Thoughts Towards an Effective Crack Arrestor Design for CO_2 Pipelines

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Abstract

Over the past 30 years, composite repair technologies have changed the landscape of pipeline repairs. Composites have reinforced many defects, including corrosion, cracks, dents, and vintage girth welds. Composite crack arrestors have also played a role in this period. However, their use in this capacity has not been as widespread as in structurally reinforcing pipelines as part of integrity management programs. Interestingly, the Clock Spring technology was initially developed as a crack arrestor; however, the pipeline industry could conceive alternative uses for composite reinforcing technologies that spawned one of the fastest-growing technology applications in the pipeline industry.

Composite crack arrestors have been proven to effectively arrest brittle and ductile running fractures, primarily focused on high-pressure gas transmission pipeline systems. This has been validated via full-scale testing on high-energy pipes. Design guidance needs to be provided to the pipeline industry for how a composite crack arrestor should be designed. The approach employed by most researchers has been to design and install a robust arrestor and then conduct testing to validate its ability to arrest running fractures experimentally. The composite crack arrestor design is considered successful if it stops the running fracture. Although the science behind modeling fracture is well understood, gaps exist in arresting running fractures using composite materials using a well-thought-out design process. Methodologies have established a “qualified” approach rather than a “quantified” approach for design. This paper presents a framework for using composite materials as crack arrestors to arrest running fractures when transporting either CO_2 in the gas or dense phases. This framework could be helpful for pipeline companies seeking to build new pipeline systems or convert existing assets to CO_2 service.

Introduction

The use of composites for pipeline repair has been well-established in the oil and gas industry. Industry experience has matured and developed the appropriate “know-how” to ensure repairs using different types of composite materials based primarily on carbon fiber as well as glass fiber. As the energy transition starts to be developed, challenges regarding CO_2 transport using pipelines for carbon capture and other commodities, such as transporting hydrogen, have begun to be considered. Government, industry, and academia have been working together this past year to evaluate gaps and ensure safe transport of CO_2 through pipelines[1,2,3,4]. Among the gaps analyzed, fracture control against ductile fracture and propagation for repurposed and new pipelines are currently being evaluated. When pipelines do not have enough toughness to prevent a crack from propagating, the use of composite crack arresters is warranted. This paper provides a framework including methodology and historical background for the development of mixed crack arrestors for CCUS.

Assessment of Key Design Factors

An assessment of key factors for designing composite crack arrestors is presented. The four design category considerations are in parentheses at the end of each bullet, including design, installation, service life, and operational threats.

- Material properties for the composite material, including elastic modulus and strain-to-failure (design)
- Pipe properties – primarily toughness (design)
- Temperature limitations of the composite material (design)
- UV degradation (installation)

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- Cure of resin (installation)
- Pipe interaction, including cyclic service (service life and operational threats)
- Defects in the pipeline located beneath the crack arrestor (service life and operational threats)
- Outside damage or force imparted to the crack arrestor (service life and operational threats)
- Energy associated with a CO_2 release (service life and operational threats)

Crack arrestor considerations - gas vs. dense phase CO_2 transport

Notably, the requirement for composite crack arrestors will significantly differ between transporting gas phase or dense phase CO_2. It is expected, though, that, for the most part, the pipes that will be repurposed for transporting CO_2 will do so primarily in the gas phase. Therefore, the requirements presented in this paper will focus mainly on the ones for transporting gas phase CO_2.

Historical Background

A historical perspective on composite crack arrestors and current thoughts related to design considerations are presented. Historical background on crack arrestors and their impact on fracture management programs include:

- Critical design elements associated with composite crack arrestors.
- Suggestions for design validation.

Before discussing specific aspects associated with composite crack arrestors, it is essential to address the concepts of "hard" and "soft" crack arrestors. When a high-energy CO_2 pipeline fails in a catastrophic manner, the fracture can occur in one of two extremes. One manner is the pipeline opening and flattening, as shown in Figure 2, taken from a small-scale test on a 6-inch diameter pipe. In this condition, it is possible for fractures to run long distances, including thousands of feet. Another option is for the pipe to separate, or part, such that the exiting gas acts to generate significant levels of thrust where the pipe catastrophically separates and often some section of the pipe launches from its buried condition. Sometimes, pipeline operators do not want the pipeline to fail in this manner, and using a soft crack arrestor can help ensure the pipe does not part.

Unfortunately, limited resources are available in the open literature discussing the subject of soft vs. hard arrests, although the work completed by Alexander et al.[5] provides valuable insights on how to vary certain design variables to achieve either a hard or soft arresting condition. Figure 3 shows a photograph from a test showing a "hard" arrest where the fracture was stopped before running into the composite. Conversely, a "soft" arrest is depicted in Figure 3, where the fracture is arrested within the confines of the composite material itself. The composite designs for these two different composite technologies were notably different. For a "soft" arrest to occur, the stiffness of the modulus must be low enough so that the stress state in the pipe adjacent to the composite is not appreciably different than it is far away from the installed crack arrestor, but it must be stiff enough to arrest the running fracture once it makes impact with the composite material.

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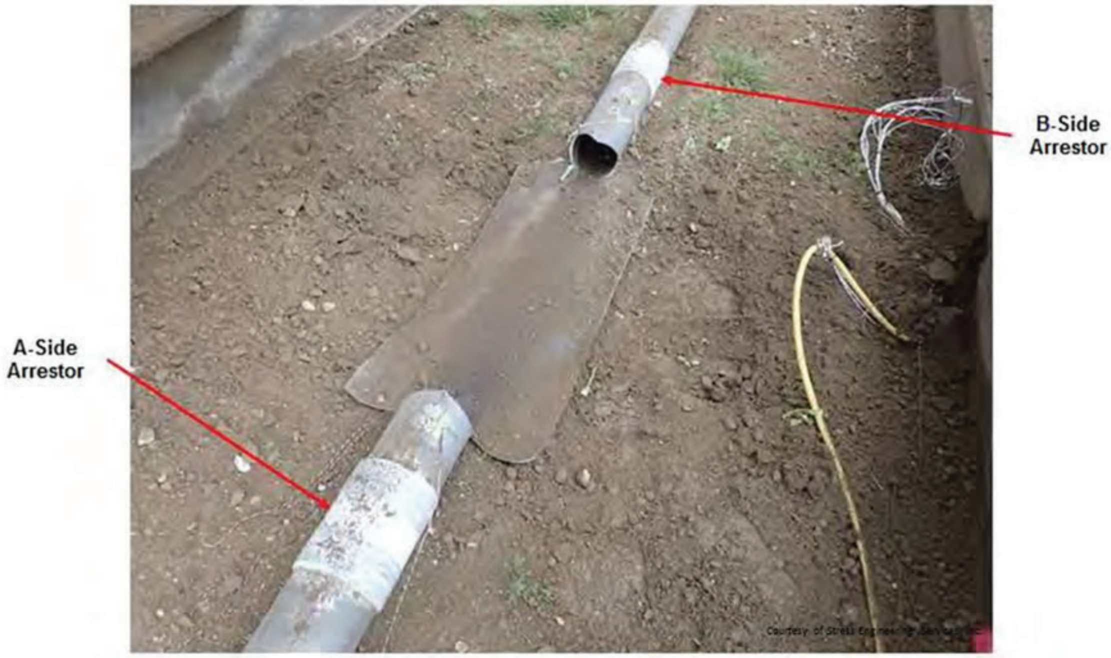
Courtesy of Stress Engineering Services, Inc.

Figure 1. Photographs showing the post-test response of a running fracture**.**



Courtesy of Stress Engineering Services, Inc.

Figure 2. Photographs showing the post-test response of a "hard" arrest response.

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Figure 3. Photographs showing the post-test response of a "soft" arrest response.

- From a knowledge standpoint, composite crack arrestors have been proven to arrest brittle and ductile running fractures effectively. This has been validated via full-scale testing on high-energy pipes.
- Design guidance needs to be provided to the pipeline industry for how a composite crack arrestor should be designed. The approach employed by most researchers has been to design and install a robust arrestor and then conduct testing to validate its ability to arrest running fractures experimentally. The composite crack arrestor design is considered a "success" if it stops the running fracture.
- Although the science behind modeling fracture is well understood, gaps exist in terms of how to arrest running fractures using composite materials using a well-thought-out design process. The soundest approaches appear to have involved quantifying the energy associated with running fractures and then ensuring that the "resisting energy" present in the designed composite crack arrestor is sufficient to prevent the fracture from running through the composite crack arrestor. This methodology has established a "qualified" approach rather than a "quantified" approach for design.
- It is important also to point out that full-scale testing for complete validation would be ideal. However, full-scale testing is significantly costly.

F. Van den Abeele et al. [6]. described that newly developed high-strength, large-diameter gas pipelines, when operated at severe conditions (rich gas, low temperatures, high pressure), may not be able to arrest a running ductile crack through pipe due to low material properties (low toughness) and that the use of crack arrestors are required to design safe and reliable pipeline systems. F. Van den Abeele et al. measured the properties of unidirectional glass fiber-reinforced epoxy and micromechanics modeling of composite materials. Then, large-scale tensile and four-point bending tests were performed and compared with finite element simulations. Di Biagio et al.[7] explained that safety and risk considerations emerging in pipelines transporting anthropogenic CO_2 service are primarily the effect of contaminants and impurities in the composition of the CO_2 and the volume transported that forces the use of larger diameter pipelines for longer distances with several crossings of highhazardous areas having a dramatic impact on fracture propagation arrest in case of pipeline failure caused by any large enough defect (corrosion, third party damage, construction defect, etc.). where a pipeline running fractures, potentially involving rapid "unzip" of the pipeline up to several hundred meters length, causing the release of large fluid amounts in a short time span.

The susceptibility to long-running shear fracture of any pipeline transportation system involving high-pressure gases, dense phase fluids, two-phase fluids, or high vapor-pressure liquids such as carbon dioxide is well known. In this context, SARCO$_2$[12], "Requirements for Safe and Reliable CO$_2$ Transportation Pipeline", was launched, an RFCS project with the support of EPRG and DNV. The project aimed to contribute to the pipeline design to assure long-term integrity and included full-scale testing on CO$_2$ pipelines as part of the fracture propagation prevention program. Testing of X65 24-inch OD pipelines, ranging from 12.5mm to 13.7 mm wall thickness pipes, with upper shelf Charpy V-notch impact energy (toughness) up to a maximum of 320 J was developed routes, and the use of composite crack arrestors was considered.

Crack Arrestor Joint Industry Program (JIP)[5] Participants contracted Stress Engineering Services, Inc. (SES) to perform a study to evaluate the performance of different composite technologies in functioning as pipeline crack arrestors. In total, SES performed nine (9) full-scale crack arrestor tests, seven (7) of which had composite arrestors. Nine (9) out of the fourteen (14) propagated cracks (two on each sample) were self-arrested in a ring before reaching the arrestor. These designs successfully stopped the crack propagation but did not prevent the pipe from arresting in a ring-out.

The nine (9) ring-out samples shared common characteristics of long lengths (several pipe diameters), high overwrap thicknesses, and/or higher modulus systems. These characteristics combined to add significant reinforcement to the base pipe surrounding the arrestor. This reinforcement altered the strain field development in front of the propagating crack tip, causing the self-arrest ring-out. The five (5) other crack tips reached the composite arrestor. Of these five (5), only three (3) completely prevented the crack from being arrested in a ring out. These designs had characteristics opposite from those described above. These composite overwraps provided less reinforcement to the surrounding pipe and allowed the crack to propagate into the composite before slowing it to an arrest.

The Crack Arrestor JIP[5] provided a foundation for continued work in composite crack arrestor design. The following steps towards bringing composite technology functioning as crack arrestors include further full-scale testing on more extensive pipe diameters with higher yield strength and toughness materials than those studied in the 2016 program.

Critical Design Elements

With the recent extensive interest in transporting CO$_2$, the pipeline industry is again at a crossroads where existing approaches, processes, and programs are insufficient to ensure that CO$_2$ can be safely transported. Composite crack arrestors have been identified as a viable means for achieving the required level of additional fracture resistance[5]. Advantages include customizing an arrestor based on required energy levels and installing the crack arrestors on an existing pipeline. The following sections discuss specific aspects of the composite crack arrestor design.

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Pipe Material Properties

The pipe material properties govern the response of the overall pipeline system to a running fracture. A pipe constructed of high strength, high toughness material will be able to resist a running fracture greater than low strength, low toughness pipe material. When designing a composite crack arrestor, the pipe, and composite pipe materials work together to resist the running fracture. For this reason, it is critically important that the engineer designing the composite crack arrestor be cognizant of the reinforced pipe's capabilities (and limitations), which includes modeling the pipeline fracture process as has been done in this study.

Composite Material Properties

One of the advantages of using composite materials is the ability to modify the architecture of the composite fabric to achieve desired properties. This typically involves achieving a directionally specific tensile strength and stiffness (i.e., elastic modulus). In addition to strength and stiffness, one of the composite material performance variables available to design engineers is elongation or strain to failure. In the composite world, this is driven by fiber selection. As a rule of thumb, carbon fabrics have a strain to failure of 1%, while E-glass materials have a strain to failure of 2%. Aramid fibers like Kevlar can have strain-to-failure values of 3% or greater. This is important in a crack arrestor design because the design's elongation to failure will dictate whether a soft arrest can be achieved. A soft arrest requires a flexible design where the composite has a moderate elastic modulus (i.e., 4 Msi) and strain to failure of about 2%, as would be available in an E-glass technology. Another design consideration that has limited data for current composite repair technologies is the impact of loading rate. Most composite repair applications occur in a quasi-static condition; however, the loading of a composite crack arrestor resisting loads associated with a running fracture exceeding 500 feet per second will occur at a much higher loading rate. Based on existing test data, the performance of today’s composite technologies appears adequate; however, CO_2 pipelines could produce conditions that have not been previously addressed or evaluated.

Temperature Limitations of the Composite Material

Although most CO_2 pipelines do not operate at elevated temperature conditions, it is essential that when composite material is exposed to elevated temperatures, the resin selected for these applications is appropriately designed. This typically requires the use of a high-temperature resin that requires a post-cure at high temperatures. For example, one high-temperature system designed for temperatures up to 250°F after installation requires a post-cure “bake” at 350°F for four hours before the product can achieve the required material strength properties. Another design consideration that could be important in the case of a running fracture in a CO_2 pipeline is the performance of the composite at extremely low-temperature conditions, especially at high loading rates.

Installation Considerations

Where and how composite materials are installed will impact their subsequent performance. Composite materials installed on above-ground pipelines, which are unlikely in a CO_2 pipeline, will require an overcoat, such as a coat of paint, to prevent the exterior surface of the composite from being damaged by the sun’s ultraviolet rays. Additionally, as part of the installation process, the composite material must be fully cured to ensure the required material properties can be achieved.

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Experienced composite repair technology companies like CSNRI have detailed installation procedures with required hold points to achieve post-installation properties.

Service and Operational Considerations

Although not unique to composite crack arrestors, it is known that the strength of composite repair materials will decrease (slightly) over time. This has been easily addressed from a design standpoint by increasing the thickness of the composite material to lower stresses in the composite under design conditions. What has yet to be addressed in previous testing is the impact that future service conditions, namely cyclic pressure, will have on composite performance. This issue is most likely to occur in pipelines subjected to aggressive pressure cycling, which is unlikely for most CO_2 pipelines.

Should they exist, the presence of defects in a pipeline beneath a composite crack arrestor requires additional consideration. This is most likely to be an issue with seam welds of vintage pipes where the seam welds are not likely to be as strong as the base pipe. From a design standpoint, this should be evaluated by the engineer evaluating the fracture characteristics of the unreinforced pipe, which can then be used to provide additional information required for the design of the composite crack arrestor. If defects do exist in the pipeline, the installation of supplemental composite materials will be required.

Outside Damage or Force Imparted to the Crack Arrestor

Unlike steel, which is damage-resistant to external impacts and has a high strain to failure (i.e., greater than 20%), composite materials are sensitive to external damage that can break the matrix and reinforcing fibers. Testing has been conducted on composite reinforcing technologies, demonstrating a reduction in performance occurs when the composite reinforcement is externally impacted. Of course, the reduction in performance will be scenario-specific; however, it is important for pipeline operators with composite crack arrestors to protect the pipeline from external damage.

Decompression of CO_2 Considerations

Decompression of CO_2 for pipeline systems using operating pressure, temperature, and gas chemical composition has to be considered when evaluating the use of composite crack arrestors.

BTCM Methodology

A method for predicting the fracture propagation toughness requirement for lean natural gas pipelines was developed by the Battelle Memorial Institute in 1970, and it is referred to as the Battelle Two-Curve Method (BTCM). Although not validated yet through full-scale testing, for pipelines to be transporting gas phase CO_2, the BTCM is considered applicable. This is not the case for dense phase CO_2 pipelines where new empirical equations such as the ones presented in DNV RP F104[13] are more applicable. Figure 4 depicts the BTCM methodology.

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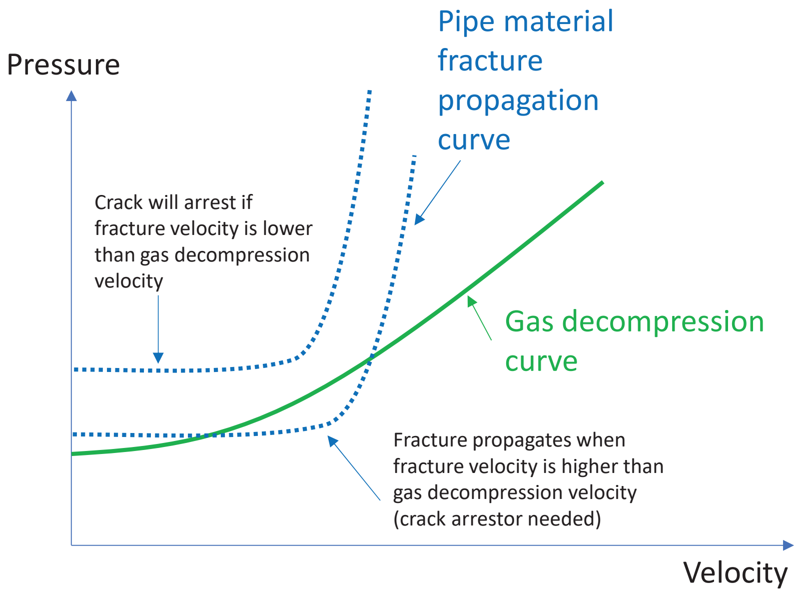

Figure 4. BTCM Methodology.

The BTCM calculates the material toughness required to arrest a propagating ductile fracture in a gas pipeline by correlating the velocity of the plastic wave propagating through the pipe material using Battelle's standard fracture velocity equations against the pressure wave velocity of rapidly decompressing gas.

The calculated crack velocity is compared with the velocity of the decompressing gas to determine whether ductile fracture arrest will occur. An arrest will occur when the crack velocity is below the gas velocity at the crack tip at all pressures. Correction factors have been developed to account for rich natural gas, which is considered applicable for CO_2 in the gas phase.

The toughness calculated is used as the minimum system energy required to arrest the crack, which translates into the number of layers required for the composite material to arrest the crack, whereas the critical decompression velocity has been used to estimate the kinetic energy and the length of the necessary composite wrapping.

Crack Arrestor Design

The stress sharing with the pipe reduces loading at the crack tip. This stress sharing is represented through a simple modulus ratio. An artificial increase to the fracture toughness capacity of the pipe. This is due to the composite restraining the crack tip opening displacement, which requires the load to be higher than K_{Ic} to propagate the crack.

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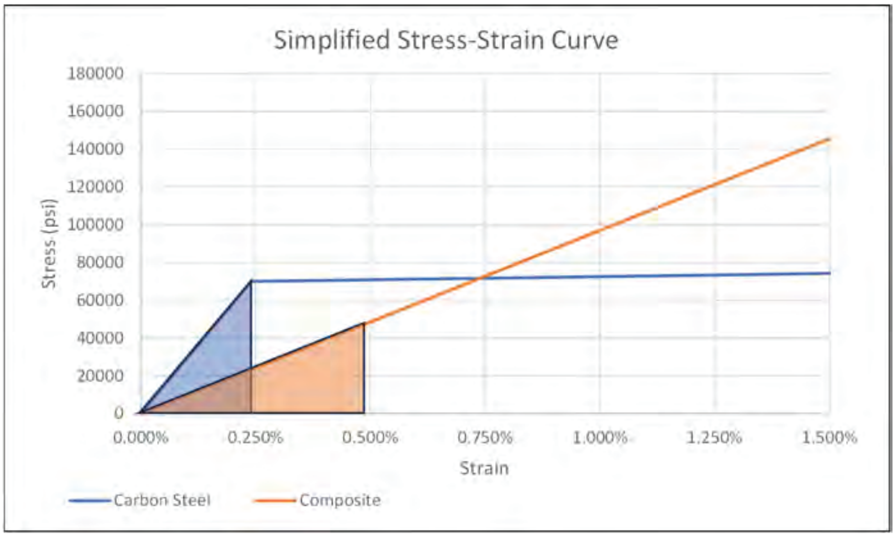

Figure 5. Simplified Stress-Strain Curve Showing Material Load Share.

Ring-Out Calculation

The objective of this design methodology is to determine an estimated minimum thickness required to reinforce the pipe to such a degree that the crack is no longer able to propagate. This energy is still in the system and may cause the crack to transition from axial to circumferential, leading to a ring-out condition.

The inputs required for this estimate include:

- Pipe Diameter (D) and Thickness (t_s)
- Yield Strength (s) and Flow Stress (σ_F)
- Assumed Fracture Toughness (K_{IC})
- Target Fracture Toughness for crack arrest (K_{Ia})
- Modulus of Pipe (E_c) and Composite (E_s)

The arrest toughness (K_{Ia}) and fracture toughness (K_{Ic}) are set as a ratio. The target arrest toughness uses the equivalent stress of a combined system:

$$\sigma_{com} = \frac{\sigma_c t_c + \sigma_F t_p}{t_p} \tag{1}$$

The strain limit of the composite is then assumed to be equal to the strain limit of the pipe multiplied by the f_{kc} and converted back to the composite stress:

$$\sigma_c = \varepsilon_c E_c = \varepsilon_s f_{kc} E_c = \sigma_F f_{kc} \frac{E_c}{E_s} \tag{2}$$

The equation is then rearranged to solve for the composite Thickness, t_c. The final equation presented below shows this design to be based on a modulus ratio between the pipe and composite, with the f_{kc} factor modifying the modulus. The result of this ratio is then multiplied by the ratio of the fracture toughness needed to make up the gap between K_{Ia} and K_{IC}.

$$t_c = t_p \frac{E_s}{f_{kc} E_c} \left(\frac{K_{Ia}}{K_{Ic}} - 1 \right) \tag{3}$$

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Soft-Arrest Calculation

This design methodology aims to determine an estimated minimum thickness required to ensure energy dissipation and a sufficient length to ensure crack arrest under the composite reinforcement. The primary method here is to allow the composite to exceed its limit so that the crack does not change direction; however, the length needs to be accounted for to ensure that the crack terminates and does not continue beyond the reinforcement length.

The inputs required for this estimate include:

- Pipe Diameter (D) and Thickness (t_s)
- Yield Strength (s) and Flow Stress (σ_F)
- Modulus of Pipe (E_c) and Composite (E_s)
- Crack Velocity (V)
- Constant (k) – empirically derived$\sqrt{2\pi/k} = 0.38$
- Pipe Density (ρ)

The equation for Energy Release Rate (G), including kinetic energy, is the starting point for this methodology. As the crack is assumed to be actively propagating in a stable manner, G is assumed to be 0, indicating it is neither speeding up nor slowing down.

This means that the work done on the system per length, dF/da, is equal to the energy absorbed by the system, dU/da, plus the remaining energy, which is translated into kinetic energy, dE_k/da. The value for dU/da is determined for brittle pipes by calculating the area under the stress-strain curve in the elastic region and multiplying it by the wall thickness.

The value for dE_k/da is based on standard kinetic energy:

$$E_k = \frac{1}{2} m V_o^2 \tag{3}$$

Mass must be converted into the material density times a volume to obtain a usable form for crack propagation. With only the crack length, a, as a relevant length, additional relations are used to set the volume equal to $V_o = ka^2 \left(\frac{\sigma_F}{E_s}\right)^2$ times unit thickness. The work value is calculated using the estimated velocity and the pipe's flow stress by solving for dF/da. This value is then used to represent the anticipated input load when the crack encounters the crack arrestor system.

The primary impact of a composite over the crack arrestor is the load sharing that will take place. Essentially, the pipe cannot rupture until the composite system also ruptures or sees significant strain as well. This load sharing is captured by the term dU_{eq}/da, which represents the energy captured by the pipe and the energy captured by the composite over the same strain range multiplied by the term f_{kc}.

Figure 6 shows how the kinetic energy being carried dissipates as the crack enters the composite reinforcement area.

The result of the soft arrest design methodology for the two pipes is presented in **Error! Reference source not found.**.

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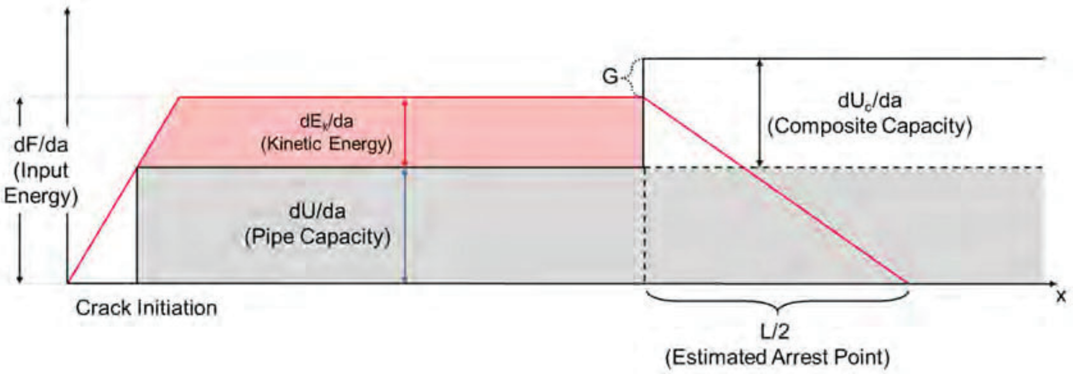

Figure 6. Illustration of Kinetic Energy Dissipating as the Crack Enters the Composite Reinforcement Area.

Closing Comments

Over the past 30 years composite materials have reinforced many defects, including corrosion, cracks, dents, and vintage girth welds. Composite crack arrestors have also played a role in this same period, although their use in this capacity has not been as widespread as in structurally reinforcing pipelines as part of integrity management programs.

This paper has addressed several of the fundamental concepts embodied in the design of a composite crack arrestor. The pipeline industry needs a more prescriptive approach for how composite crack arrestors should be designed as the approach employed by most researchers has been to design and install a robust arrestor and then conduct testing to validate its ability to arrest running fractures experimentally. The composite crack arrestor design is considered successful if it stops the running fracture. This paper has presented a framework for using composite materials as crack arrestors to arrest running fractures when transporting either CO_2 in the gas or dense phases. This framework could be helpful for pipeline companies seeking to build new pipeline systems or convert existing assets to CO_2 service.

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