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FRACTURE ARREST EVALUATION OF X100 TMCP STEEL PIPE FOR HIGH PRESSURE GAS TRANSPORTATION PIPELINES

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Abstract

In recent years, gas companies have shown an increasing interest in the possible use of higher grade steel pipes (Yield Strength ≥ 690 MPa, equivalent to X100 steel grade) for the construction of long distance gas pipelines. As a result, research programs sponsored by both gas companies and steel pipe producers, investigated the suitability of the equivalent of X100 grade steels for high pressure pipeline use, with the main emphasis placed on establishing their fracture behavior.

One of the essential points was dealing with ductile fracture arrest capability, in order to consolidate existing know-how regarding the definition of the minimum toughness requirement to control the ductile fracture propagation event. Toughness evaluations were carried out to determine Charpy V-notch shelf energy, DWTT shelf energy, and new promising toughness parameters such as the DWTT specific total/propagation energy values, and a measure of the Crack Tip Opening Angle (CTOA). To achieve this general aim extensive use of the full scale burst tests was also necessary.

The results of full scale tests, in terms of arrest/propagation conditions, discussed together with available results in the literature on API X80 and X100 pipes, show that X100 large diameter pipes are operating at the upper bound of the arrest/propagation ductile fracture propagation conditions; moreover also the applicability of the "*Battelle Two Step Analysis*", and their straightforward extrapolation from API X80 pipes to X100 grade operating at very high hoop stress values (≥500MPa) is highly questionable. So a devoted or specific "design" is mandatory to prevent/control the ductile fracture propagation event in long distance X100 grade large diameter onshore gas pipeline.

On specific fracture issues this paper presents also some conclusions useful for the safe design of long distance X100 grade gas pipelines; with regard to this specific issue the CSM proprietary code PICPRO® is presented as a valid tool for enlarging the information gathered from a single full scale burst test, to provide a solution to overcome the problems connected with the lack of a reliable procedure to transfer laboratory toughness results to the real pipe case and finally to achieve a new safe design criteria for crack arrestors.

Introduction

Large diameter pipes in X100 steel grade are nowadays industrially producible and their use has been demonstrated to be economically viable for the construction of long distance gas transmission pipelines ([1-4]). Nevertheless limitations in their application might occur if important aspects related to their structural reliability are not clarified and understood in depth: these include defect tolerance, ductile to brittle transition and fracture arrest capability. In this context, the propagation of a fast running shear longitudinal fracture is one of the most serious events; the fracture potentially affecting a long part of the line causing a long and costly gas delivery service breakdown. Therefore, the design of gas transportation X100 grade lines needs an optimal compromise between the choice of the operating pressure, linepipe geometry (diameter and thickness) and steel mechanical properties (tensile and toughness characteristics). The wide variety of possible technical/economical solutions requires the development of specific tools, able to estimate the safety margin concerning all potential events responsible for structural failure.

The determination of the toughness values required for arresting ductile fracture propagation has been historically based on the use of models in the form of predictive equations, which state the minimum required value of the Charpy V-notch upper shelf energy (used as a toughness material parameter) as a function of both pipe geometry and applied hoop stress. These semi-empirical predictive relationships have been developed using a combination of theoretical analysis and available full-scale test data [5-7].

The Battelle Two Curve approach [5], is the most appreciated or valid predictive method up to API X80 grade steel linepipes, when an appropriate correction factor for higher grade pipes is applied. This method is based upon the comparison between the driving force and the resistance force:

- The driving force (*Driving Curve*) is represented by the gas decompression curve and therefore is dependent on the initial gas pressure, temperature and chemical composition.
- The resistance force (*Resistance Curve*) is dependent on the linepipe geometry, external constraints, and the resistance of pipe to ductile crack propagation event, specific of the steel under consideration and related to its toughness.

The approach, also known as the "*Battelle Two Step Analysis*", assumes that the gas decompression behavior and the dynamic crack propagation behavior are uncoupled processes that can be related through the fracture propagation speed in the pipeline. The method was finalized for a single phase (such as air, nitrogen or essentially pure methane) medium. However the validity of the method is general and it can be applied to rich gas cases, provided that suitable gas decompression models are available. It gives minimum CharpyV upper shelf energy value which ensures that a propagating shear fracture will be stopped, without estimating an arrest distance; in the case of a stable propagation event this model can also provided the value of the steady-state propagation crack velocity.

Actually the extension of the "*Battelle Two Step Analysis*" to X100 steel grade operating at very high hoop stress (≈ 550 MPa) is highly questionable: in fact, as it will be shown in detail in this paper, in the recent years evidence appeared that the range of applicability of this semi-empirical method is limited by the experimental database and simplifications used to establish the relevant equations. At the same time, it is now quite recognized that the Charpy V-notch upper shelf energy value is inadequate to characterize fracture resistance in modern high strength-high toughness linepipe steels especially for the X100 case. Fracture behavior of these new materials lies outside the field covered by the existing experimental data and know-how, hence extrapolation could be possible but not reliable. To overcome this hindrance devoted full-scale and laboratory test programs have been made by many R&D Centres supported by Industries and/or Authorities, such as ECSC (European Coal and Steel Community) and EPRG (European Pipeline Research Groups) beginning in the '90s. Starting from both the results of two ECSC projects performed by CSM, with the contribution of EPRG ([8-9]) and the available published data in this paper, the ductile fracture propagation behavior of X100 grade large diameter pipes is shown and discussed. In particular:

- the fracture behavior of X100 grade pipes will be examined on the basis of full-scale and laboratory tests results,
- the actual available tools devoted to the safe design of X100 gas pipelines in order to prevent fracture propagation event, will be shown.

Ductile Fracture Propagation of X100 Steel Pipes: CSM Experience

Ductile fracture propagation phenomena have been widely investigated by many Institutes in the last 30 years, with particular regard to the steel gas pipelines. Among those CSM played a primary role, and the large number of CSM's full-scale tests carried out since the '70s strongly contributed to identifying a set of meaningful parameters characterizing ductile fracture propagation conditions. In particular since 1975 CSM has been conducting ductile fracture propagation full-scale tests at its test site facility located at Perdasdefogu (Sardinia, Italy): 31 burst tests have been carried out on pipe steel ranging in strength from X70 through X120.

Since 1994 CSM has been carrying out specific research projects and full-scale burst testing for national and international Oil & Gas companies, devoted to the investigation of the ductile fracture propagation behavior of ultra-high grade steel gas linepipes [10-14]. Among the total number of 14 full-scale burst tests on high grade steel linepipes (≥X80) which have been performed by CSM so far, more recent tests on X100 steel pipes which belong to the projects mentioned above are detailed below in Table 1.

Table 1. List of X100 full-scale burst test carried out by CSM.

Test	Pipe outer diameter	Pipe wall thk.	Hoop stress	Test pressure	Usage factor	Note
	(in)	(mm)	(MPa)	(bar)		
1	56	19.1	469	126	0.68	ECSC* Project: 1st full-scale test
2	36	16.0	517	181	0.75	ECSC Project : 2nd full-scale test
3	36	16.0	551	193	0.80	DEMOPIPEPr**.:1st full-scale test
4	36	20.0	517	226	0.75	DEMOPIPE Pr.** 2nd full-scale test

* ECSC: European Coal and Steel Community.
** DEMOPIPE project funded by ECSC and EPRG.

The aim of these test programs was to define the material toughness requirements for arresting a fast propagating ductile fracture, and to verify the applicability of Charpy V-notch upper shelf energy value as a toughness parameter and to verify existing design methods to fix the minimum fracture resistance requirements for a X100 grade gas pipelines.

Even though the tests have been carried out within two separate projects, their operative conditions have been chosen to be more and more severe, basing each new test upon the results of previous tests. In particular the ECSC full-scale tests were carried out using air as a pressurizing medium, on the other hand lean natural gas was used for the subsequent DEMOPIPE tests. In the following compilation starting from Table 2 to Table 5 and from Figure

1 to Figure 4, information regarding these full-scale tests are reported: including pipe steel properties, test layout and crack speeds.

ECSC Project: 1st full-scale test

Table 2. ECSC project: first full-scale test lay-out for the 56"OD x 19.1 mm, grade X100 pipes.

Test Layout	*3-W*	*2-W*	*1-W*	*Initiation*	*1-E*	*2-E*	*3-E*
Pipe number	**020**	**083**	**129**	**113**	**058**	**157**	**061**
Rt0.5 (MPa)	707	719	780	773	755	663	722
Rm (MPa)	766	766	832	858	829	762	778
Y/T	0.92	0.94	0.94	0.90	0.91	0.87	0.93
CVav.(J)	271	245	200	151	170	263	284
DWTT Tot spec.(J/cm^2)	689	692	410	482	392	654	723
CTOAc(°)	9.6	10.9	5.6	5.9	8.7	8.4	11.6
EVENT	NI	NI	NI	Init.	P	A	NI

NI: Not involved
Init. Initiation pipe
P: Propagation pipe
A: Arrest pipe

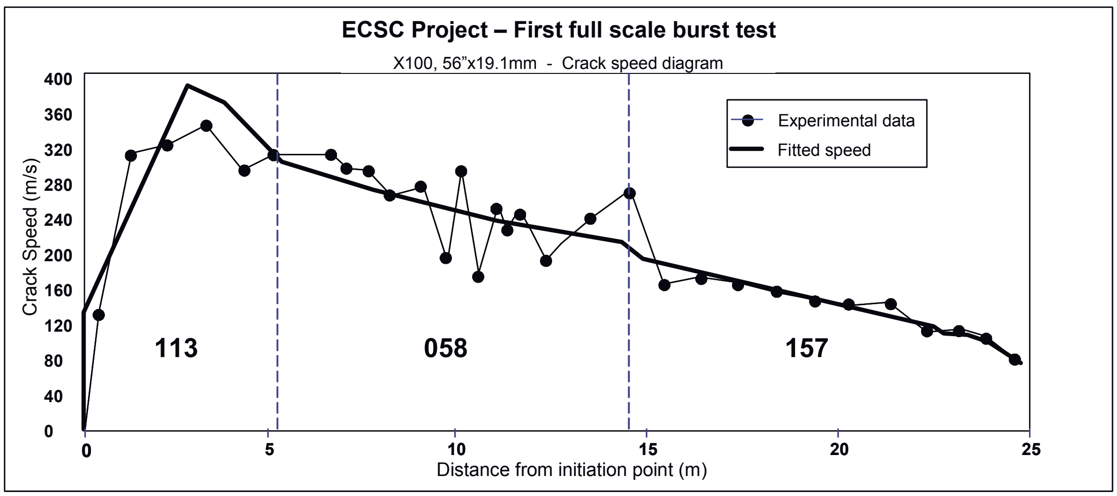


Figure 1. Crack speed diagram of full-scale fracture propagation test on ECSC 56"OD x 19.1 mm.

The first ECSC full-scale test was carried out on 56 inches diameter pipe, the line was pressurized up to 126 bar, corresponding to 68% of the SMYS. After initiation, in the West side of the line the fracture stopped due to a pipe severance in the girth weld between the initiation pipe and the first test one, for this reason only the results of the East side have been analyzed. In the East side the fracture ran straight on the pipe top generatrix decreasing its speed constantly until it stopped in the end of pipe n.157. The Charpy V-notch energy of the arrest pipe was 263J.

ECSC Project: 2st full-scale test

Table 3. ECSC Project second full-scale test lay-out for the 36"OD x 16.0 mm, grade X100 pipes.

Test Layout	*3-W*	*2-W*	*1-W*	*Initiation*	*1-E*	*2-E*	*3-E*
Pipe number	**47**	**58**	**60**	**61**	**56**	**57**	**46**
Rt0.5 (MPa)	724	750	711	709	761	740	766
Rm (MPa)	780	819	797	802	844	811	826
Y/T	0.93	0.92	0.89	0.88	0.90	0.91	0.93
CV av.(J)	297	252	202	165	259	253	274
DWTT Tot spec.(J/cm^2)	965	741	367	430	851	747	898
$CTOA_C$(°)	12.4	9.2	7.3	6.4	10.7	10.8	9.8
EVENT	A	P	P	Init	A	NI	NI

NI: Not involved
Init. Initiation pipe
P: Propagation pipe
A: Arrest pipe

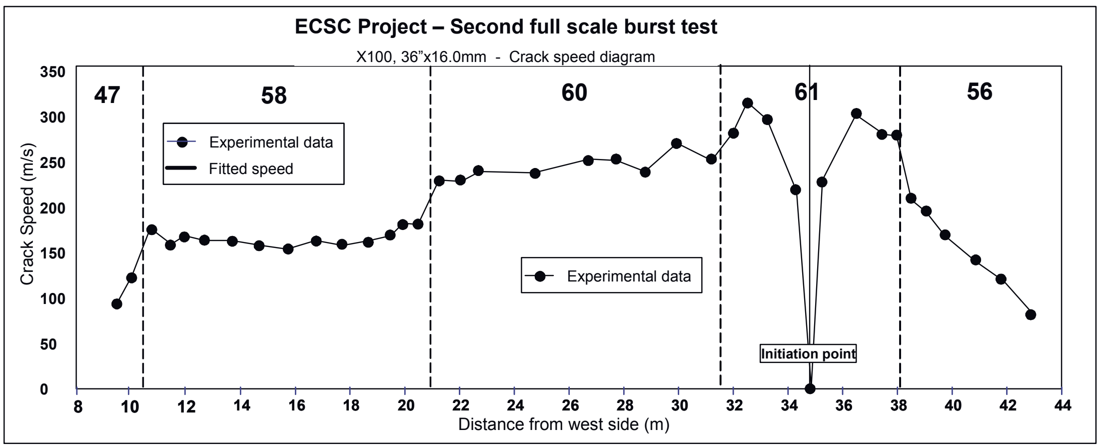


Figure 2. Crack speed diagram of full scale fracture propagation test on ECSC 36"OD x 16.0 mm.

The second ECSC full-scale burst test was carried out on 36-in diameter pipe and the line was pressurized to 181 bar, corresponding to 75% of SMYS. As shown in Figure 2 the fracture ran along the West side through the first two pipes at a constant speed and then it arrested roughly in pipe n.47. In the East side of test the fracture ran decreasing its speed constantly so as to stop in the end of pipe n.56. The Charpy V-notch energy of the arrest pipe was in the range 252J of propagation pipe n.58 and 259J of arrest pipe n.56.

DEMOPIPE Project: 1st full-scale test

Table 4. First DEMOPIPE Project full scale test lay-out for the 36"OD x 16.0 mm, grade X100 pipes.

Test Layout	4-W	*3-W*	*2-W*	*1-W*	*Init.*	*1-E*	*2-E*	*3-E*	*4-E*
Pipe number	**8808**	**8795**	**8797**	**8786**	**8781**	**8783**	**8780**	**8799**	**8776**
Rt0.5 (MPa)	772	775	792	803	794	784	802	774	750
Rm (MPa)	822	826	844	872	856	847	870	811	773
Y/T	094	0.94	0.94	0.92	0.93	0.93	0.92	0.95	0.97
CV av.(J)	291	249	237	215	193	228	223	258	355
DWTT Tot spec.(J/cm^2)	823	746	761	732	680	796	756	633	791
$CTOA_C$(°)	10.6	7.9	10.2	10.8	10.2	9.1	10.1	10.3	8.9
EVENT	P	P	P	P	Init.	P	P	P	P

NI: Not involved
Init. Initiation pipe
P: Propagation pipe
A: Arrest pipe

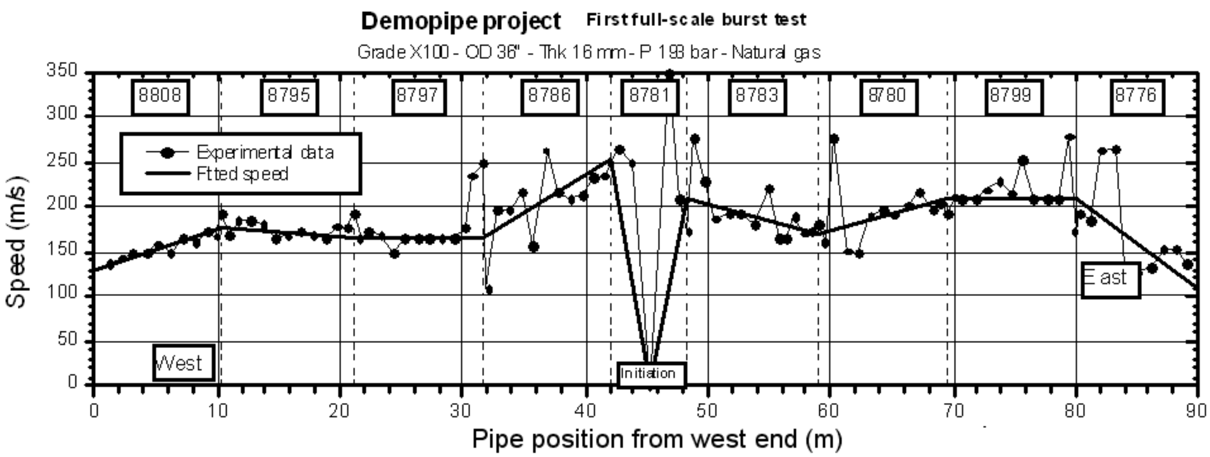


Figure 3. Crack speed diagram of first full-scale fracture propagation test within DEMOPIPE project (36"OD x 16.0 mm).

The first DEMOPIPE Project full-scale burst test was carried out on 36-in diameter pipe and the line was pressurized with lean natural gas to 193 bar, corresponding to 80% of the SMYS. As shown in Figure 3 the fracture ran along the West side and the East side up to the reservoirs, without achieving a natural arrest.

DEMOPIPE Project: 2st full-scale test

Table 5. Second DEMOPIPE Project full-scale test lay-out for the 36"OD x 20.0 mm, grade X100 pipes.

Test Layout	4-W	*3-W*	*2-W*	*1-W*	*Init.*	*1-E*	*2-E*	*3-E*	*4-E*	
Pipe number	**8824**	**8826**	**8834**	**8831**	**8837**	**8835**	**8839**	**8836**	**8851**	Crack Arrestor
Rt0.5 (MPa)	758	739	739	784	739	782	760	751	760	
Rm (MPa)	788	794	792	824	777	852	800	795	813	
Y/T	0.96	0.93	0.93	0.95	0.95	0.92	0.95	0.94	0.93	
CVav.(J)	267	240	252	247	211	206	223	249	257	
DWTT Tot spec.(J/cm^2)	781	792	779	728	635	565	741	749	809	
CTOAc(°)	11.5	10.5	8.7	10.5	10.4	9.7	11.9	12.9	11.2	
EVENT	NI	NI	A	P	Init.	P	P	P	P	

NI: Not involved
Init. Initiation pipe
P: Propagation pipe
A: Arrest pipe

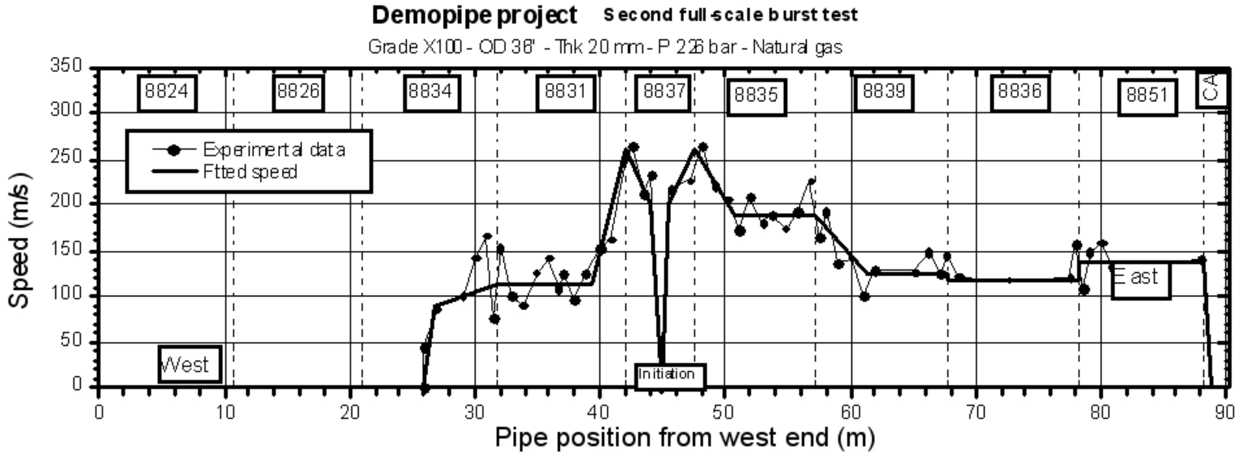


Figure 4. Crack speed diagram of first full-scale fracture propagation test within DEMOPIPE project (36"OD x 20.0 mm).

The second DEMOPIPE full-scale test was carried out on 36in x 20mm pipes. The line was pressurized to 226 bar, corresponding to 75% of the SMYS. As shown in Figure 4 the fracture ran in the West side through the initiation pipe and pipe n.8831 where it arrested rapidly. Otherwise in the East side the natural arrest was not achieved and the fracture stopped inside the crack arrestor close to its initial edge.

Figure 5. CSM's full-scale tests on X100 lines. View of the fractured lines.

From the results of these four full-scale CSM tests a few specific peculiarities about the ductile fracture propagation behavior of high pressure X100 gas pipelines have been identified:

- X100 steel grade gas linepipes with "toughness" sufficient to arrest a running ductile crack under particular operating conditions are available; nevertheless for severe service conditions (especially in terms of pressure and gas chemical composition) this new class of high grade pipes operates above the arrest/propagation boundary condition, such that the use of external devices such as crack arrestors is mandatory.

- Reporting the actual Charpy V-notch energy versus the predicted one using the "Battelle Two Step Analysis" (Figure 6), for all these pipes involved in the full-scale tests (together to CSM data about grade≥ X80, OD=42 ÷56",WT=12.5÷26mm; P=93.5÷161bar, Hoop stress=355÷445MPa, air and natural gas) it appears evident that it is not possible to determine a unequivocal correction factor for all the four tests on X100 pipes.

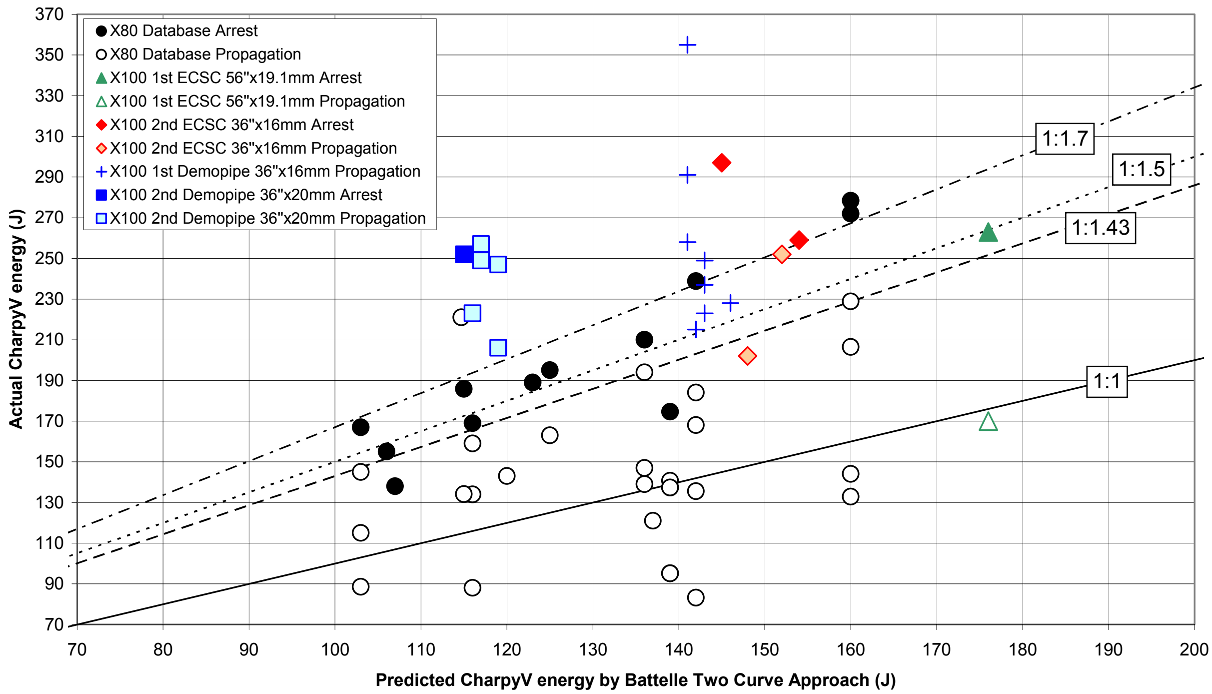


Figure 6: Actual CharpyV energy vs predicted one by Battelle Two Curve Approach (CSM database grade ≥ X80, OD=42-56", wt=12.5-26mm; P=93.5-161bar, Hoop stress=355-445MPa, air and natural gas).

In practice the existing criteria both to evaluate the "toughness" of steel pipe and to estimate the minimum "toughness" requirements to have a safe crack arrest are not reliable for X100 gas linepipes. This non-safe condition is due to both the inadequacy of Charpy V-notch upper shelf energy value to characterize fracture resistance in modern X100 grade steel pipes and to the simplifications (and database) used to develop the "*Battelle Two Step Analysis*". It is concluded, with regard to the ductile fracture propagation event, new criteria are needed for safe design of X100 large diameter gas pipelines.

Alternative Methods to the Charpy V-notch Energy to Evaluate the Toughness Properties of X100 Steel Pipe

As mentioned above, experimental evidence has shown the inadequacy of the Charpy V-notch upper shelf energy value in representing the pipe fracture propagation resistance. This limitation could be due to the reduced specimen size that does not allow the crack to reach steady-state propagating conditions and to find a ligament extension where propagation is not more influenced by edge effects. These constraint effects can play a relevant role in the case of X100 steel that generally shows high crack initiation "toughness" together with low ductility (such as higher values of Y/T ratio and/or lower value of both strain hardening and uniform strain at failure) and with low crack propagation resistance.

One of the most considered approaches, as an alternative to the Charpy V-notch specimen, for ductile fracture propagation control is the DWT Test, in particular the fracture parameter measured using this last specimen such as DWTT total upper shelf energy value, DWTT propagation upper shelf energy value, or a fracture mechanics parameter such as the Crack Tip Opening Angle (CTOA) appear promising. ([17-19]).

Drop Weight Tear Test Specimen: total and propagation upper shelf energy value

The Drop Weight Tear Test specimen appears more adequate compared with the Charpy V-notch specimen since it is full thickness and has a sufficient ligament length thus allowing the crack to propagate steadily and far from the edge for a considerable extension. Nevertheless the recourse to DWTT specimen is far from being considered a full resolution for the identification of the best crack propagation resistance parameter.

With the aim to evaluate the benefits of the DWTT total upper shelf energy parameter for the characterization of fracture behavior of X100 steel pipes, the DWTT vs Charpy V-notch total upper shelf energy values are reported in Figure 7. It is evident that for new high toughness/strength steel materials the CV-DWTT correlation is very scattered and tends to loose its historical linearity. Nevertheless the arrest pipes show higher values of DWTT total upper shelf energy (above 700 J/cm^2) and higher values of the DWTT/CV ratio.

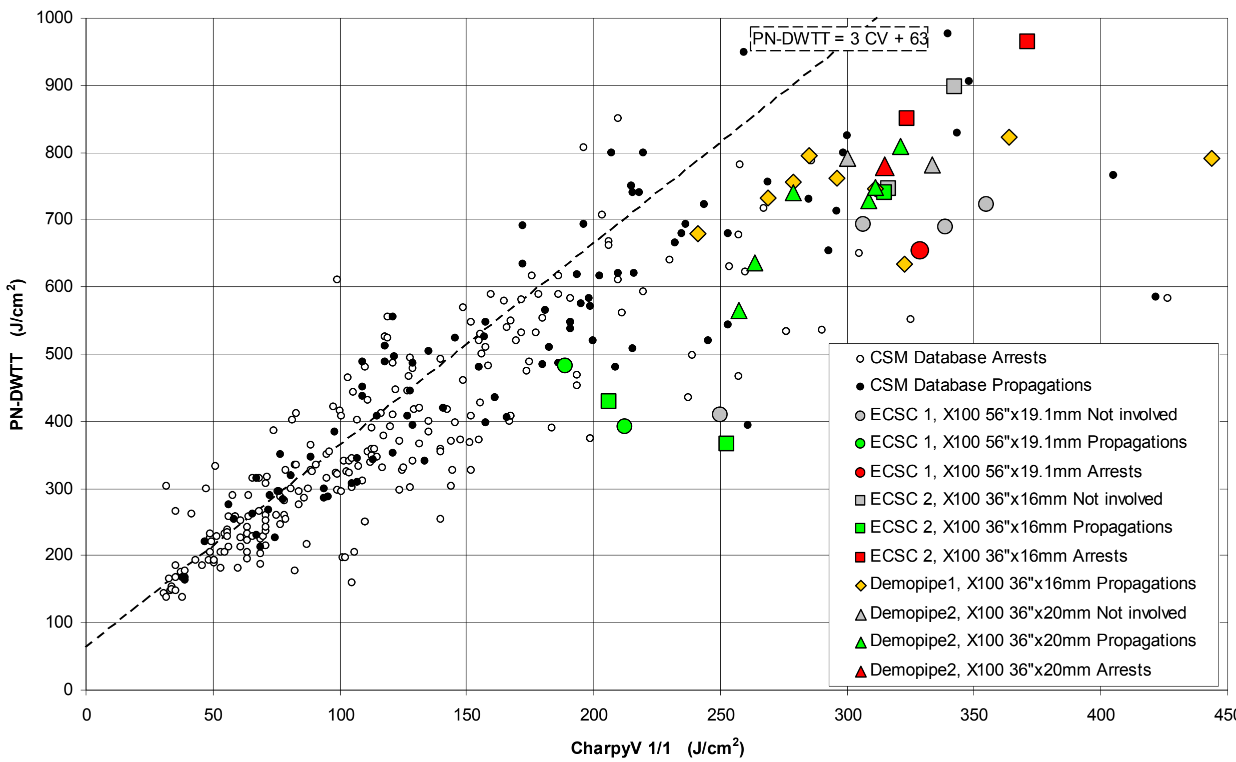


Figure 7: Actual specific Charpy V-notch versus DWTT energy (CSM database Grade≤X90 and X100 tests).

Finally to check in depth the adequacy of the parameters mentioned above to describe the toughness of X100 steel pipes regarding the fracture propagation event a specific analysis of the 2nd full scale test performed in the DEMOPIPE Project has been made. In Figure 8 the diagram of crack speed is shown together with the Charpy V-notch total upper shelf energy value, DWTT total upper shelf energy value and DWTT propagation upper shelf energy value of each pipe involved with fracture. As far as this analysis is concerned, the best candidate to characterize the correct fracture resistance of modern high strength pipe steels could be DWTT propagation upper shelf energy; nevertheless the differences found are not very great, and for practical purposes could be considered to fall within the same level of experimental scatter. Anyway, these differences, considered negligible in the test design process, could be responsible for the different behaviour of the tested pipes.

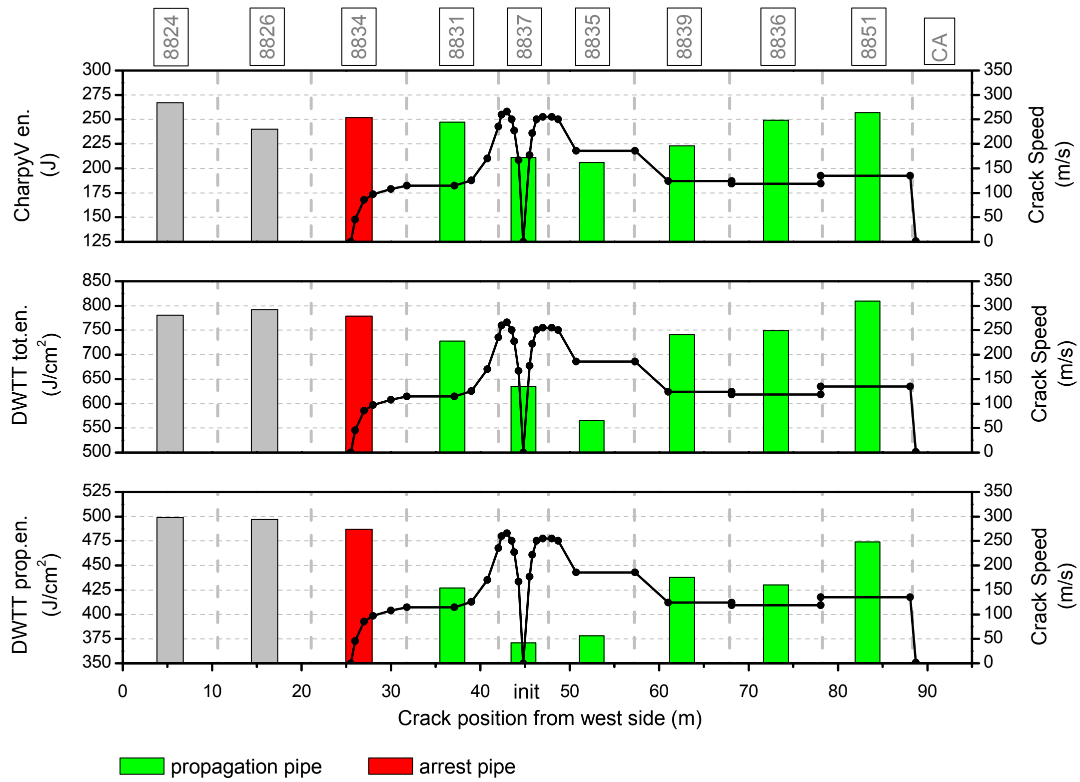
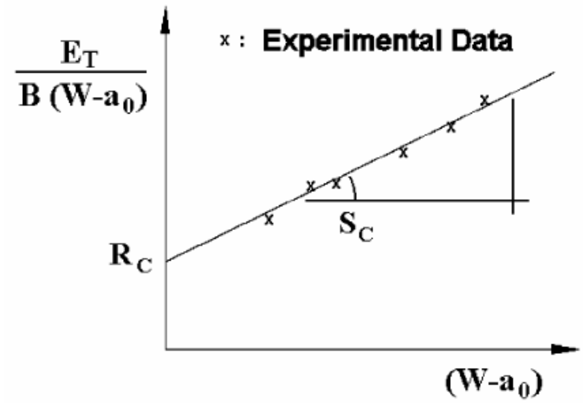


Figure 8: 2nd test DEMOPIPE project – Charpy V-notch energy, DWTT energy (total and propagation contribution) vs crack speed.

Crack Tip Opening Angle, CTOA

Crack Tip Opening Angle is one of the most acknowledged fracture mechanics parameters to characterize pipe material toughness when a large crack length is associated with fracture event. Experimental evidence show that CTOA value depends on the initial residual ligament length of the specimen and that its value decreases as the ligament increases, down to an asymptotic value, which corresponds to a theoretical infinite ligament (being, this situation, well representative of the typical constraint of a pipe during a fast longitudinal crack propagation event). For the estimation of the critical CTOA value ($CTOA_C$) many laboratory methodologies have been developed in the past; such as the Two Specimen CTOA Test (TSCT) method [15] that it is found to be relevant since it allows one to evaluate the effective ligament independent $CTOA_C$ value.

Even though the CTOA parameter has been recognized as useful for this kind of pipeline failure, nevertheless a deep analysis of results of full scale tests on X100 pipes reported above shows some pitfalls, in particular in the second full scale test of DEMOPIPE project, (Table 5 and Figure 4) incongruity is evident between the CTOAc values and the fracture behavior. This discrepancy can be caused by the TSCT laboratory method used to evaluate the critical value of CTOA especially by the hypothesis to “transfer” the laboratory critical value of CTOA obtained on small specimen to the pipe with a theoretically infinite ligament. In fact in its original form, TSCT was addressed to low to medium strength line pipe steels and based upon the hypothesis that the specific initiation energy was independent of the ligament length; this hypothesis allows one to calculate the toughness by using directly the total fracture energy of two full thickness three point bending specimens with two different ligament length. In **Figure 9** a guideline for the calculation of the critical CTOA of a pipe material by TSCT is reported.



$$
\begin{cases}
R_C = \dfrac{E_I}{B \cdot (W - a_0)} \\
CTOA_C = \dfrac{2 S_C\, r^*}{K \sigma_0}
\end{cases}
$$

Figure 9: Calculation of the CTOA critical of a pipe material by TSCT.

The notation used in **Figure 9** is the following:

r^*	:	non-dimensional constant parameter (rotation factor);
K	:	parameter which account for the real stress distribution in the residual ligament – 0.35 for Single Edge Notch Bending (SENB) specimen;
σ_0	:	material flow stress;
B, W, a_0	:	specimen thickness, specimen width, depth notch respectively;
E_I	:	Initiation energy.

In the case of modern X100 grade pipe materials the hypothesis of the independence of initiation energy of the initial ligament length seems not to be confirmed anymore, and it could be the cause of failure of the CTOA parameter to describe the toughness level of tested pipes. To overcome this problem a new TSCT method is being developed which considers the propagation energy contribution only, for the $CTOA_C$ calculation [19]. Even though this new procedure appears to be very promising, some in-depth investigations are required especially for estimating the exact contribution of propagation energy, before it can be considered as a reliable method for the "transferability" of laboratory toughness results to the real pipe situation. As a matter of fact the $CTOA_C$, calculated by laboratory testing and appropriately transferred to the real case of a gas pipeline by the application of the TSCT method, is not yet adequate for predicting the effective fracture behavior. As will be shown below, this problem could be partially overcome by performing numerical simulations of full-scale tests through a devoted Finite Element code.

Finite Element Code to Describe the Ductile Fracture Propagation Behavior of X100 Steel Pipes: CSM PICPRO® code

As mentioned above, the most considered alternative approaches for crack arrest in fast running ductile fracture are either propagation energy or Crack Tip Opening Angle based. Nevertheless two specific difficulties can limit their use:

- the correct way to "transfer" the laboratory toughness value from the specimen to the full scale pipe;

- the physical model, based on the mentioned toughness parameters, to quantify the driving force of the fracture event.

As a matter of fact, some of the problems found during experimental measurement of the mentioned parameters, in the case of modern steels, can be overcome using a Finite Element code which allows one to calculate the trend of the main fracture-characterizing parameters during crack propagation. In addition, FE analysis also permits one to evaluate the driving force available to sustain crack propagation, expressed in terms of CTOA ($CTOA_{APPLIED}$) vs. crack length, under given line pipe operating conditions.

In the recent years, CSM developed a proprietary Finite Element code, named PICPRO® (Pipe Crack PROpagation), for simulating the ductile fracture propagation in steel gas pipelines [20-22]. The driving force estimate is given in terms of CTOA and computed during simulation; its value is then compared with the material parameter $CTOA_C$, inferred from small specimen tests to evaluate the arrest of a running crack in a given linepipe.

The code includes elastic-plastic large-displacement shell elements and integrates them explicitly in time through a central difference scheme. PICPRO® offers special features devoted to buried gas pipelines when ductile fracture propagation occurs. In more detail, the CTOA is assumed as the dominant fracture propagation parameter and its value is used to check the stability of fracture propagation. The correct estimate of CTOA requires the introduction of a fracture model able to account for, in a simplified form, the ductile Fracture Process Zone (FPZ) where the final stretching of the material and formation of new fracture surfaces takes place (**Figure10**). The model is based on a one-dimensional cohesive layer, with length Δ (cohesive layer size), and allows the gradual node release ensuring regular changes of the internal reactions as required in order to avoid numerical instability during explicit FE integration and direct connection with material softening/stretching and the energy dissipated by formation of new fracture surfaces.

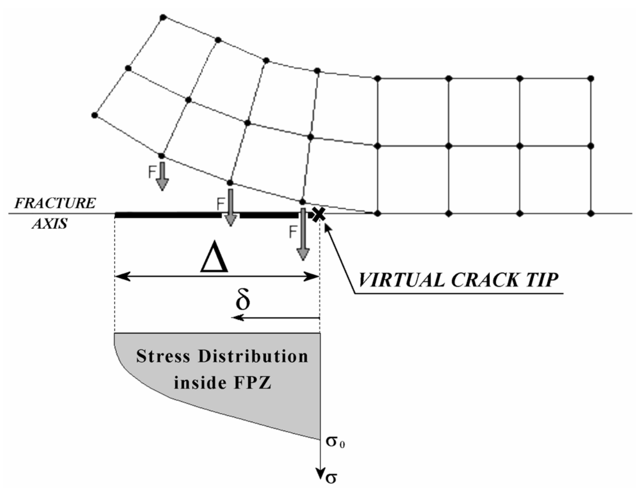


Figure10. Gradual nodal release inside the FPZ.

The goal of any cohesive model is to account for the energy dissipation associated with the crack as a whole when no local information is needed. Therefore, the cohesive distance does not necessarily represent an observable quantity, even if the value assumed by Δ is related to several mechanical and geometrical properties, mainly: toughness, work hardening law and thickness.

A phenomenological model of soil dynamics has been introduced in PICPRO® to account for the effect of soil backfill constraint on ductile fracture propagation in buried gas pipelines. This soil behavior is modeled by an equivalent system of lumped masses and springs actively only when compression occurs and whose characteristics are derived from similar data found in the literature as well as from energetic considerations. The reliability of this approach has been demonstrated in recent CSM full-scale tests, where a dedicated instrumentation made by *ad-hoc* designed pressure transducers embedded in the trench soil showed the consistency of the experimental backfill constraint with the numerical model.

Regarding the gas behavior analysis two regions are studied separately. The first one-dimensional model is adopted to account for decompression ahead the crack tip; it is based on the one-dimensional solution for the shock tube problem and the equation of state for both lean and rich gases. The solution represents the asymptotic pressure value inside the pipeline for a given steady-state crack propagation speed. A second, two-dimensional model is used for the region behind the crack where the flap opening occurs; here the model comes from simplified fitting of pressure maps given by pressure transducers during past full-scale propagation tests carried out by CSM.

At the moment, PICPRO® is able to account for dynamic conditions in a more sophisticated way that is in a step-wise manner: in other words, the stress is appropriately incremented by a factor calculated step by step and for each element. This is essential since the elements located on and near the crack tip experience high strain rate, but at the same time other elements are subjected to static loads (or quasi-static).

PICPRO® code can be used both in “direct” and in “reverse” way. The two ways are substantially different for the input quantities (and as a consequence for the output) to be used to start the simulation. In fact, in the former way it is necessary to supply the code with the information about: test conditions, gas mixture, pipe geometry, trench geometry and dimensions, soil characteristics, tensile material properties, toughness material properties ($CTOA_C$). With this set of information, PICPRO® is able to simulate a ductile fracture in “free” propagation modality and to supply the following information as output results: crack speed diagram during the propagation and then also the crack arrest event.

The results of this kind of simulation can be used to predict the arrest or propagation conditions for a given line or full-scale test. Nevertheless, this “direct” way to simulate the ductile fracture propagation has the drawback since it is based on the knowledge of the critical fracture parameter ($CTOA_C$) that has been demonstrated to be difficult to be extrapolated from experimental assessments carried out on small-scale specimens for the new high strength steels grade X100. This aspect is essential to simulate correctly the fracture speed that is the natural result of the comparison between applied and critical fracture parameters.

To overcome this shortcoming, further investigations to delineate a reliable procedure for the transferability of laboratory toughness results to the real pipe situation are strictly needed. The PICPRO® code can also be used in a “reverse” way, the substantial difference consists of replacing the input toughness material properties with the crack speed diagram inferred from a previous full-scale test performed on similar X100 pipes. Starting from the hypothesis that in a fracture propagation event the applied fracture parameter and the critical one must own the same value, this method permits one to infer, as result of simulation in “reverse” way, the value of pipe fracture parameter to be used in “direct” simulation. In other words, by imposing the experimental crack speed diagram it is possible to evaluate the implied CTOA or, that is the same, the corresponding critical value.

Starting from the consideration that the pipe materials used in the first and second DEMOPIPE full-scale burst tests have been supplied by the same producer, manufactured with the same

TMCP parameters and exhibiting similar toughness characteristics, it has been possible to use the result of the first test for the design of the second one. In particular in a first step, the PICPRO® code has been used to simulate the first full-scale test in "reverse" way, imposing a crack advance according to the experimental speed diagram acquired during the first full scale DEMOPIPE Project test. As a result a more realistic correlation to "transfer" the laboratory value of CTOA to the pipe has been obtained. Then starting from these results, the second full scale DEMOPIPE test has been "design" using the PICPRO® in "direct" way. In particular the test parameter in terms of pressure and chemical composition of the gas has been fixed on the base of results of PICPRO® simulations.

Concerning this finite element approach proposed by CSM using PICPRO® code it is possible to conclude that once a full-scale burst test has been simulated by PICPRO® parameters, such as the material toughness properties are known even though by a "reverse" use of the code, various numerical analysis can be performed in order to investigate the effect of variation of parameters of special interest on fracture behavior. This permits one to "enlarge" the results of one full-scale burst test, for example, by changing the test temperature conditions, the gas composition, and gas pressure, etc. By the way, the results of a single full-scale test can be usefully generalized.

External Mechanical Devices for Arresting Fracture Propagation on Pipes

The problem to overcome the increasing severity of pipeline operating conditions together with the difficulty in reaching an adequate value of toughness as an intrinsic property of the new class of X100 pipe materials, very frequently brings the gas companies to resort to additional mechanical devices (usually named "crack arrestors" CA) in the attempt to ensure the arrest of an eventual running fracture. At present, different types of crack arrestors are available which can be mainly classified into two categories, integral and non-integral, depending on their method of installation in the gas pipeline. The first ones are inserted in the pipeline and act as an integral part of it, the others are made of several parts assembled externally to the pipeline and generally bear a minimum part of the load due to the internal pressure during operative conditions.

Integral crack arrestors are generally made of pipes and/or rings with mechanical and/or geometrical properties which are different from those of the main line. Their advantage consists of an easier assembly during pipeline construction. On the other hand, they are difficult to adopt on pre-existing lines. Most of them consist of pipes with higher thickness and/or greater toughness but other alternatives, such as multi-layer CAs, have been developed. In particular, in recent years a new solution using composite materials has been developed (formed by high strength E-glass fibres drawn through an iso-polyester resin system and wound around the external surface of the main steel pipe), their fracture arrest capability is very promising. An alternative solution consists of a composite crack arrestor wrapped around the pipe with an imposed pre-stress. Such a solution would permit one to increase the CA carrying capacity under the same wall thickness. An example of E-glass Composite CA (not pre-stressed) adopted in the 2nd test within the DEMOPIPE project is shown in **Figure 11**.

Figure 11. Composite CA section used in 2nd full-scale DEMOPIPE project (CA provided by Europipe).

On the other hand, non-integral crack arrestors consist of additional structures to be applied upon existing pipelines. The main types are sleeve steel arrestors (with or without grout), welded and/or clamped rings, rope or steel thread rings and Clock Spring® crack arrestors.

Though the use of crack arrestors could be a realistic solution for safe design of a new X100 grade long distance pipeline, nevertheless the know-how to design a crack arrestor is not notable. In fact until the ‘80s, many line pipes exhibited inadequate toughness in comparison with the value required by the operative conditions. As a consequence, at that time PRCI performed wide ranging experiments with the aim of evaluating the basic design and usage criteria for different kinds of crack arrestors. As a result, a CAs design and optimization guideline was developed [23-24], which is mainly applies to ductile fracture control and provides the main CA dimensions such as CA length and, if the case, the clearance, for a given (calculated or assumed) entering fracture velocity. In the second half of the '80s, with the introduction of TMCP technology, better performing steel pipes (in terms of toughness, weldability and grade) were available, which were demonstrated to be able to arrest ductile fracture propagation by means of their inherent properties. For this reason, the recourse to mechanical devices such as CAs appeared not to be needed anymore, and the interest concerning their development and use substantially decreased.

Afterwards, a further improvement of the TMCP technology allowed manufacturers to produce higher grade line pipes (X100, and also X120), which though exhibiting a nominal high toughness (in terms of Charpy V-notch energy), showed inadequate resistance to fracture propagation, especially when operated under severe conditions. In the light of that, in order to ensure a sufficiently large safety margin against ductile fracture propagation, the recourse to crack arrestors has been found to be strongly recommended. Unluckily, experimental evidence has proven that the existing PRCI guidelines for CA design, in case of high grade steel pipes, provide unsafe outcomes as clearly demonstrated in the full-scale burst tests conducted by CSM on behalf of ExxonMobil URC [14].

As a consequence, the inadequacy of traditional available PRCI guidelines in designing CA for high strength steel pipelines requires in-depth investigations in order to improve suitable and *ad hoc* CA design methodologies, capable of taking into account the nowadays severe operating conditions and newly available CA designs and types. With regard to this, CSM has implemented into PICPRO® a devoted algorithm able to evaluate the effects of CA constraint on the running crack, thus making PICPRO® an appropriate and reliable numerical tool to describe and predict the fracture behavior in the presence of such devices. The effectiveness of various CA types and geometries can be correctly investigated by using PICPRO® [25].

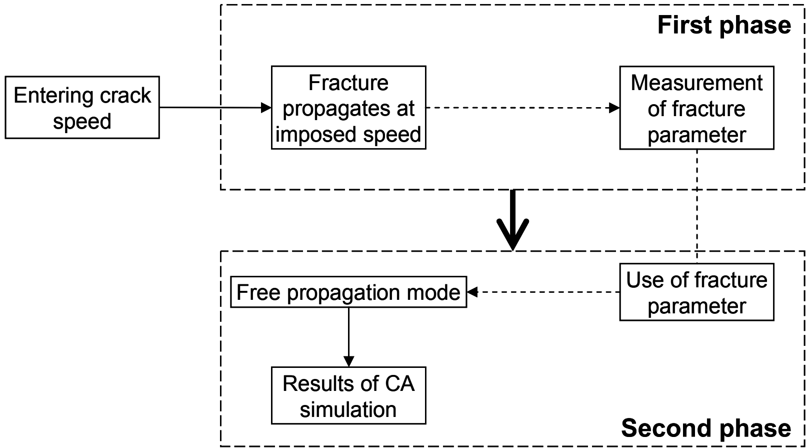


Figure 102. Schematic of Finite Element simulation procedure by mean of PICPRO®.

The main approach to be followed (Figure 12) considers crack propagation at an imposed constant speed. In this phase, just before the crack enters the CA, the specific energy consumed for fracture advance is evaluated and stored in PICPRO® internal database. Thus, in relation to the CA (or immediately before) crack advance is managed in "free" modality: from now on the crack speed is not more imposed but it is the result of the comparison between the energy applied (driving force) and the energy resistance value (which is that previously recorded). When the fracture enters into the CA, the variation in the external constraint can cause, if the CA is properly designed, fracture deceleration until its arrest. This approach also allows one to highlight that situations where the deceleration imposed by the CA is not sufficient to completely arrest the fracture, which starts again to propagate at high speed once the CA is passed through.

In order to demonstrate PICPRO® capability in predicting CA effectiveness in arresting fracture, numerical predictions have been compared with the results of recent experimental full-scale tests carried out on X100-X120 large diameter pipelines, such as the BP test [25], the 2nd DEMOPIPE test and the ExxonMobil test. Comparison between actual and predicted behavior is given in Table 6. It can be observed that not only the general CA fracture behavior (arrest or propagation) is well predicted but the model also provides good precision in terms of the values of the fracture arrest length or exiting propagation fracture speed. As an example, simulation result for the fracture behavior is given in Figure 13.

Moreover, CA optimization can be supported by PICPRO® also to investigate, through a sensitivity analysis, the influence of CA design parameters on the capability to arrest a crack. This approach in practice offers the potential to replace expensive full-scale burst tests with finite element calculations.

Table 6. Comparison between actual and predicted behavior of the CAs tested in the recent full scale burst tests in steel grade ≥X100.

	X100, BP full-scale test		**X100, 2nd Demopipe full-scale test**	**X120, ExxonMobil full-scale test**
CA Type	CRLP	X80 grouted sleeves	Composite	X65 loose sleeve
Predicted behavior	Arrest in the first part (equiv. to pipe wt)	Arrest in the first one	Arrest	Propagation
	Arrest length <0.5m	Arrest length<0.3m	Arrest length<0.5m	Exit fracture propagating speed 300m/s
Actual behavior	Arrest in the first part (equiv. to pipe wt)	Arrest	Arrest	Propagation
	Arrest length~0.3m	Arrest length ~0.5m	Arrest length~0.2m	Exit fracture propagating speed ~309 m/s

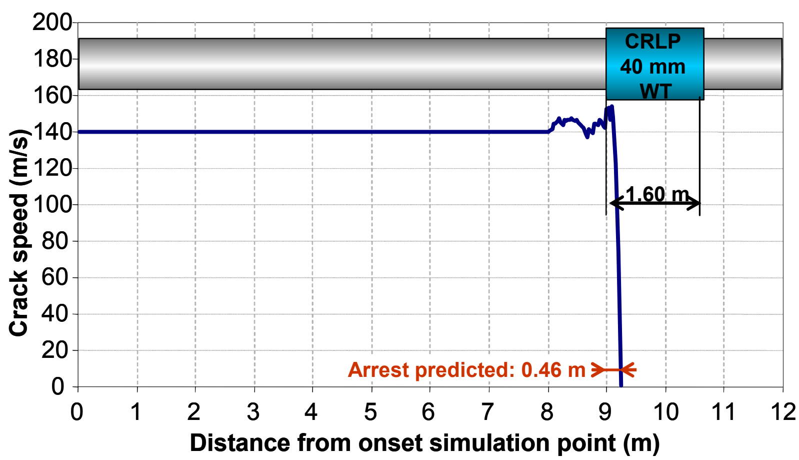


Figure 13. Simulation of fracture behavior for a composite CA. Photo of the CA after the test. (2nd Demopipe test)

Conclusions

A brief review has been presented concerning the results obtained in the last years by CSM in the field of fracture properties assessment of large diameter X100 steel pipes for long distance gas transmission lines. Looking at the results of the extensive full-scale testing activity carried out so far on the various fracture related topics, it appears that the general fracture behaviour of X100 large diameter pipes resulted is substantially good, although a devoted "design" is mandatory to prevent/control the ductile fracture propagation event. Concerning specific fracture issues, some conclusions useful for the safe design of long distance X100 grade gas pipelines can be made.

The Charpy V-notch shelf energy over-estimates the real pipe resistance to the ductile fracture propagation event under full-scale burst test condition; therefore, also the use of "Charpy

V-notch conventional criteria" as the Battelle Two Curve approach is highly questionable for the new materials.

The DWTT specimen, which is full thickness and longer in ligament, was recognized as one of the most promising specimens for properly taking into account the fracture event, and fracture parameters obtained adopting similar specimen (such as DWTT total upper shelf energy value, DWTT propagation upper shelf energy value, or fracture mechanics parameters such as Crack Tip Opening Angle) appear promising, but they are still far from being widely validated for X100 grade pipes.

CSM proprietary code PICPRO® is at present a valid tool for enlarging the information gathered from a single full scale burst test and provides a solution to overcome the problems connected to the lack of a reliable procedure to transfer laboratory toughness results to the real pipe case.

Finally it is possible to assert that X100 large diameter pipes are working on the upper bound of the arrest/propagation ductile fracture propagation boundary. Therefore in the most severe cases, additional crack arrestors are required to ensure safe fracture arrest; thus, in the near future, dedicated work on the use and design of crack arrestors, must be encouraged; with regard to this last point the use of PICPRO® code emerges to be the most promising.

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