DESIGN OF CRACK ARRESTORS FOR ULTRA HIGH GRADE GAS TRANSMISSION PIPELINES MATERIAL SELECTION, TESTING AND MODELLING

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Abstract

One of the major challenges in the design of ultra high grade (X100) gas pipelines is the identification of a reliable crack propagation strategy. Recent research results have shown that the newly developed high strength and large diameter gas pipelines, when operated at severe conditions, may not be able to arrest a running ductile crack through pipe material properties. Hence, the use of crack arrestors is required in the design of safe and reliable pipeline systems.

A conventional crack arrestor can be a high toughness pipe insert, or a local joint with higher wall thickness. According to experimental results of full-scale burst tests, composite crack arrestors are one of the most promising technologies. Such crack arrestors are made of fibre reinforced plastics which provide the pipe with an additional hoop constraint. In this paper, the material selection, testing and modelling for the design of composite crack arrestors is presented.

First, an overview of the most commonly used (integral and non-integral) crack arrestors is given, indicating that fibre reinforced devices are one the most promising solutions to arrest running fractures. Then, material characterization of unidirectional fibre glass reinforced epoxy is addressed to measure the orthotropic properties of this composite material. Traditional mechanical characterization is compared with a non destructive testing method to measure the elastic constants of the composite material. In the end, micromechanics of fibre reinforced plastics is applied to predict the material properties. The theoretical predictions are compared with experimental values.

In an accompanying paper, numerical tools to simulate crack initiation, propagation and arrest for this type of crack arrestors are introduced. The combination of numerical simulation and experimental research allows deriving design guidelines for composite crack arrestors.

Keywords crack arrestors, toughness modelling, pipeline materials, fibre reinforced plastics, integrity

1 PIPELINE INTEGRITY: A TOUGH CHALLENGE

The occurrence of a longitudinal crack propagating along a gas pipeline is a catastrophic event, which involves both economic losses and environmental damage. Hence, the fracture propagation control is an essential strategy to ensure pipeline integrity. Fracture control is a tough task, since it requires knowledge of the interaction between the dynamic forces driving crack growth, and the resistance forces opposing fracture propagation.

Ductile fracture is typically characterized by wide crack flanks opening, relevant bulging at the crack tip and a large amount of plastic deformation in the vicinity of the flaps. *Brittle* fracture, on the other hand, is mainly driven by the amount of elastic energy stored in the pipe wall, while only a small amount of plastic deformation occurs near the crack tip. In addition, the elastic surface energy is rate dependent at the typical velocities of brittle fracture, which imposes another level of complexity.

The fashion of crack propagation (brittle or ductile) influences the rupture length. The energy required for brittle fracture propagation is low, which makes it very difficult to control brittle fracture once crack initiation has occurred. On the other hand, ductile fracture propagation requires a large amount of energy, and can be arrested in a controlled manner. However, mixed fracture propagation mechanisms may also occur, depending on the operation conditions and temperature. For instance, typical pipeline steels used in arctic regions exhibit an intermediate behaviour between brittle and ductile fracture.

The distinction between ductile and brittle fracture propagation is particularly relevant for gas pipelines, for which the decompression of the gas during failure is an important driving force. Experimental burst tests [1] reveal that the typical crack speed during ductile fracture propagation in steel pipelines does not exceed 350 m/s. Since the acoustic velocity of gas (such as lean gas or rich methane) under the usual operation conditions is in the range of 350 – 500 m/s, the decompression of the pipe is faster than the crack speed. This implies that the local pressure in the vicinity of the crack tip is lower than the initial (operating) pressure, and decreases with decreasing crack speed. On the contrary, the crack speed during brittle fracture is equal to or higher than the acoustic velocity of the gas, so the crack tip experiences the full initial pressure as it propagates, and the resulting driving force is much more severe.

While brittle fracture control is typically achieved by ensuring that the pipeline is operated well above the Ductile to Brittle Transition Temperature, the ductile fracture propagation can be avoided (or at least limited) by increasing the minimum specified toughness of the pipeline steel. However, for ultra high pipeline grades (≥ X100), the identification of a reliable crack propagation strategy is not longer straightforward. Indeed, despite excellent toughness values at lab scale (Charpy upper shelf energy and Battelle shear fracture area), one can no longer rely on pipe body arrest [1-3]. As a result, additional mechanical devices such as crack arrestors have to be mounted on the pipeline in order to stop a running ductile crack.

2 REVIEW ON CRACK ARRESTORS FOR HIGH PRESSURE GAS PIPELINES

Although a clear distinction can be difficult, crack arrestors are usually classified as either *integral* or *non-integral*, according to their installation procedure. Integral crack arrestors are inserted in the pipeline, and act as an integral part of the system, while non-integral crack arrestors are made of several parts, assembled externally onto the pipe. In this section, the most commonly used crack arrestors for high pressure gas pipelines are reviewed.

2.1 Integral crack arrestors

Integral crack arrestors are generally made of pipes and/or rings with mechanical or geometric properties different from those of the main line. The aim to arrest a running fracture can be achieved by

- increasing fracture resistance (e.g. lengths of higher toughness line pipe)
- decreasing relative driving force (e.g. lengths of heavier wall pipe)
- inducing ring-off (e.g. lengths with weaker spiral seam weld)

Inserting lengths of *high toughness pipe* with the same wall thickness as the main pipeline, like schematically shown on Figure 1, is one of the most simple and straightforward forms of integral crack arrestors.

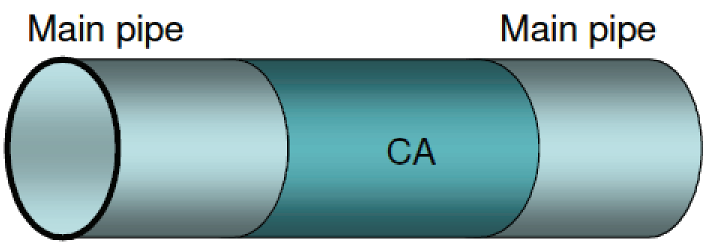


Figure 1: Inserting high toughness pipe as integral crack arrestor

In order to assure a good effectiveness of the crack arrestor, the decrease of the crack speed has to be sufficiently high to achieve arrest within the crack arrestor, which requires fracture resistant properties (much) higher than the main pipe. If the toughness of the insert is not adequate, the crack may exit from the arrestor and propagate further down the line. Moreover, since ductile fracture propagation could initiate at *any* location (e.g. in a remote pipe, but also in a pipe adjacent to the crack arrestor), the device should be capable to cope with the adverse event of a crack initiating nearby, where the crack driving force (governed by the initial pressure) is higher than under steady state conditions.

Heavy wall pipe inserts used as crack arrestors, like shown on Figure 2, are somewhat similar to the high toughness pipe inserts described above. The arrest concept involves a hoop stress reduction in the thicker pipe that has sufficient toughness to cause fracture arrest within the specified crack arrestor length. The required toughness should promote arrest in about half the length of the crack arrestor.

Typically, such a pipe would be manufactured to controlled outer diameter (OD) tolerances, with the excess wall thickness on the inside. However, a pipe with a constant inner diameter (ID) with excess wall thickness at the OD can also be produced, solving possible problems associated with in line inspection and fluid dynamics.

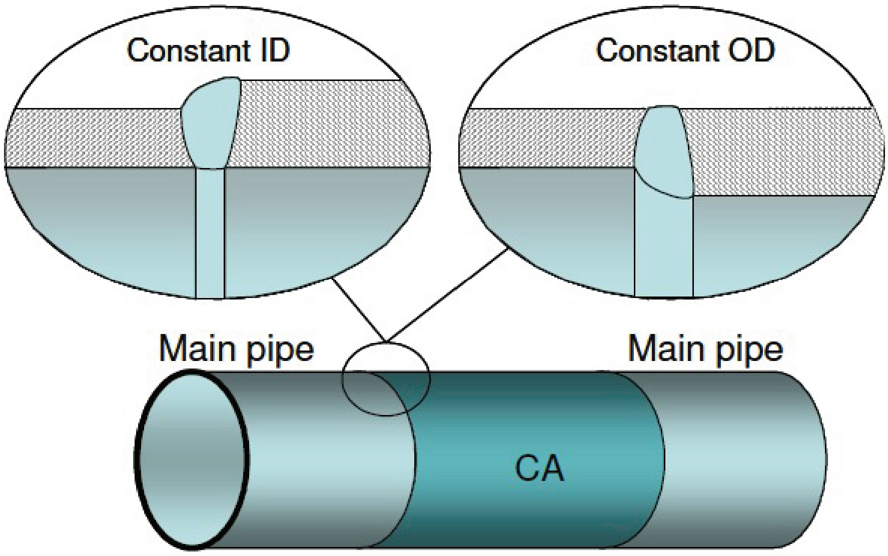


Figure 2: Heavy wall pipe inserts

Other integral devices consist of *layered pipe lengths* with helical mid-layer slits or notches, which deviate the crack path and dissipate crack propagation energy. Inserts with weaker spiral seam weld or brittle girth welds can be used [4] to induce pipe ring-off. New, but less proven, crack arrestors consist of short inserts of girth welded sections with alternating brittle and high toughness segments, to divide the propagation energy into multiple cracks that run through the brittle sections, but lack the axial orientation and energy to re-initiate in the high toughness segments.

Recently, a *Composite Reinforced Linepipe* (CRLP) system has been developed from the patented glass fibre reinforced resin technology of NCF industries [5]. The CRLP system consists of E-glass fibres drawn through an iso-polyester resin, and wound round the external surface of the main steel pipe. The wall thickness of the pipe is reduced to approximately half of the thickness required by conventional design codes, and the reinforcement is applied and auto-frettaged during hydrotesting. As a result, the steel pipe is under compression and the composite material is under tensile stress in the hoop direction, prior to pressurizing the whole line. The CRLP system is designed to be operated at pressure values that correspond to less than 40% of the ultimate strength of the composite to ensure long-term durability.

Pipe manufacturers have designed their own *composite crack arrestors*, based on similar concepts. Europipe, for instance, used the composite crack arrestor shown on Figure 3 (40 mm by 2 meter) on a 36" pipe that was used in the Demopipe full-scale burst test [6].

In general, integral crack arrestors (particularly composite arrestors and those obtained from pipes with greater thickness and/or toughness) have the advantage of easier assembly during the pipeline field construction, although they are more difficult to use on already existing lines. A possible alternative is the use of a composite crack arrestor wrapped around the pipe with an imposed pre-stress. This would permit to increase the crack arrestor bearing capacity under the same wall thickness, hence giving a higher effectiveness in arresting a propagating crack.

Figure 3: Composite crack arrestor used in the Demopipe project

2.2 Non-integral crack arrestors

The competitive advantage of non-integral crack arrestors is the capability of being assembled externally to the pipeline. Hence, they are recognized as particularly adequate for intervention on already existing pipelines, since no considerable operative shutdown or large interventions are required.

As early attempts for developing external crack arrestors, several devices of similar design have been conceived, including *multi-strand wire ropes*, single strands of small diameter (~ ¼") wire, or rod that is wrapped around a pipeline to restrain the pipe deformation and flap opening associated with a running ductile fracture. The latter one, shown on Figure 4, can consist of one or more rods and has also been described as a *toroidal* crack arrestor [7]. *Steel rope* and steel thread crack arrestors are realized by winding a steel rope or thread around a portion of the pipeline. Steel rope devices, like shown on Figure 4, have been patented since the seventies by CSM [8].

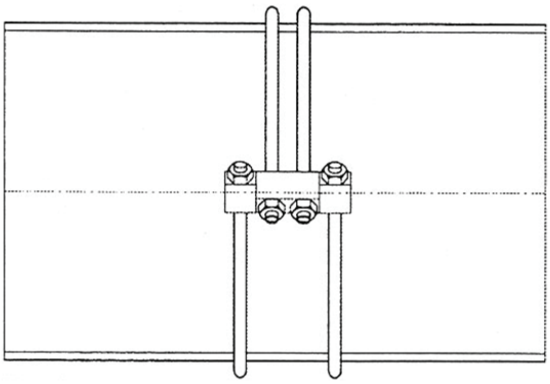
Toroidal crack arrestor [9]	**Steel rope crack arrestor [8]**
	

Figure 4: Examples of different external crack arrestors

Various types of *weights* (like lead, concrete, etc) have been proposed [10] as they increase the restraining force of the flap opening associated with a ductile fracture propagation by adding mass to the pipe wall. Although some of them were successfully tested, they do not offer a practical approach and have never gained wide application in service.

Cast iron clamps have been suggested [11] as a ductile fracture control method as well. These clamps are bolted around the main pipe like indicated on Figure 5, and supply the line with a constraint to the deformation associated with a running ductile fracture. As these devices are exposed to soil conditions, they may suffer from accelerated corrosion, which triggers the need for coating and long term protection.

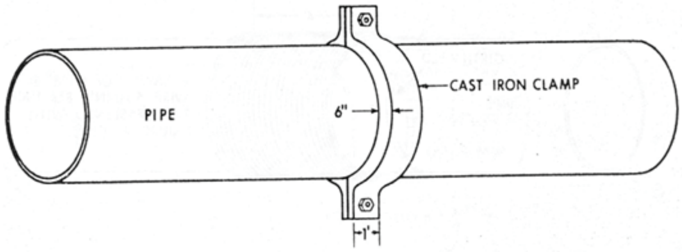


Figure 5: Cast iron clamps as crack arrestor [11]

The most acknowledged and commonly used non-integral arrestors are steel sleeve crack arrestors and Clock Spring. Steel sleeve crack arrestors, shown on Figure 6, are classified as

- *Tight sleeves*, which are placed around the main linepipe with a close-fitting connection. Since no gap is allowed between the pipe and the arrestor, their installation is not straightforward.
- *Loose sleeves* and *grouted sleeves*, which have a radial clearance with respect to the pipe. For grouted sleeves, the gap is filled by cement mortar or epoxy resin.

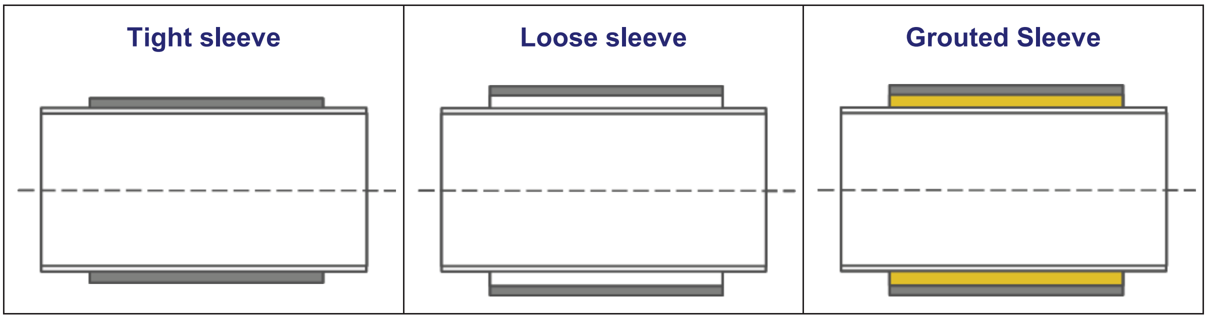


Figure 6: Classification of steel sleeve crack arrestors

Clock Springs, developed and patented by NCF Industries [12], consist of wound ribbons made of fibre glass dipped in a resin matrix. Such ribbons are wound around the pipe, and their clamping is ensured by an elastic spring-back component, like shown on Figure 7. Thanks to the ease of transportation and assembly on existing pipelines, Clock Springs are especially suitable as repair systems and crack stoppers. Moreover, since their application does not require an interruption in the pipeline service, they offer an adequate solution for those cases where operative pressure reduction is not feasible or allowable [13].

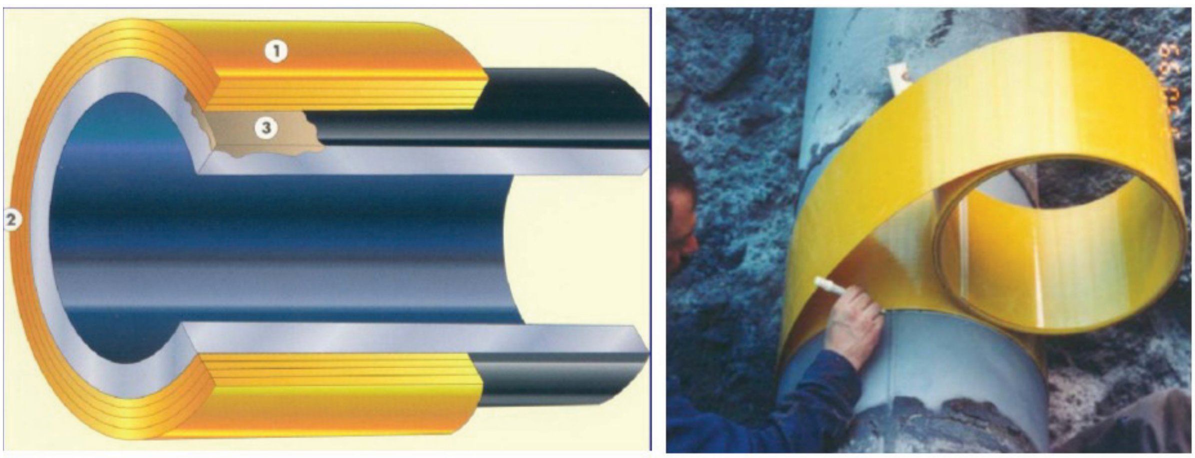


Figure 7: ClockSpring crack arrestor (1: composite coil, 2: adhesive and 3: filler)

2.3 Design criteria for crack arrestors

Given the wide variety of crack arrestor typologies, geometries and properties, no single set of design guidelines can be developed to account for *every* crack arrestor. Moreover, no design criteria exist and only very limited experimental data is available for crack arrestors designed to deviate running cracks into a helical path. As a result, this type of crack arrestors is not frequently used in the industry.

The design of *integral* crack arrestors mainly consists in defining the adequate wall thickness, length and/or toughness values to assure fracture arrest. Since integral devices act within the line, their design can be achieved by using similar predictive tools normally used to outline the ductile fracture propagation control of the main pipe, e.g. the Charpy based Battelle Two Curve method [14-15].

For *non-integral* crack arrestors, design guidelines have been proposed by the Pipeline Research Council International PRCI [7]. In addition, an alternative approach has been proposed by Leis [16].

Today, numerical methods like finite element analysis are commonly used in the design of crack arrestors [2]. In [17-18], a combined numerical/experimental approach is presented to design composite crack arrestors.

First, micromechanics of fibre reinforced plastics is applied to predict the properties of the composite material. The micromechanical predictions are compared with experimental values. Then, orthotropic failure measures are introduced to describe the onset of material failure under complex loading patterns. In addition, the in-use behaviour of composite crack arrestors is evaluated by means of large scale tensile tests and four point bending experiments. In the end, computational fracture mechanics is applied to simulate crack propagation and arrest. The combination of numerical simulation and experimental research allows deriving design guidelines for composite crack arrestors.

3 COMPOSITE MATERIAL MODELLING AND EXPERIMENTAL VALIDATION

For this investigation, a composite crack arrestor made out of unidirectional glass fibre reinforced epoxy was selected as the best compromise between mechanical performance and cost considerations. For such fibre reinforced plastics, the material properties depend on the fibre orientation. The most commonly used composites are *orthotropic* materials, requiring 9 independent elastic constants to define the compliance matrix. When unidirectional (UD) glass fibre reinforced epoxy is used, the constitutive law reduces to *transverse isotropy*, where only 5 constants are to be determined to build the stiffness matrix [19]. In this section, the properties of the composite material under study are determined by means of traditional mechanical characterization, non destructive testing and micromechanical modelling.

3.1 Mechanical characterization

Due to the orthotropic nature of unidirectional glass fibre reinforced epoxy, the elastic properties of this composite material are not straightforward to measure. An extensive testing program has been completed to characterize the composite material by means of tensile tests, compression tests and rail shear tests. This experimental program is documented in detail in [20], and the results are summarized in Table 1.

Table 1: Orthotropic properties of unidirectional glass fibre reinforced epoxy

E_1^T 36.4 GPa	E_2^T 8.5 GPa	E_1^C 35 GPa	E_2^C 6.5 GPa
X^T 700 MPa	Y^T 7.2 MPa	X^C 588 MPa	Y^C 42 MPa
G_{12} 3 335 MPa	S 30.1 MPa	R 30.1 MPa	

3.2 Non destructive testing

The in-plane elastic properties {E_1, E_2, ν_{12}, G_{12}} can be determined by a dynamic modulus identification using resonant frequencies [21]. Both the determination of the real part (elastic constants) and the imaginary part (damping behaviour) are based on the measurement of the vibrational response of a rectangular test plate, submitted to a controlled excitation. A test plate is suspended on a frame with elastic threads, simulating completely free boundary conditions. The plate is then excited by an impulse with a hammer. The vibration amplitude of the plate as a function of time is monitored by the data acquisition system. The resonance frequencies of the plate in the band of interest are detected by taking the Fast Fourier Transform (FFT) of the signal. Then, a sinusoidal signal with a frequency coinciding with each resonance frequency is sent to a loudspeaker, acoustically exciting the test plate. The decay of the signal allows extracting the modal damping ratios and the mode shapes associated with the resonance frequencies.

Figure 8 shows a typical Frequency Response Function (FRF). Such a signal is a frequency domain function expressing the ratio between the response signal (output) and the reference signal (input). The peaks in the FRF indicate that low input levels correspond to high response levels, which reveals resonance frequencies. The corresponding mode shapes (torsion, saddle and breathing) are shown as well.

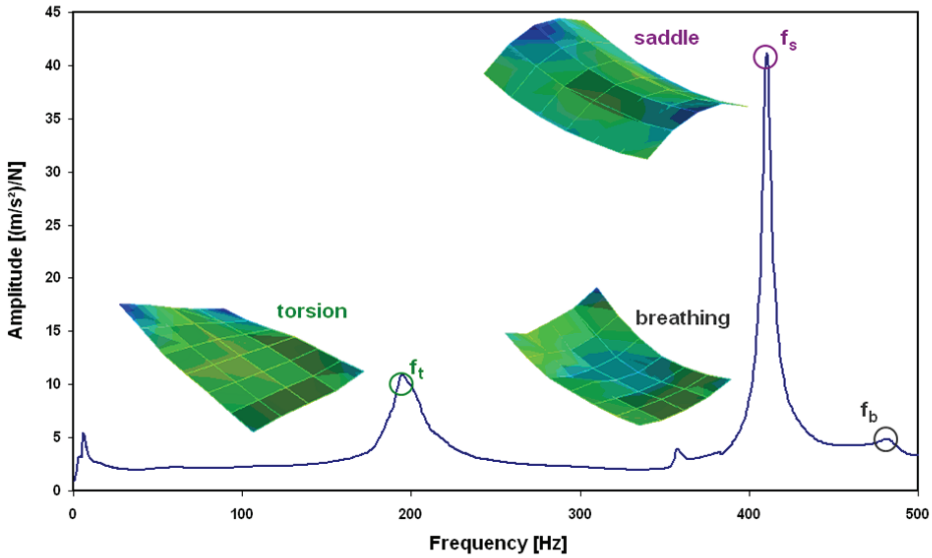


Figure 8: Measured frequency response function and mode shapes

The measured frequencies are compared with the computed resonance frequencies of a numerical parameter model of the test plate. The parameters in the model are the unknown elastic properties. Starting from an initial guess, the parameters of the numerical model are tuned until the computed resonant frequencies match the measured ones. This tuning technique is a Bayesian parameter estimation method, based on the sensitivities of the resonant frequencies for parameter changes. The obtained elastic material properties are homogenised over the plate surface, and hence suitable as averaged input values in finite element models for composite structures like crack arrestors.

Table 2: Comparison between mechanical and non destructive testing

		TRADITIONAL	NON DESTRUCTIVE
E_1	[MPa]	36 400	44 200
E_2	[MPa]	8 500	11 400
G_{12}	[MPa]	3 335	4 420
ν_{12}	[-]	0.32	0.356

The non destructive testing (NDT) methodology is described in [22], and the results of the NDT experiments are compared with the values measured in the traditional mechanical tests in Table 2. The tensile test results yield stiffness values which are considerably lower than the non destructive test results. The rail shear test gives a rather low value for the shear modulus as well. The NDT method tends to over-estimate the values measured in the traditional experiments. Indeed, non destructive testing will typically give higher stiffness values because

- It allows measuring the virgin material properties. When performing traditional mechanical testing, sample preparation can already induce microscopic damage, leading to a lower stiffness and strength. Moreover, the effects of slip are avoided when performing NDT, again resulting in higher (and more accurate) estimates for the elastic constants.
- It measures the global (homogenized) properties of a composite structure, rather than the local stiffness of a small specimen, which can exhibit quite some scatter. Hence, the NDT results are recommended as input values for finite element simulations of crack arrestors.

3.3 Micromechanical modelling

Micromechanical models are used to calculate the elastic constants of composite materials, based on the properties of the (glass) fibre and the (epoxy) matrix. The properties of the constituents, and their volume fraction, are listed in Table 3.

Table 3: Properties of the glass fibre and the epoxy resin

	E-GLASS FIBRE	EPOXY RESIN
Stiffness	E_f = 74 GPa	E_m = 3.5 GPa
Poisson	ν_f = 0.3	ν_m = 0.35
Density	ρ_f = 2 555 kg/m³	ρ_m = 1 175 kg/m³
Tensile strength	X_f = 3.45 GPa	X_m = 60 MPa
Volume fraction	V_f = 0.6	V_m = 0.4

A detailed review of micromechanical mixture rules for fibre reinforced plastics was presented in [23]. The results of those calculations are summarized in Table 4. While the Voigt rules of mixtures are generally accepted [24] as a good approximation of the longitudinal stiffness E_1 and the Poisson coefficient ν_{12}, the Reuss series model provides merely a lower bound for the transverse modulus E_2 and the shear modulus G_{12}. Tsai [25] predicts a very high value for the shear modulus G_{12}.

Table 4: Micromechanics of unidirectional reinforced laminates

	E_1 [GPa]	E_2 [GPa]	ν_{12} [-]	ν_{23} [-]	G_{12} [GPa]	G_{23} [GPa]
Voigt-Reuss	45.8	8.17	0.32		3.033	
Puck-Foye	45.8	14.86	0.32	0.389	5.497	5.349
Greszczuck	45.8	13.2	0.32	0.389	5.960	4.750
Hashin	45.8	13.5	0.317	0.343	4.436	5.027
Tsai	45.8	14.66	0.313	0.389	7.956	5.274
Halpin-Tsai	45.8	14.98	0.32	0.319	4.436	5.677

In order to evaluate the performance of the different micromechanical models, a comparison with the experimental data (i.e. the elastic constants obtained by the NDT method, listed in Table 3) is shown on Figure 9. The Voigt parallel model provides an excellent approximation for the longitudinal stiffness E_1, and a good one for the Poisson coefficient ν_{12}. The Reuss mixture rules provide a lower bound for E_2 and G_{12}, but do not correspond well with the experimental data. Only Greszczuck [26] and Hashin [27] give a reasonable estimation for the transverse modulus E_2, and the shear stiffness G_{12} is predicted very well by both Hashin and Halpin-Tsai [28]. The other authors overestimate the shear stiffness considerably.

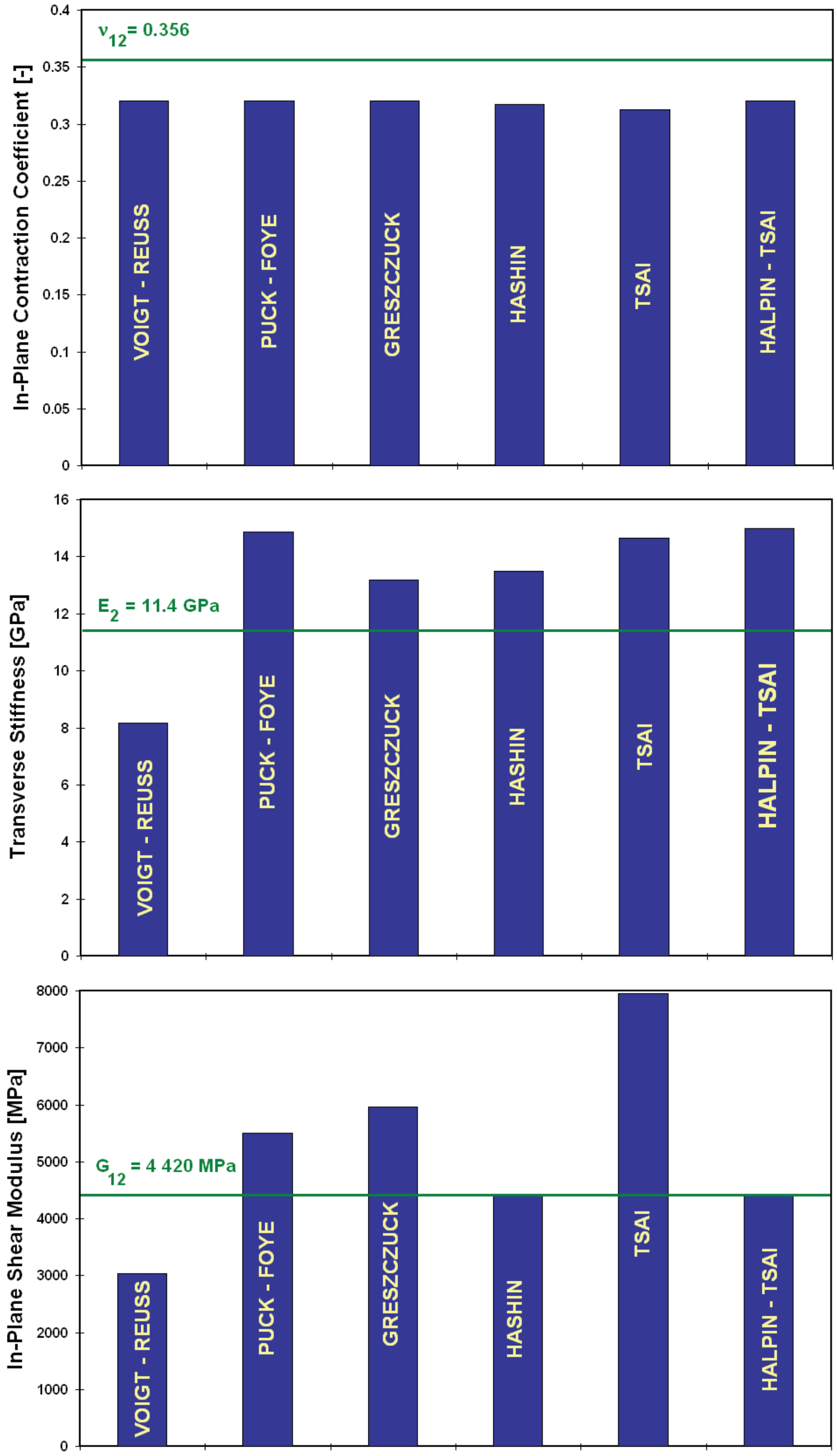


Figure 9: Comparison between the different micromechanical models

When considering the four in-plane elastic constants $\{E_1, E_2, G_{12}, \nu_{12}\}$, the Hashin model –which has been derived for unidirectional reinforced composites- shows the best overall agreement with the non destructive test results.

4 CONCLUSIONS AND OUTLOOK

In this paper, the requirements for material selection, testing and modelling were reviewed for the design of crack arrestors for ultra high gas transmission pipelines. First, a review on different types of crack arrestors and their application was presented. Crack arrestors are usually classified as integral or non-integral, the first one consisting of (parts of) pipes acting as an integral part of the line, whereas the latter type is being made of mechanical devices mounted externally onto the pipeline. According to experimental results of full-scale burst tests, steel sleeve arrestors and composite crack arrestors are the most promising technologies.

For composite arrestors, unidirectional glass fibre reinforced epoxy was identified as the best balance between mechanical properties and cost considerations. Traditional mechanical characterization was performed to determine the orthotropic properties: both tensile tests, compression tests and three rail shear tests were conducted in fibre direction and in transverse direction. The in-plane elastic properties were determined by a dynamic identification technique using resonant frequencies. This non destructive method compares the measured vibrational response of a rectangular test plate with the computed frequencies of a numerical parameter model of the plate. The unknown material properties of the numerical method are optimised until convergence is reached. The obtained elastic properties are homogenised over the plate surface, and hence suitable as averaged input values in finite element models for composite structures like crack arrestors.

In the end, several micromechanical mixture rules were evaluated to calculate the elastic constants of the unidirectional laminate, based on the properties of the (glass) fibre and the (epoxy) matrix. The Hashin model –which has been derived for unidirectional reinforced composites, shows the best agreement with the experimental data.

In an accompanying paper [18], numerical techniques to simulate subsequent crack initiation, propagation and arrest are introduced. The combination of numerical simulation and experimental research allows deriving design guidelines for composite crack arrestors.

5 ACKNOWLEDGEMENTS

The research results, presented in this paper, were obtained in the scope of the LINESPEC project on *Special Components and Strain Based Requirements for High Strength High Pressure Pipeline Applications*. This project is funded by the Research Fund for Coal and Steel (RFCS).

The authors gratefully acknowledge the support of the project partners BP, SZMF, Corus, ISQ, RWTH and the Soete Lab (UGent).

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