Crack arrestors

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ABSTRACT

Full- and small-scale tests have demonstrated the usability of fibre reinforcements as crack arrestors for steel pipelines of higher-strength grades such as X100. In all cases the crack arrestors were able to absorb the energy of the crack to such an extent that the crack was stopped at the crack arrestor or retarded and arrested behind the crack arrestor.

Further experiments have been carried out in order to examine the mechanical characteristics of fibre-wrapped reinforcements of the crack arrestor and the behaviour of such composite components during service. Additional experiments will help to optimise the application of fibre reinforcements. Europipe is now ready to include fibre reinforced crack arrestors in its production program.

KEY WORDS: Reinforced linepipe, full-scale tests, mechanical properties, crack arrestors, fibre reinforcement

1 Introduction

The use of higher grade steel pipelines for gas transmission offers benefits such as higher service pressures or reduced wall thicknesses. However, for ultra-high strength materials (Grades ≥X100) the ability to arrest long running cracks, initiated e.g. by external impact, fatigue, corrosion or other effects such as like earthquakes, landslides or cavities, is limited because the required toughness is on the borderline of or even beyond technical feasibility. This was demonstrated, for example, by full-scale burst tests on grade X100 pipes [1-4]. For similar reasons, crack-arrest capability must also be taken into account at lower service temperatures.

To limit the level of damage occurring in such cases, crack arrestors can be installed at predetermined intervals along the pipeline, so that any propagating crack would be arrested at least within a few pipe lengths under the particular operating conditions, minimizing harm to the environment and pipeline operation.

Europipe intends to supply crack arrestors as a supplement to its linepipe range. The activities examined below were intended to show the usability of crack arrestors, particularly for ultra high-strength linepipe grades, and to find cost-effective and simple ways of evaluating various types of crack arrestors. Type and design, and also investigations of mechanical behaviour, are discussed below.

2 Types of Crack Arrestors

Where it is not possible to achieve crack arrest via adequate toughness of the pipe material or by reduced hoop stresses by using thicker walled pipes of the same grade, crack arrestors have to be used to guarantee safe pipeline operation. In recent decades, various crack arrestor designs have been developed. Nearly all designs aim at preventing the crack flaps from opening up under the influence of gas pressure, thereby reducing the crack driving force [5]. Especially noteworthy are crack arrestors which take the form of a single or multi-part sleeve and are applied around the pipe [6-10]. They range from simple steel bands to thick-walled steel sleeves, where the radial space between the pipe and the sleeve may be filled with a curing material. They do, however, have some disadvantages. Due to the dimensions and weight of sleeves for large diameter pipes, difficulties must be anticipated particularly in handling during production, transport and installation. It is generally necessary to take limits on the economical production of thick-walled pipes or pipe sections into account. Furthermore, special precautions may need to be taken to avoid corrosion at the interface between the pipe and the sleeve [11].

In this respect, light-weight fibre wraps lend themselves to use as crack arrestors, as was proposed and developed by Chabrier [12] and Fawley [13] and described for example in [14]. Europipe therefore selected this type of crack arrestor with the intention of applying fibre reinforcement during pipe production. Their crack arrest ability and behaviour in case of external damage was studied using prototype test bodies on the basis of both small and large diameter pipes.

3 Behaviour under External Impact

Mechanical damage to crack arrestors can occur during transportation, handling or installation of a pipeline, and especially during excavation work, as a result, for instance, impact of an excavator shovel, stone chipping, or sharp objects, such as rocks in the trench. Quasi-static and dynamic tests were performed to simulate and ascertain the effects resulting from such impact on fibre-wrapped crack arrestors.

A crack arrestor consisting of individual glass-fibre rowings with epoxy resin as the matrix, unidirectionally wound in the circumferential direction around a steel pipe (36" x 20 mm, Grade X100) was utilised for this purpose. The wall thickness of the armouring was selected at around 12.5 mm. Individual plates of a base area of 300 mm x 300 mm were then cut out of the crack arrestor.

<u>Dynamic</u> drop tests were performed in order to simulate sudden application of load, such as the impact of a falling stone. These tests were carried out in conformity with a standard procedure for plastic coatings [15], using a 25 mm diameter steel ball attached to a weight with a total mass of 10 kg. The falling weight was dropped from a height of 2 m (producing an impact force of 196 J) on to the exterior of the crack-arrestor material. The result was primary damage of the composite wrap, involving the destruction of fibre/resin composite, in the immediate sub-surface zone (Zone 1 in **Figure 1a**). Secondary damage to the crack-arrestor material was observed in the vicinity of the point of impact (Zone 2 in Figure 1a), with detachment of fibres from the matrix (light areas). The zone of secondary damage extends in the radial direction almost down to the wall of the pipe (**Figure 1b**). A damage zone depth of around 11 mm could be ascertained, equating to approx. 88 % of the thickness of the reinforcement.

In a quasi-static denting test, a plate was positioned on a support ring and an excavator-shovel tooth with a tip radius of 8 mm continuously forced down into the plate perpendicular to the outer surface of the pipe (**Figure 2**). The necessary thrust force and denting depth were recorded during this test. Breakage of the individual fibres led to spontaneous reduction of the force applied (**Figure 3**). The test was stopped when the pipe started to exhibit pronounced denting after penetration of the fibre-wrapping. The deformation of the steel pipe resulted in a detachment of the fibre-armoured part (**Figure 4**). Complete detachment was promoted by the limited dimensions of the test piece; for a real crack arrestor, it can be assumed that the armouring would detach from the steel pipe only in the area of the dent.

A dynamic drop test was carried out using an impact hammer (tip radius R = 25 mm) with a weight of 2800 kg. The hammer was dropped perpendicularly from a height of 1 m onto a test plate as used in the quasi-static test. The plate was also located on a support ring, and the hammer completely penetrated the fibre armouring; breakage of the individual fibres occurred. The steel material of the pipe was dented inward and plastically deformed (**Figure 5**). The maximum force measured was 804 kN, which covers dynamic impact loads possibly generated by typical excavating machines [16]. Denting of the steel pipe also caused detachment of the armouring, as seen in the quasi-static case. Secondary damage, including detachment of the fibres from the matrix (light areas) is also observable here (**Figure 6a**), as also seen in Figure 1b. These zones spread primarily in the direction of the fibres. On the pipe surface (**Figure 6b**) a small gauge could be seen.

Although, only a limited number of tests have been carried out on one type of crack arrestor design, it appears possible to derive some general findings about the behaviour of fibre-wrapped crack arrestors in case of external impact. Destruction of the fibre wrap occurs, depending on impact energy and the geometry of the impact body. In all cases, however, and even in case of complete penetration of the outer wrap, only local weakening takes place, with only slight spread in the circumferential direction. The probability that a propagating crack will hit the damaged areas is, on the one hand, thus low and, on the other hand, the support of the surrounding material is extremely high. An appropriate design of the crack arrestor in terms of thickness and length of the outer wrap will give additional safety.

4 Full-Scale Burst Test

In the scope of the “Demopipe” test program [2], two full-scale bursts tests on Grade X100 pipeline sections were planned and it was possible to integrate a Europipe crack arrestor into the set up of the second test.

On the basis of experience at Salzgitter Mannesmann Forschung GmbH (SZMF, formerly MFI) in connection with the development, testing and production of fibre-reinforced pressure vessels, a simple preliminary design criterion was proposed for the strength distribution between the pipe and the fibre reinforcement. It was such that the hoop stress generated by the test pressure was shared in equal measure by the composite wrap and the pipe. To study and achieve confidence in the chosen design, a trial burst test at a smaller scale had been carried out before manufacturing of the crack arrestor to be delivered for the Demopipe X100 full-scale burst test.

A 50 m long pipeline section of HFI welded pipes of size 291 mm Ø x 10 mm was used to form a test line. The pipes were subjected to a special heat treatment in order to make the longitudinal weld brittle (K_v = 12 J) so that the crack could propagate very rapidly along the longitudinal welds. The test conditions were thus very severe, compared to ductile fracture propagation. The thickness of the aramid fibre outer wrap was about 5.0 mm, with a length of 1610 mm. The crack arrestor was located at a distance of 600 mm from an artificial defect (notch), which was used to achieve controlled crack initiation (**Figure 7**). The test section was pressurized with air up to 25.9 MPa (usage factor 72 %), at which point the crack started spontaneously from the artificial notch. While the propagating fracture with a velocity above 300 m/s was not arrested on the east side (no crack arrestor), the crack arrestor on the west side retarded the long running fracture so that it stopped shortly behind the fibre composite wrap.

This test provided confidence that the design concept of distributing the hoop stress in the crack arrestor equally between the steel pipe and the fibre wrap and a length of the reinforced section of around 1.6 m should be safe, especially with regard to the much lower crack speed anticipated in the case of ductile fracture propagation.

The crack arrestor for the Demopipe test was manufactured, similarly to the one used for the impact tests, using a bare steel pipe of Grade X100 (36" x 20 mm). The glass fibre-composite material used had a tensile strength of 1050 MPa and a linear ultimate elongation of 2.5 %. The thickness of the composite wrap was selected on the basis of the criterion of equal hoop stress distribution between pipe and reinforcement with an additional safety factor of 1.45. A total of sixty individual layers were applied. The total wall thickness of the crack arrestor thus produced was 41 mm ±2 mm (steel + composite wrap). An outer diameter of the fibre-reinforced zone of approx. 37.7" (956.4 mm) thus resulted.

The width of the crack arrestor on the pipe segment was selected in such a way that the length of the pipe segment (2000 mm) supplied was exploited to its maximum. A total crack-arrestor width of 1600 mm thus resulted (**Figure 8a**). Around 200 mm of the pipe on each side of the crack arrestor was not treated with fibre armouring, in order to permit standard welding into a test pipeline and, in addition, in order not to cause any excessive exposure of the outer wrap material to heat during welding.

The crack arrestor described above was then integrated into the arrangement of the second Demopipe X100 full scale burst test in Sardinia (Italy). Nine large-diameter linepipes of external diameter 36" (914.4 mm) and wall thickness 20 mm were used for the construction of a pipeline section. The crack arrestor was applied at the east end of the test line (**Figure 8b**) as a final “safety belt”, while the aim of the test was to achieve crack arrest within both the regular west and east X100 test section. The specific test arrangement is shown in [17].

While the propagating crack on the west side stopped in the pipe material, that on the east side passed through the “plain” X100 pipes and entered the crack arrestor at a speed of about 135 m/s. After roughly 200 mm it was then deflected into the circumferential direction (direction of fibres) and stopped (**Figure 9**). Although not intended by the test arrangement of the Demopipe full-scale burst test, it was demonstrated that fibre-reinforced crack arrestors like the one supplied by Europipe are generally capable of stopping long running-fractures even in ultra-high grade steel pipes under conditions of high pressure (22.6 MPa) and high usage factor (75 %).

5 Small-Scale Tests

The design chosen for the X100 crack arrestor was successful, but more or less on the basis of rule of trial and error, and therefore needs optimisation, especially with regard to cost-effective production. It is to be expected that a major part of the optimisation will be performed by means of computer modelling in the future; the calculation methods will also need experimental verification however. Since full-scale tests proved to be very expensive, small-scale tests were developed to support optimisation of the design of such crack arrestors. In these tests, different designs and load situations can be studied more flexibly and on a much reduced cost-basis compared to full-scale tests. Pipes with a small outer diameter (85 mm) and wall thickness of 2 mm, with geometric ratios similar to those of the dimensions of the large-diameter linepipe, were selected for this purpose. The pipes had a yield strength of 710 MPa.

In a first step, pipe lengths of 2000 mm were chosen for the test arrangement, permitting comparison of different thicknesses, lengths and materials for a fibre wrap on a qualitative basis. In a further stage, the test lines will be equipped with a system for crack speed measurement and will be extended to avoid, for example, the influence of reflected decompression waves; here comparison is made only between crack propagation in the direction of the west and east ends of the test section.

Glass-fibre wrapping was again applied using the endless winding method, and was impregnated with epoxy resin. Variations were tested in terms of number of layers (two and four) and the length of the reinforcement (45 mm and 90 mm). A flaw was machined into the mid-section of the test pipes in the longitudinal direction, and the pipe ends were closed with caps. The flaw dimensions were chosen to cause rupture at an internal pressure of around 12 MPa followed by fractures propagating in the direction of the pipe ends. Compressed air at room temperature was used as the pressure-exerting fluid.

The performance of the pipes containing crack arrestor sections on one side in the rupture test is shown in **Figure 10**. The two layers of composite wrap with a length of 45 mm (Figure 10a) were not able to stop the crack. The outer wrap was completely broken; the crack was arrested by the pressure wave reflected by the end of the pipe. Both the four-layer, 45 mm long (Figure 10b), and the two-layer, 90 mm long composite wraps (Figure 10c) resulted in the arresting of the crack.

It was demonstrated that even the simple test arrangement used for the small-scale tests up to now permits differentiation between various crack arrestor designs. It is anticipated that the intended modification of the test method will produce results adequate for calibration and validating calculation models and for selection of appropriate types of fibre reinforcements.

6 Summary and Outlook

Recent full-scale burst tests have confirmed that, for pipelines of Grades X100 and higher, crack arrestors will most probably be needed to avoid ductile fracture propagation. The use of crack arrestors can also be beneficial in pipelines operated at low temperatures.

Crack arrestors for ultra-high-strength pipes made from steel sleeves have the disadvantage of their great weight and may cause handling difficulties during production and pipe installation. Crack arrestors applied using fibre reinforcement provide the advantage easy handling; application of the fibre wrap can be included in the pipe-production process.

In the case of external impact caused, for example by an excavator shovel or by stone chipping, the fibre wrapping may be damaged; but even in case of complete penetration of the composite wrap, only local weakening occurs; this can be compensated by appropriate reinforcement thickness and length.

Full-scale tests on large and medium-sized pipe diameters have proven the usability of fibre-reinforced pipes as crack arrestors. The crack arrestors tested were designed on the basis of a simple preliminary design concept of distributing the hoop stress equally between the steel pipe and the outer wrap, in the case of the X100 crack arrestor with an additional safety factor of 1.45. They were able to absorb the energy of the crack to such an extent that the crack was stopped at the crack arrestor or retarded and arrested at a short distance behind the crack arrestor. It was shown that fibre-reinforced crack arrestors are generally capable of arresting propagating fractures in ultra-high-strength pipelines (X100) even at high pressures and usage factors.

In future, a major part of the estimation and optimisation of the necessary geometry and mechanical properties of crack arrestors will be performed by means of calculation models, e.g. on the basis of FE analysis; experimental verification and calibration will nonetheless be necessary. Small-scale tests have been developed and will be improved to provide this data in a most flexible and cost effective way. Even a simple arrangement makes it possible to differentiate between various crack arrestor designs.

Europipe intends to include fibre reinforced crack arrestors in its production program for ultra-high-strength steel grades and also for low temperature applications and is ready to cooperate with users on specific applications to further confirm practical usability and optimise the design of crack arrestors

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8 Figures

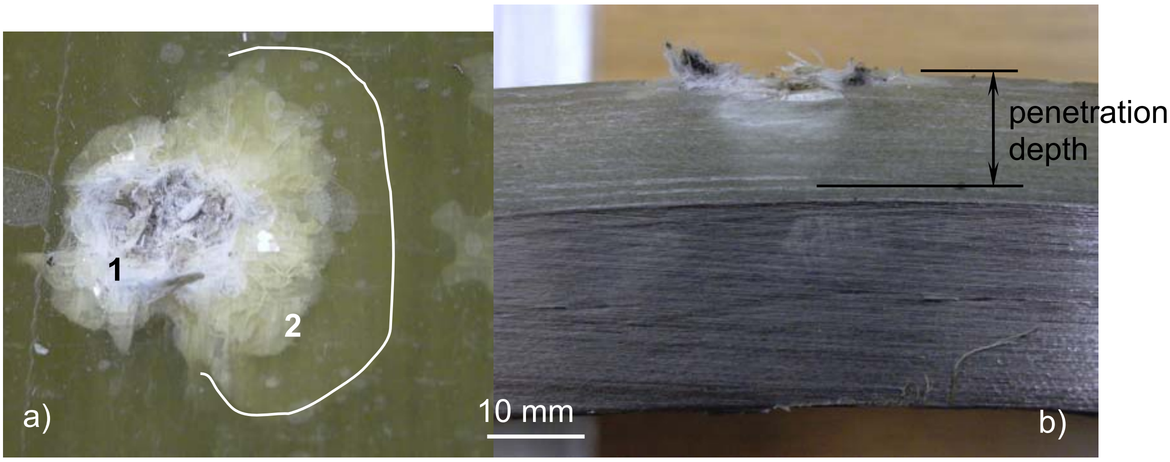

Figure 1: a) Crack arrestor after the ball-impact test showing primary (1) and secondary (2) damaged zone
b) Cross-section of the crack-arrestor zone damaged in the ball-impact test

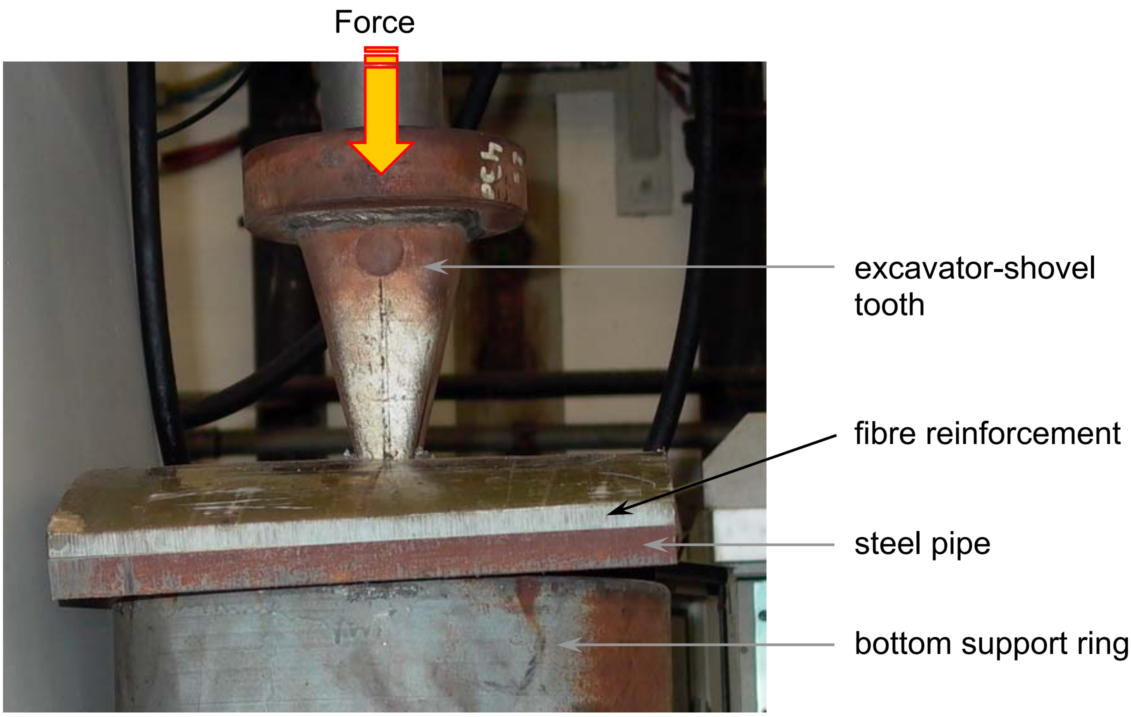

Figure 2: Quasi-static denting test during application of load (excavator-shovel tooth R = 8 mm)

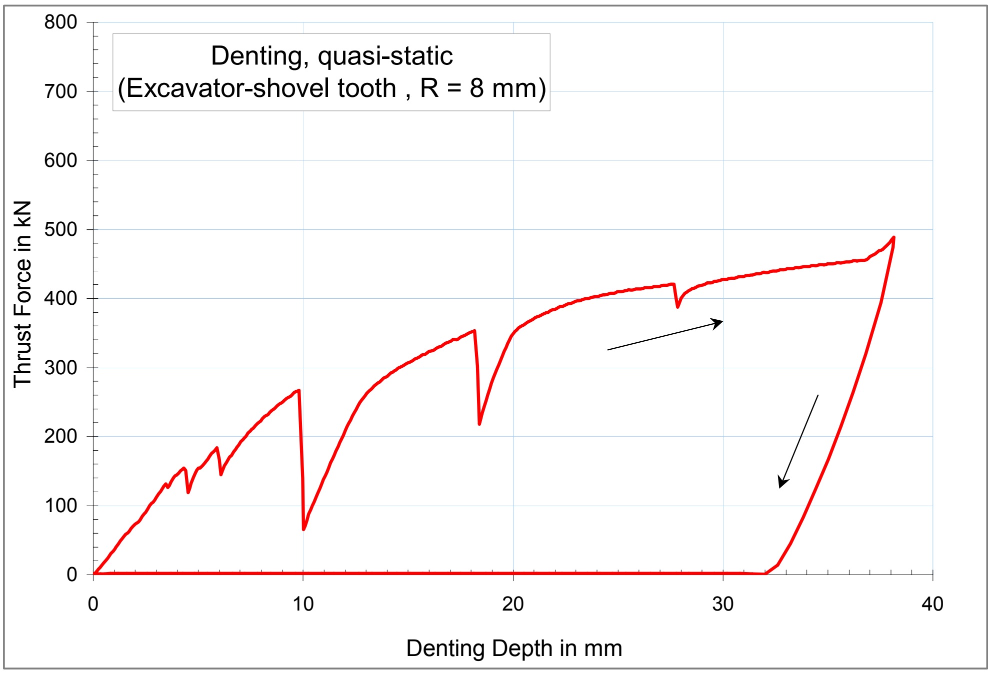

Figure 3: Plot of thrust force as denting depth rises in quasi-static denting test

Figure 4: Crack arrestor after the quasi-static denting test

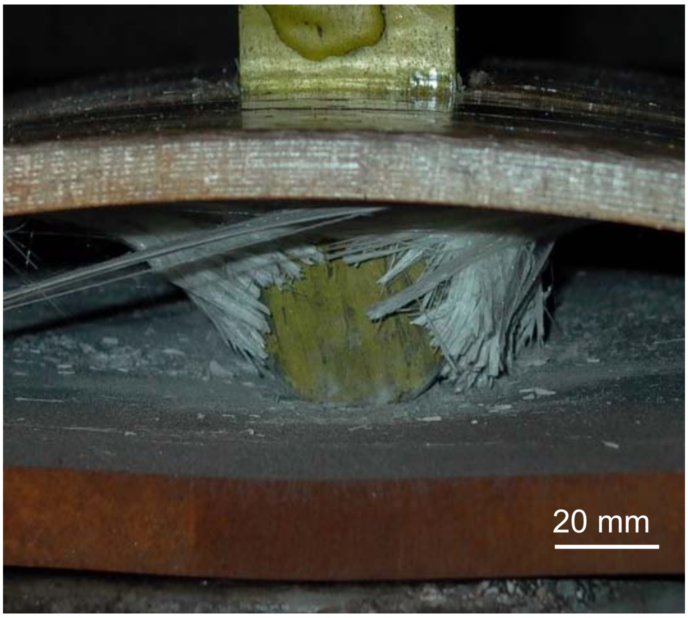

Figure 5: Dynamic drop test after application of load

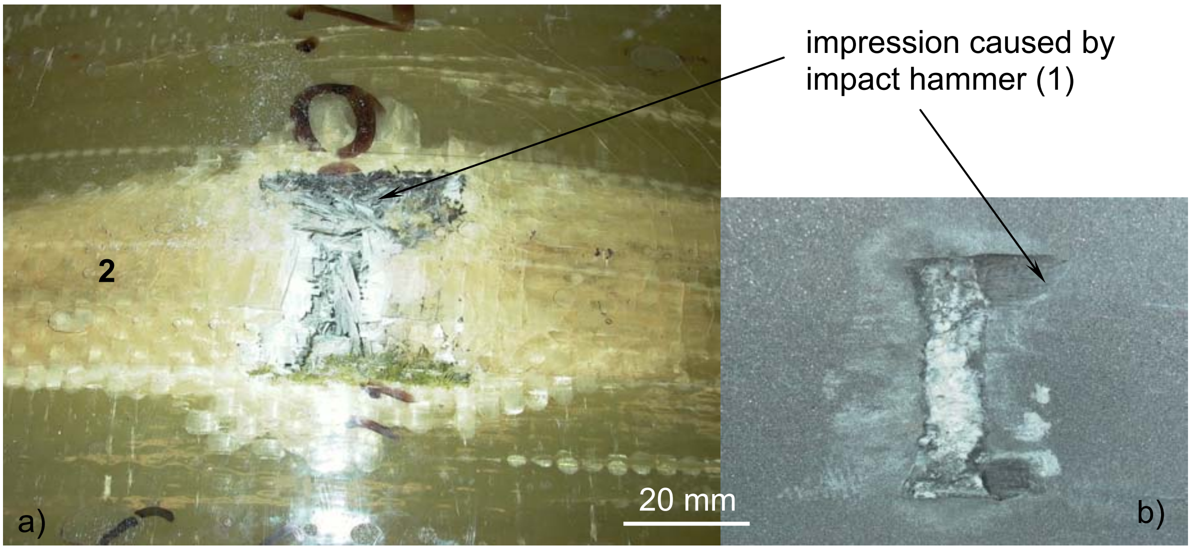

Figure 6: Crack arrestor after the dynamic denting test showing primary (1) and secondary (2) damaged zone; a) Fibre wrap, b) Impression in the outer side of the steel pipe ball-impact test

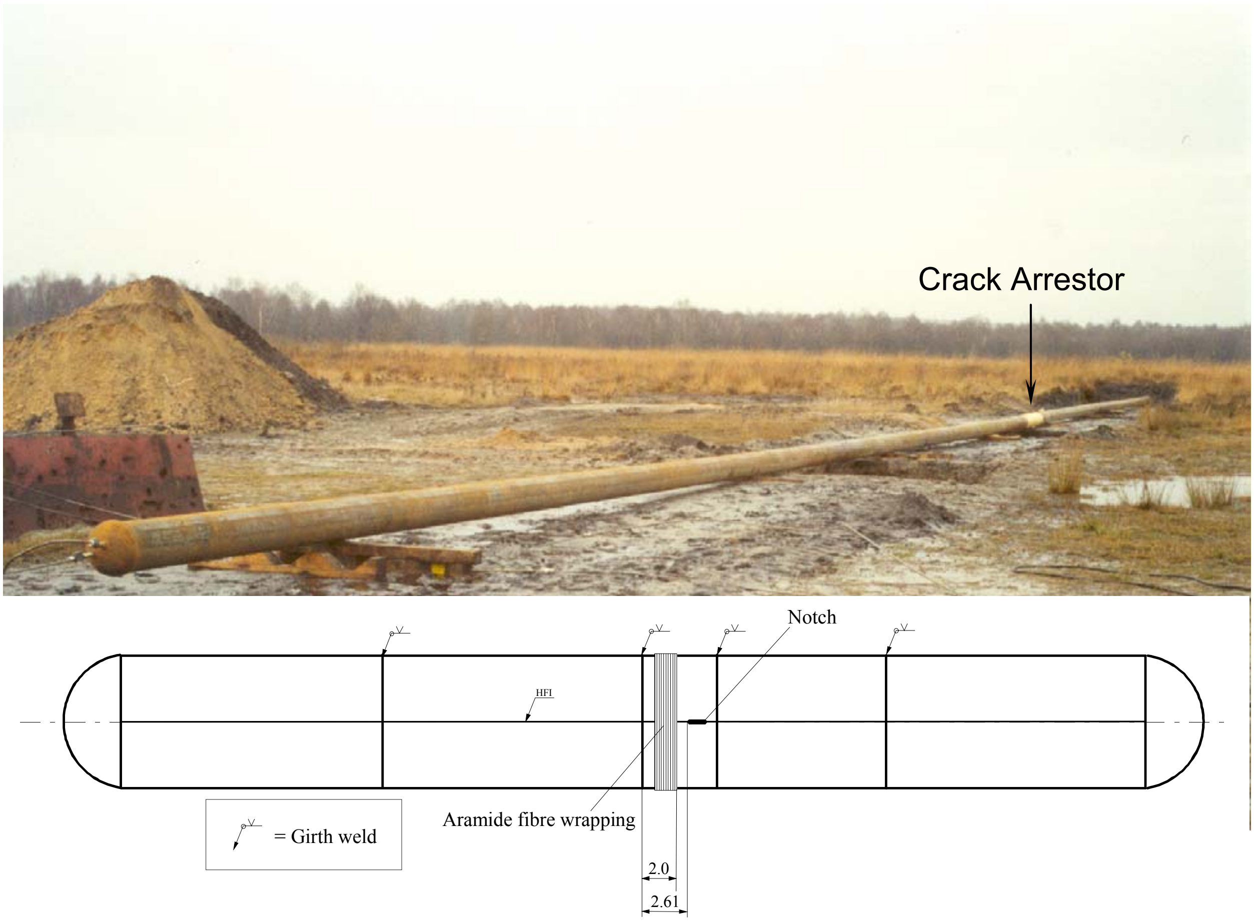

Figure 7: Test setup of the burst test on a HFI pipeline section

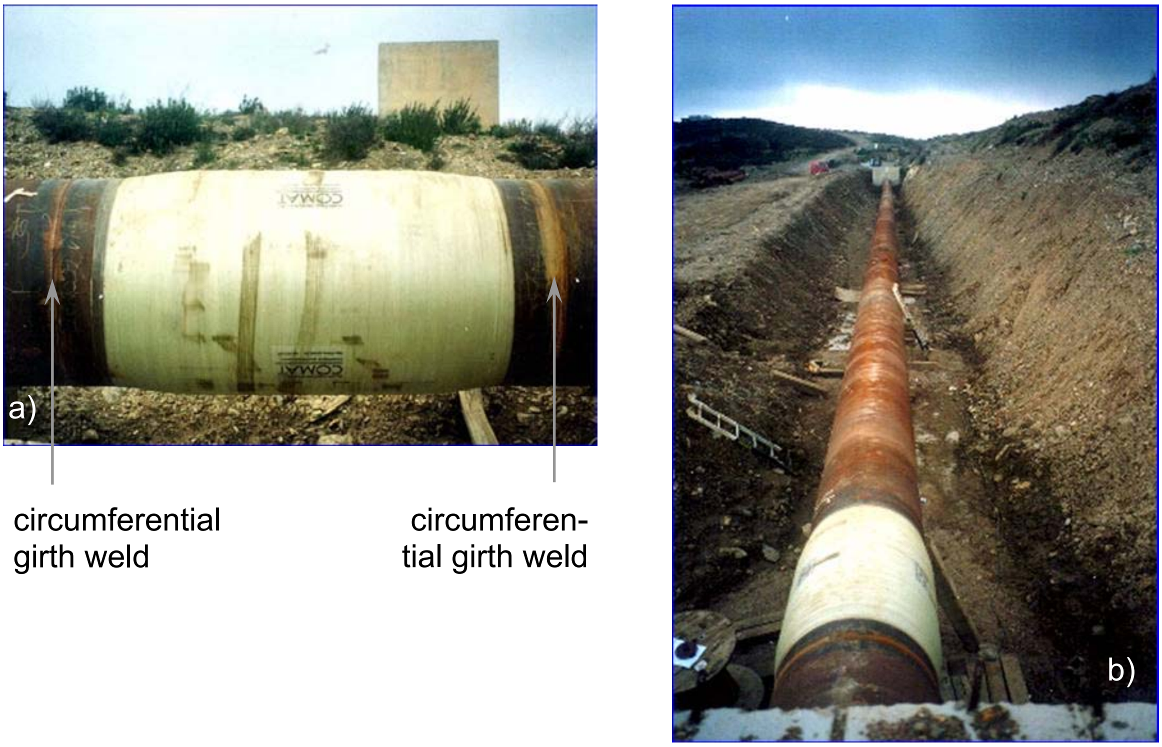

Figure 8: Fibre-reinforced pipe segment following the wrapping process and integrated into the test line (full-scale test)

Figure 9: Crack arrestor after the full-scale test

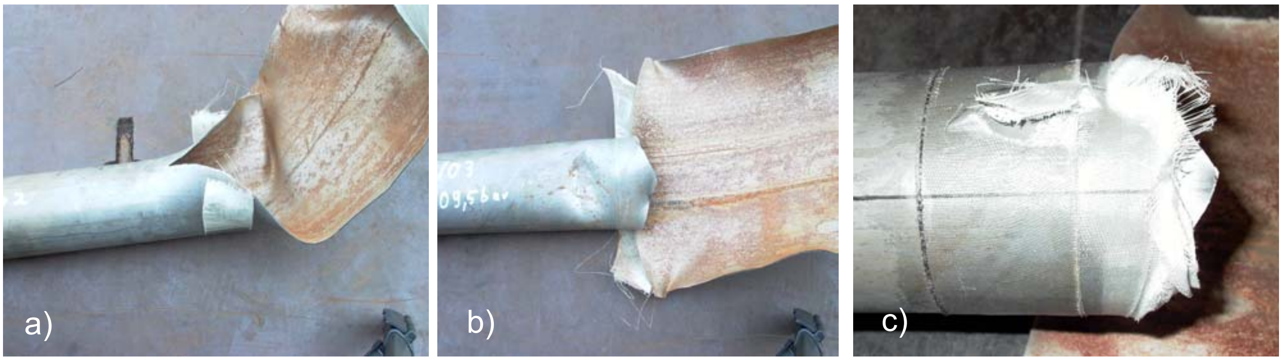

Figure 10: Similarity tests on crack arrest
a) Pipe with two layers of outer wrap (width = 45 mm)
b) Pipe with four layers of outer wrap (width = 45 mm)
c) Pipe with two layers of outer wrap (width = 90 mm)

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