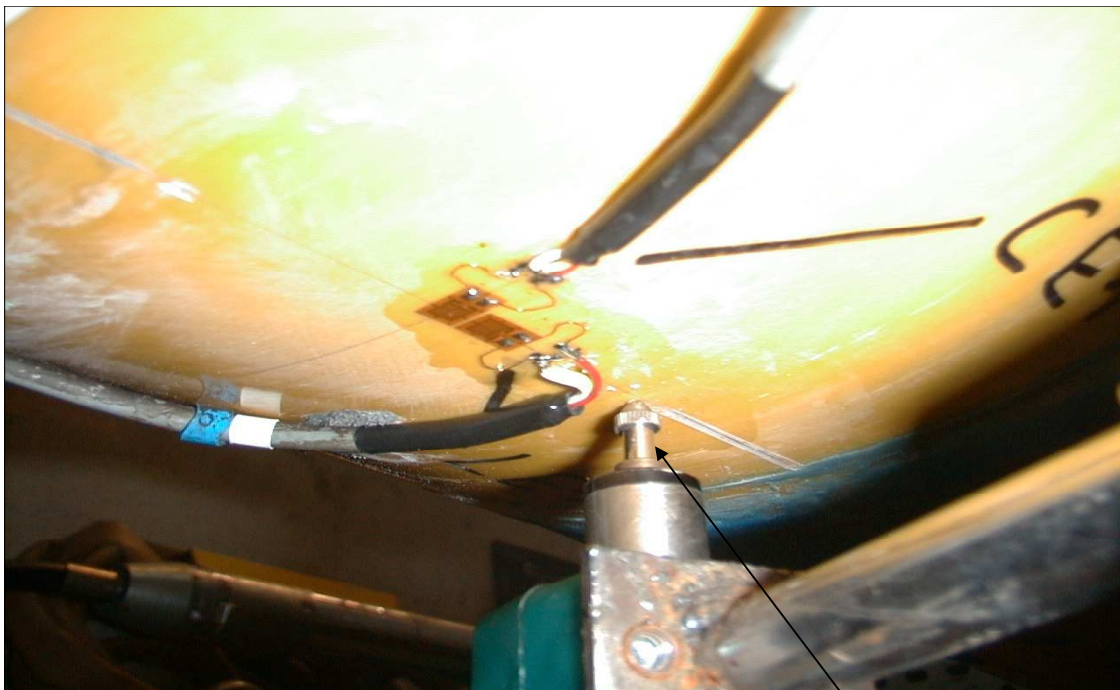


Figure 7: LVDT

displacement sensor (LVDT)  
on CS in the centre of the  
defect beside gauge CE1

## 5.4. Burst test procedure

Before the test, the thickness has been measured by laser method to get thickness cartography in all part of the defect (figure 8).

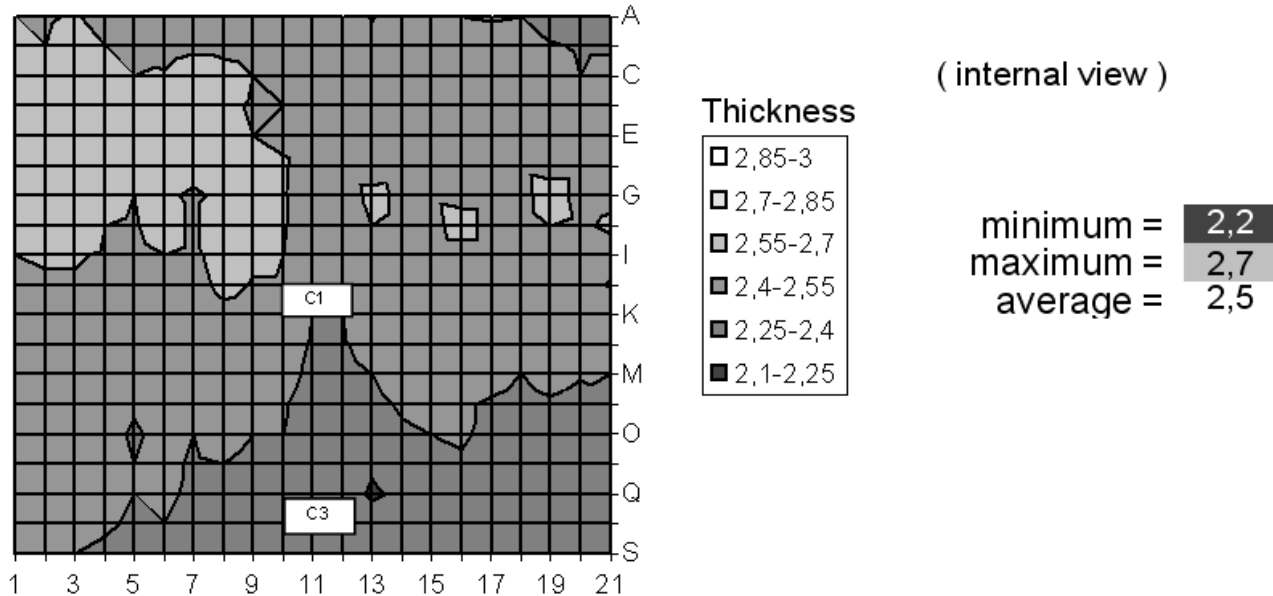


Figure 8: thickness cartography of the defect

The burst test procedure is presented in details in appendix 1.  
The main steps are following:

1. Increase the pressure to plastify the defect at 1% of deformation. (35 bar)
2. Decrease the pressure to 0 bar before the putting of the Clock Spring
3. Increase the pressure to 20 bar for putting the Clock Spring
4. Putting up the Clock Spring at 20 bar
5. Decrease the pressure to 0 bar
6. Increase to the pressure OSP (Operating service pressure) at 75 bar for checking the behaviour of the defect reinforced with the Clock Spring
7. Decrease the pressure before the step of the burst
8. Increase the pressure to the burst pressure.

For reasons of a technical nature, the rising of the pressure proceeded three times before the burst.

The pressure versus the time is recorded. The figure 9 summarizes the pressure load.

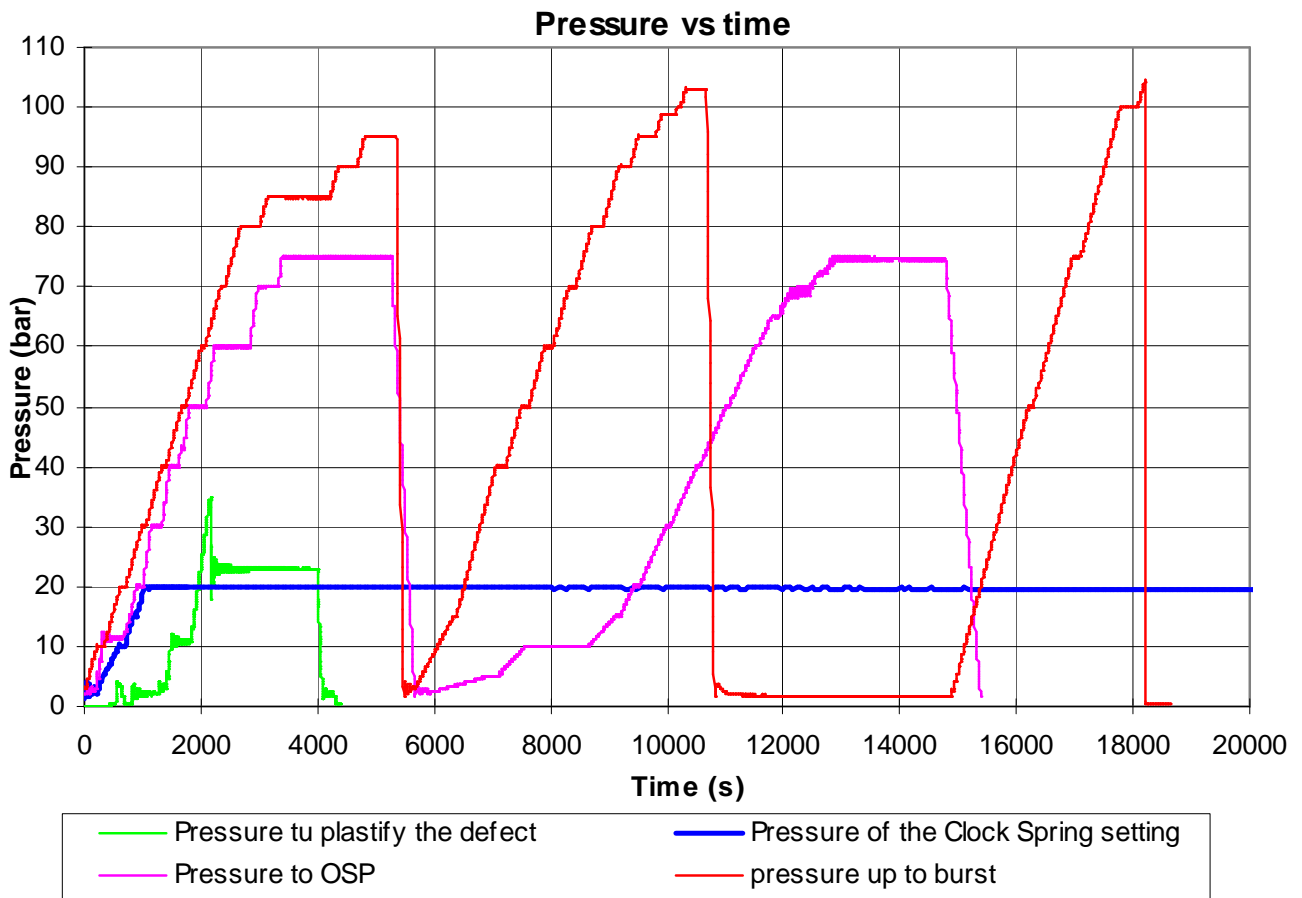


Figure 9 : Pressure load graph

The specific card of synthesis to the test is in Appendix 1.

## 5.5. Results

The rupture reached in steel, near the gauge Ci3. The evolution of the Ci3 gauges (near to the rupture) and Ci1 (far away from the rupture) during the phase of failure clearly shows that the deformations are not homogeneous in the defect (figure 10).

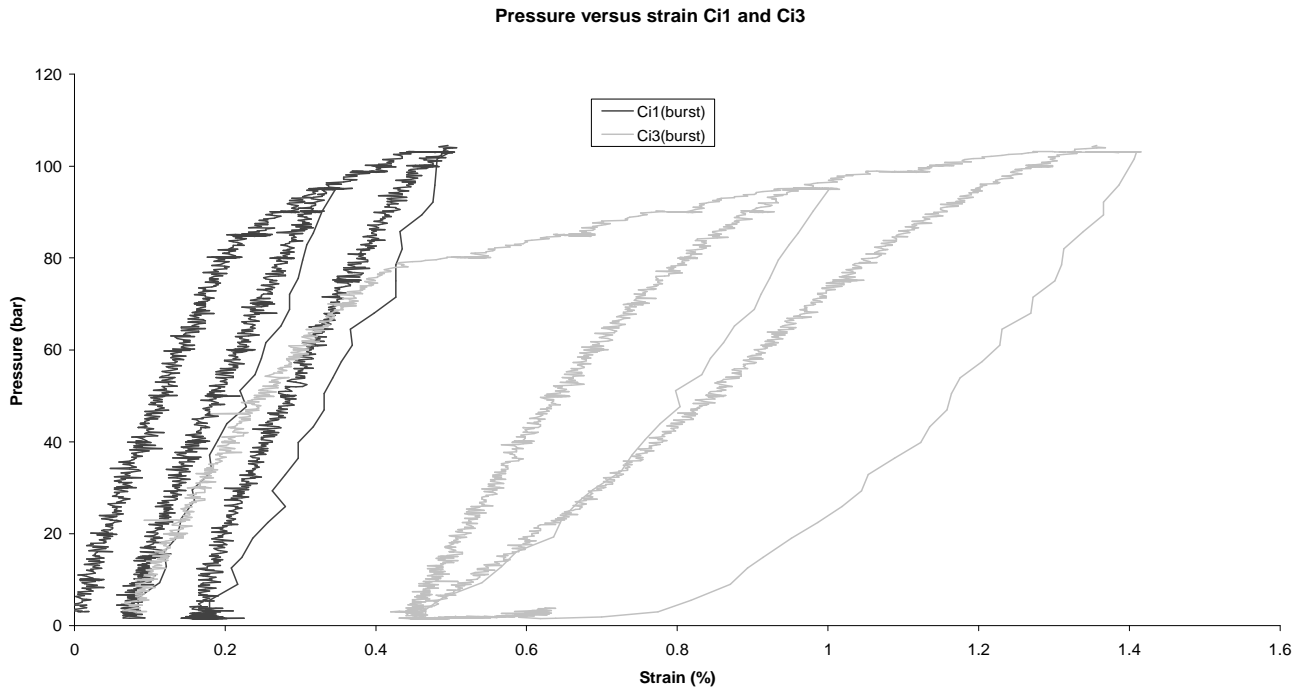


Figure 10: Evolution of the internal circumferential gauges positioned in the defect

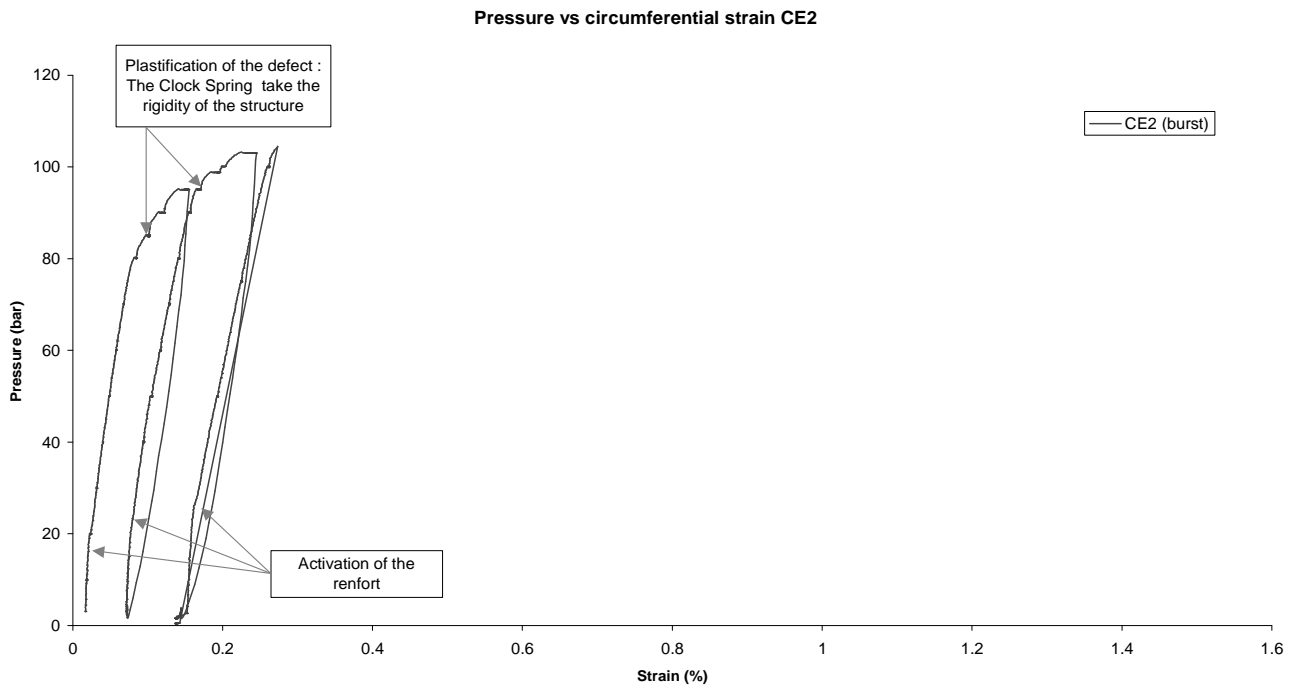


Figure 11: Evolution of the gauge located on the sleeve in the opposite to the defect at the time of the phase of failure

The Ci3 gauge is at the deeper place of the defect with 77% of metal loss. At the Ci1 gauge, there is 72% of metal loss. So, with 5% of difference of the metal loss, the Ci3 gauge is more strained than Ci1. So the strain is high in the place of the less thickness.

The evolution of CE2 gauge positioned at the opposite to the defect, during this same phase of failure, highlighted well the various aspects of the reinforcement brought by Clock Spring (figure 11):

- For pressures lower than the setting load (here, 20 bar), the sleeve is not requested and practically does not become deformed (CE2)

- For pressures higher than the setting load, one has activation of the reinforcement; the efforts are then transmitted to the whole of the sleeve,

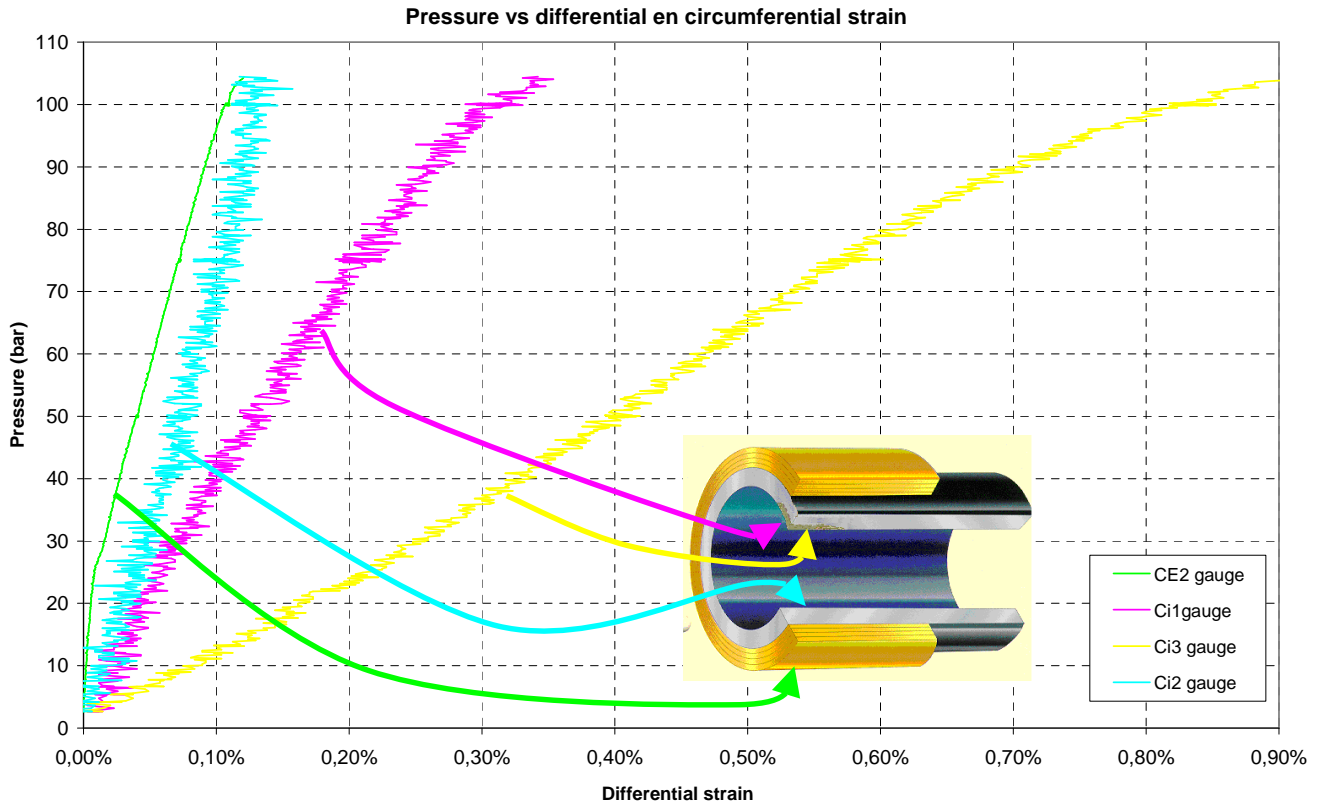


Figure 12: Differential strain from gauges during the burst

Figure 12 shows that a defect of the type of internal metal loss holds to inflate under the action of the internal pressure.

With the burst, the rupture reached in steel first, near the gauge Ci3. It is the place of the less thickness. The rigidity of the structure is then assured only by the sleeve in the place of the defect.

So, for this burst, the failure has been occurred at a pressure of 105 bar.

According to the theoretical calculation based on BS7910 [5], the pipe with non-repaired metal loss would have failed at a pressure of 32 bar.

So, the Clock Spring is a good alternative to repair the pipe with type of defect as metal loss.

## 6. NUMERICAL MODEL TO SIMULATE THE BURST OF A PIPE DAMAGED BY A METAL LOSS AND REPAIRED BY CLOCK SPRING

This chapter brings the elements to check the numerical model developed for the simulation of the defects (metal losses) repaired by composite sleeve Clock Spring. The relevance of the numerical model is evaluated by the numerical and experimental results comparison.

This calculation was carried out by taking account of the specificity of the experimental configurations selected, in terms of boundary conditions (capacity under pressure, cuffs reinforced apart from the reinforced zone) and of materials properties.

For this numerical model, the failure criterion is established according to the law of behaviour of materials.



## 6.1. Behaviour Law and failure criterion

The Failure Criterion is defined as a critical stress corresponding to the strain at the UTS (Ultimate Tensile Strength). So, the critical stress is the UTS value corrected by the strain :

$$\text{Critical stress} = \text{UTS} (1 + \text{strain})$$

For this steel, the ultimate tensile strength is got for a strain of 12.2% on the tensile curve. In the FEM analysis, the equivalent stress is calculated and compared with the critical stress in each finite element. When the equivalent stress equals to the critical stress in all finite elements under the defects through the thickness, the failure is considered to have been reach. Steel and Clock-Spring data are respectively given in tables 4 and 5. The graph of the steel behaviour law used in the FEM calculation is shown in figure 13.

Yield strength	390 MPa
UTS	509 MPa
Strain of the UTS	12.2 %
Critical stress	571 MPa

Table 4 : Steel data

Young Modulus E33 (longitudinal)	1 MPa
Young Modulus E22 (Circumferential)	33850 MPa
Young Modulus E11 (Radial)	9100 MPa
Critical stress	571 MPa
Poisson ratio $\nu_{12}$	0.075
Poisson ratio $\nu_{13}$ and $\nu_{23}$	0
Shear Modulus G12 and G23	9520 MPa
Shear Modulus G13	9520 MPa
Critical stress for Clock Spring failure (without ageing)	500 MPa

Table 5 : Clock Spring data

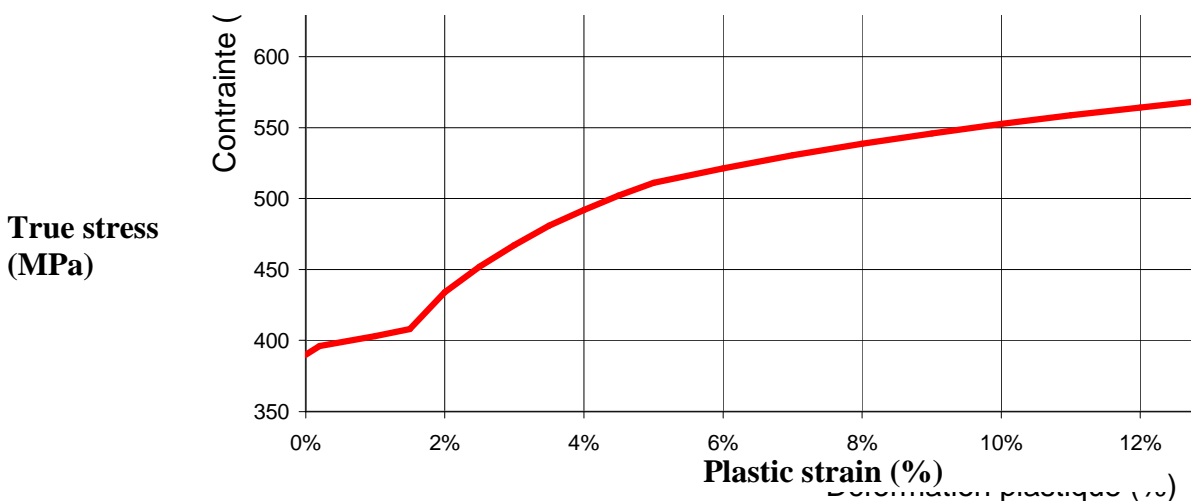


Figure 13: law of steel behaviour

## 6.2. Meshing and elements

Here, a model of the test with Clock Spring was created; the elements are Quadrilateral elements with eight nodes and one point of integration to gain in computing times and preserve the quality of the results. The model is composed of three parts, the tube, the filler and Clock Spring. (Figure 14)

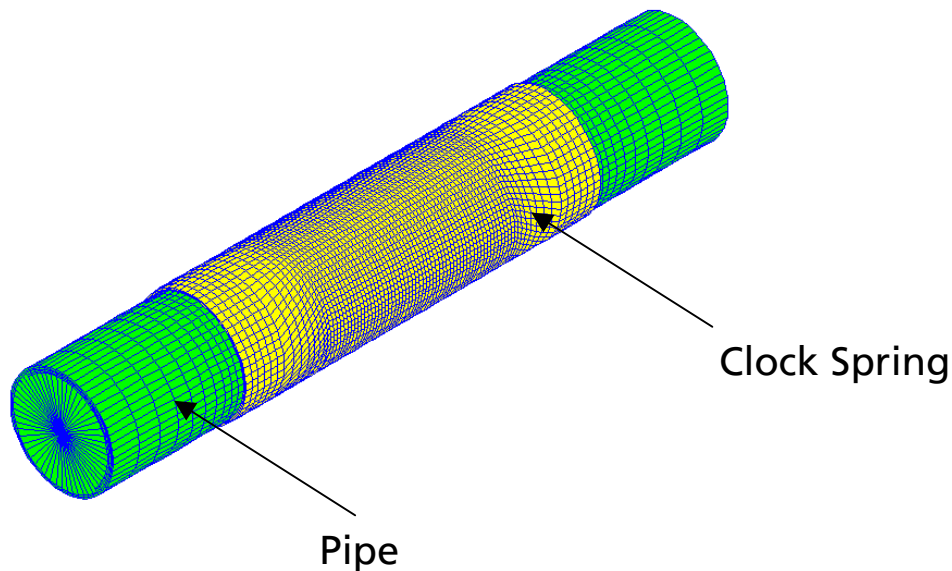


Figure 14 : numerical model of the tube and the Clock Spring

The strains are also calculated to compare with the gauges results. The gauges on the defect are in the figure 15.

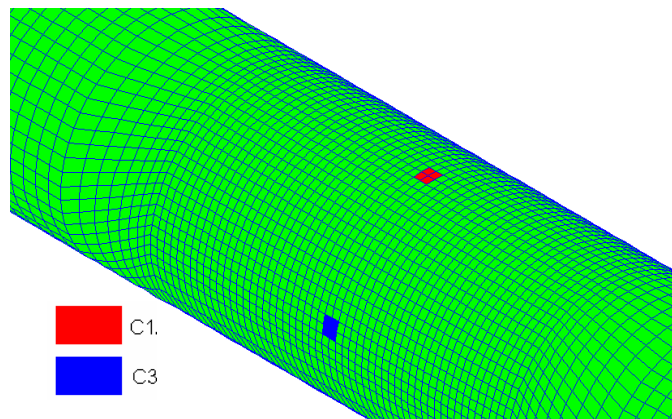


figure 15 : model of the gauges on the defect

## 6.3. Boundaries conditions

Then figure 16 shows the place of the boundary condition with the symbol (black triangle). Four nodes were locked in the two directions X and Y which represent the square that the tube test was putting. A central node is locked in Z direction (longitudinal direction).

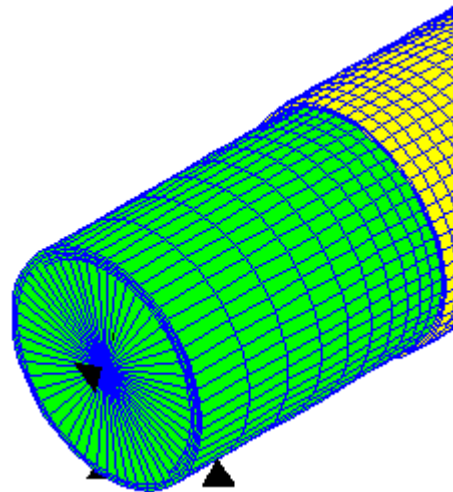


Figure 16: place of the boundaries conditions

## 6.4. Loading

The relevance of the finite elements model is appreciated by comparing numerical and experimental results (table 4). The calculation stage has been done like below and in the figure 17:

- First increase of the pressure at 35 bar
- Decrease of the pressure at 20 bar
- Setting of the Clock Spring at 20 bar
- Second increase of the pressure (OSP) at 75 bar
- Increase of the pressure to the burst

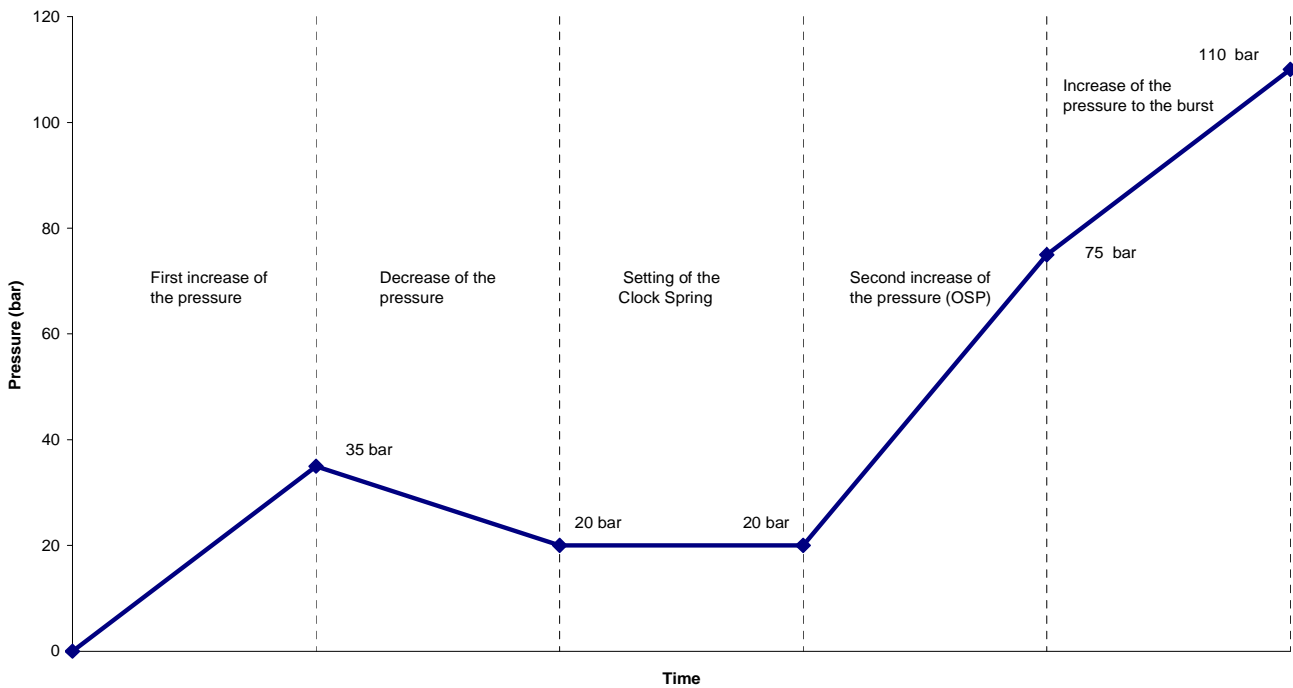


Figure 17: different steps of loading



## 6.5. Results

The relevance of the finite elements model is appreciated by comparing numerical and experimental results (table 6)

	Experimental results	Numerical results
Gauge Ci1	0.50%	0.73%
Gauge Ci3	1.36%	1.06%
Gauge C2	0.12%	0.35%
Gauge CE2	0.27%	0.23%
Burst pressure	105 bar	110 bar

Table 6 : numerical and experimental results comparisons

This comparison shows a good coherence between the simulation and experimental results. Based on the gained results, the model can be used to predict the influence of hydrogen on the Clock Spring repair.

## 7. SENSITIVITY NUMERICAL STUDY: HYDROGEN EFFECT ON THE CLOCK SPRING REPAIR CRITERION

The previous paragraph is showed that the numerical model can predict with a good accuracy the burst pressure of damaged pipe by metal loss repaired by Clock Spring. Now, this model is used to estimate the hydrogen effect on this repair method.

The failure criterion is established according to the material behaviour law. In this study, only the steel is supposed to be affected by hydrogen environment. The Clock-Spring degradation by hydrogen permeation is not here considered.

### 7.1. Behaviour Law and new failure criterion for the steel affected by hydrogen

Due to the lack of material properties based on testing it was decided to choose a very severe failure criterion value in order to show a worst-case scenario. this scenario, the sleeve has to stand a higher stress. According to the hydrogen effect on the reduction of plastic strain ability of steel (see paragraph 4), it was decided to divide severely by two the critical strain at UTS in hydrogen environment. So, the critical stress for the steel failure decreases too (see table 7)

Critical strain in hydrogen environment	6%
Critical Stress at 6% uniform strain	521 MPa

Table 7: New criterion of the steel failure in hydrogen environment

### 7.2. Results

The table 8 summarizes the results.



	Test Results	Model Results without steel degradation by Hydrogen	Model Results with steel degradation by Hydrogen
Ci1	0.50%	0.73%	0.67%
Ci3	1.36%	1.06%	1.00%
C2	0.12%	0.35%	0.26%
CE2	0.27%	0.23%	0.17%
Burst Pressure (bar)	105	110	104
Failure Location	In the defect	In the defect	In the defect

Table 8: comparison of the experimental and numerical values without and with steel degradation by hydrogen

In the table 8, the severe degradation of steel by hydrogen has not a significant consequence on the burst pressure of a defect "internal metal loss" repaired by Clock-Spring. In this case, an addition of high quantity of hydrogen in the pipeline do not affect the burst pressure of a large internal metal loss repaired by Clock-Spring. This result encourages the Clock-Spring as a candidate repair for existing pipelines transporting hydrogen-natural gas mixtures.

## 8. CONCLUSION

A model to determine the burst pressure of a pipe damaged by a large and deep internal metal loss repaired by Clock-Spring has been compared with a burst pressure experimental result. The assessment of the burst pressure by the model has been acceptable and very close of the realistic burst pressure (a difference less of 5%)

Then, the model has been used to evaluate the hydrogen effect on Clock-Spring repair method for the same damaged pipe. A severe degradation of steel by hydrogen has been assumed consisting dividing by two the strain at rupture of steel. Even with this strong condition, the calculated burst pressure do not decrease significantly, the burst pressure decrease being about 5% to compare with the none degradation steel by hydrogen.

This result selects the Clock-Spring as a potential candidate as a repair method for pipelines transporting hydrogen or hydrogen-natural gas mixtures. Nevertheless, to validate this repair method in hydrogenating condition, the following studies have to be explore :

- Take into account the ageing of the Clock-Spring for the burst pressure;
- Effect of hydrogen on fatigue behaviour of damaged pipe repaired by Clock-Spring ageing and not ageing;
- Possibility of a Clock-Spring degradation by hydrogen gas inside the pipeline and if yes, the effect on the Clock-Spring repair criterion.



## REFERENCES

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- [3] « Oil and Gas Pipeline Systems » - Z662-9, Canadian Standards Association, 1999
- [4] <http://www.clockspring.com/>, Clock-Spring Corp. web site.
- [5] NATURALHY Deliverable D6 : State of Art Durability & Integrity, 21 December 2005



## APPENDICE 1 : BURST TEST PROCEDURE AND RESULTS BURST

### 1. Main steps of the test procedure

- Steel Characterization of the pipe
- Creation of the defect
- Manufacture of the capacity
- Measurements on the pipe: diameters, thicknesses, sizing of the defect, cartography of thicknesses.
- Photographs during each phase of the tests
- 1st increase in pressure, plasticization of the defect
- Installation of Clock-Spring with 20 bar of the pressure
- Joining of the deformation gauges on the Clock Spring.
- 2nd increase in pressure, checking of the behaviour of the defect reinforced with real PMS of category A.
- Joining of the gauges of rupture and installation of the LVDT
- Increase the internal pressure until the failure.

The pressure in the pipe goes down again to the pressure of network between the various stages: first rise, second rise, burst.

### 2. Measurements carried out

Seven sizes were measured:

- Five were recorded during tests:
  - The pressure P (in bar).
  - The deformations E on the pipe and Clock Spring (in %).
  - Tensions of the LVDT and the gauges of rupture (in volt).
  - The swelling of the pipe (displacement in mm) using a sensor placed at the center of the defect.
  - Change of the temperature during test (in °C).
- Two were carried out before and after each phase of test:
  - The thicknesses E (in mm).
  - The diameters D of the pipe on steel and CS in various sections (in mm).

The results of these measurements are gathered in this appendix:

- The site of measurements of diameter.
- The cartography thicknesses.
- The positions standards of the gauges of deformation.
- A table which indexes all the instrumentation used at the time of the tests (reference of the instruments, precision...).
- An example (in the form of photograph) of measurement of swelling of the tube.
- Detailed results of the test whose generic synopsis is:
  - Synthesis of the test
  - Given complementary
  - Measurements of thicknesses and cartography of the defect
  - Photographs before and after test.

Gathered by page, curves of test:

For the monotonous loadings (1st rise, 2nd rise, and burst):

$P = f(t)$  and  $P = f(\text{displacement})$

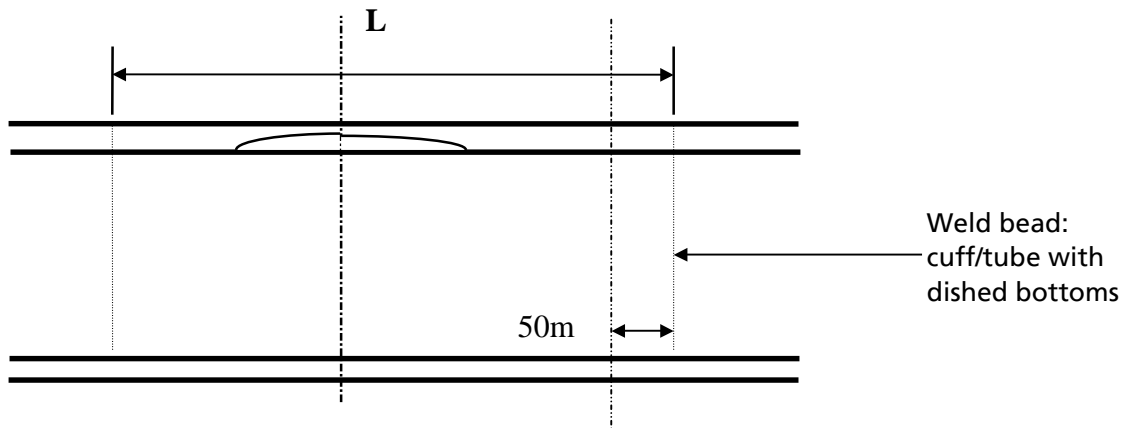
The gauges by which one has measurements, in great deformation (14 % maximum) C1, Ci1, Ci3 and in small deformation (4 % maximum) C2, CE2:

- $P = f(\epsilon_{C1})$
- $P = f(\epsilon_{Ci1})$
- $P = f(\epsilon_{Ci3})$
- $P = f(\epsilon_{C2})$
- $P = f(\epsilon_{CE2})$
- $P = f(\text{rupture indicator})$  et  $T(^{\circ}\text{C}) = f(t)$

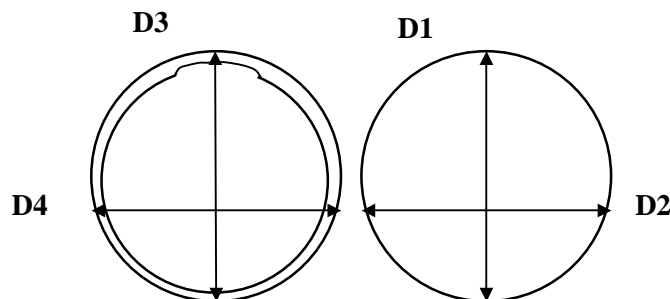
### 3. Plan of positioning of measurements of diameter

For each pipe tested, one carries out 4 measurements diameters to 3 phases of the test:

- After grinding.
- Before the installation of Clock Spring.
- After the installation of Clock Spring.



Measure in the plan passing by the centre of the defect





#### 4. STANDARD CARTOGRAPHY THICKNESSES

type of defect : metal loss

##### LENGTH (m)

10 20 30 40 50 60 70 80 90 100 110 120 13 14 150 160 17 18 19 20  
/A /B /C /D /E /F /G /H /I /J /K /L 0 0/ /O /P 0/ 0 0/S 0/T  
/M N Q /R

10																			
20																			
30																			
40																			
50																			
60																			
70																			
80																			
90																			
100																			
110																			

The locatable letter or figure is useful when finer complementary measurements are carried out.

#### 5. TEST RESULTS

##### BURST TEST

##### 1) result

Pressure of the machined defect (bar)	1 <sup>st</sup> increase of the pressure P <sub>max</sub> (bar)	Pressure of the setting CS (bar)	2 <sup>nd</sup> increase of The pressure P <sub>max</sub> (bar)	Burst pressure (bar)	Length of the breaking (mm)	width of the breaking (mm)
0	35	20	75	<b>105</b>	960	16

##### Maximum deformation in %

Gauge	C1	Ci1	Ci3	CE2	C2	
1 <sup>st</sup> increase	0.55	-	-	-	0.04	
2 <sup>nd</sup> increase	0.77	0.19	0.4	0.06	0.15	
Burst	broken	0.51	1.41	0.27	broken	



Welding pipe



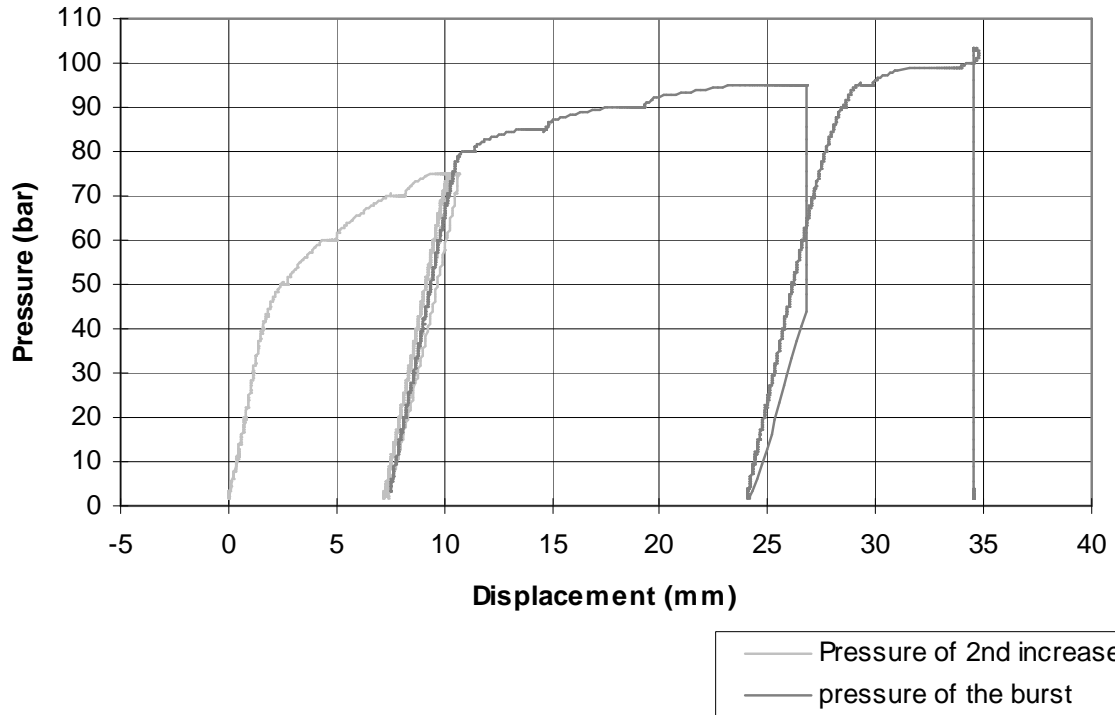
Scored pipe



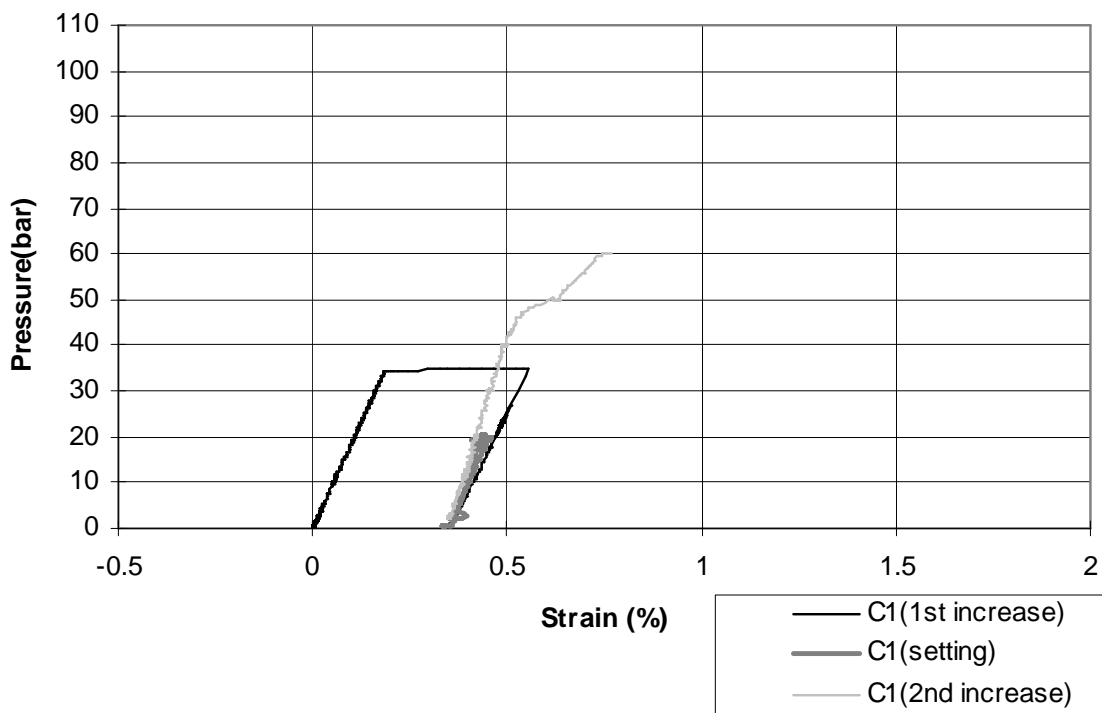
Clock Spring position



### Pressure vs displacement

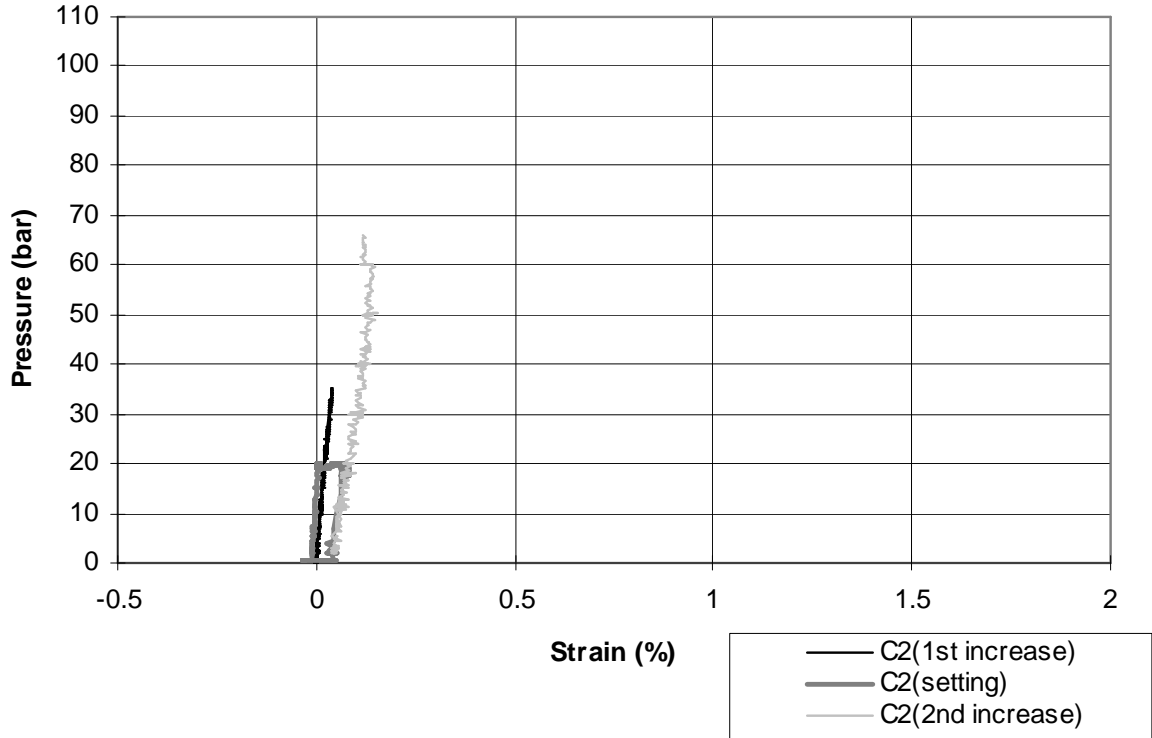


### Pressure vs circumferential strain C1

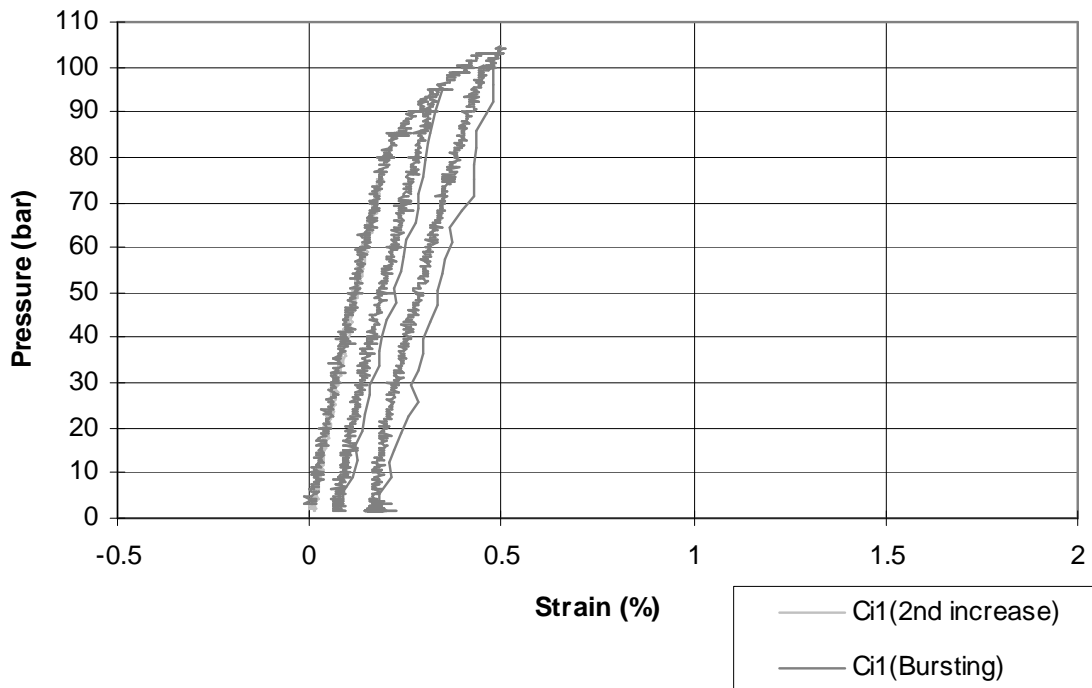




Pressure vs circumferential strain C2

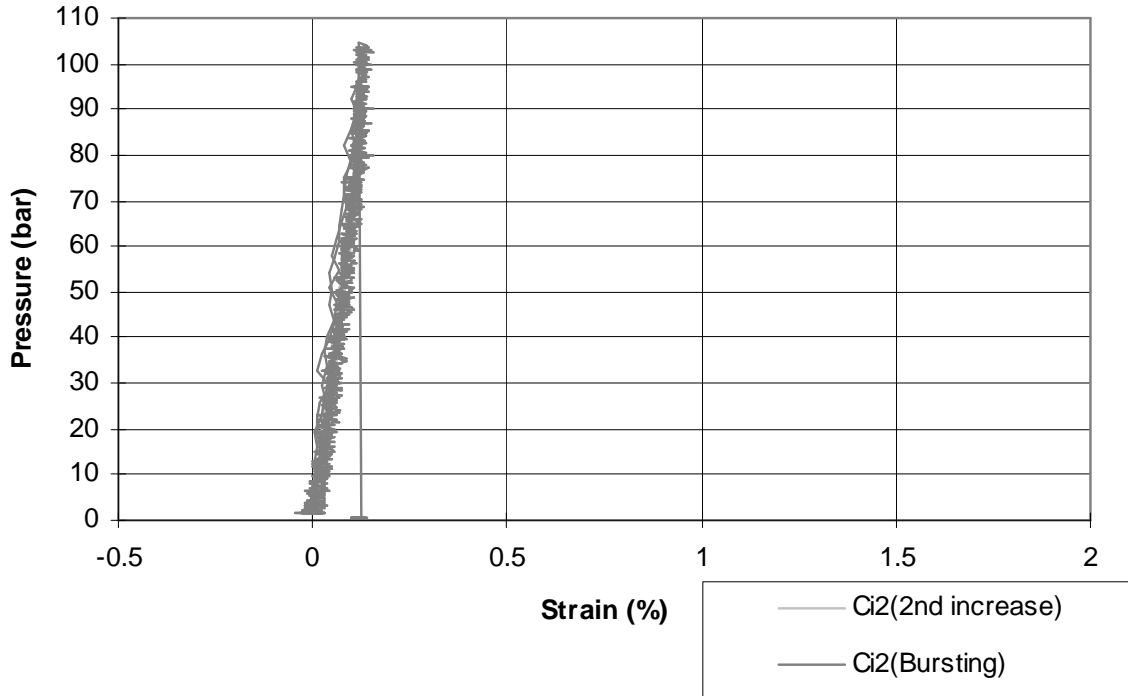


Pressure vs circumferential strain Ci1





Pressure vs circumferential strain Ci2



Pressure vs circumferential strain Ci3

