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ARRESTING PROPAGATING SHEAR IN PIPELINES (Part 2. See no. 1, 2015 for part 1)

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Abstract. The consequences of what has been termed running ductile fracture require that pipelines be designed to arrest propagation, and so avoid major incidents due to this type of failure. Approaches to characterize pipeline response and their resistance to such failure to ensure arrest rely on semi-empirical models developed in the mid-1970s. Continuing reliance on such semi-empirical models, which were calibrated using full-scale tests done on segments of pipelines, persists because this failure process involves three interacting nonlinearities, and so is complex. These nonlinearities include: 1) plastic flow and tearing instability, 2) soil-structure interaction, and 3) expansion wave response and decompression in the pressurizing media. This paper first reviews the history and related developments that represent almost 40 years invested in fracture-based approaches to quantify propagating shear in pipelines. Graphical evidence of the full-scale failure process and related phenomenology lead to an alternative hypothesis to quantify this failure process that is based on plastic collapse rather than fracture. It is shown that the phenomenology does not support a fracture-controlled process, and that instead the metrics of arrest should reflect the flow properties of the steel. Finally, aspects of fracture-based approaches are related to the collapse-based concept as the basis to understand the success that at times has been achieved using fracture-based approaches. Surrogates for CVN energy that has been used in the BTCM as a measure of fracture resistance are reevaluated as functions of the flow response, which provides the basis to rationalize the historic successes on the fracture-based formulation. Finally, remaining gaps and issues are addressed.

Keywords: propagating shear, fracture, arrest, arrestor, tough steel, Battelle two-curve model, through-wall collapse, plasticity, CVN, DWTT, steel, separations/splits, model development.

Alternative concept to quantify propagating shear

Insight into the question of where to start follows from several observations. First, in reference to the CAGSL data it appears that issues with fracture-based approaches became evident as toughness increased even before the BTCM was published. Second, in comparing the results in Fig. 5 and 6 (see no. 1, 2015) it is apparent that issues with the BTCM also develop when predicting the arrest requirements at CVN energy levels well within its calibration database. Finally, beyond some threshold CVN energy level failure under quasi-static conditions is controlled by plastic collapse rather than fracture [e.g., 1]: by analogy it is reasonable to expect that the same occurs under dynamic conditions. Along with the observation that collapse solutions are much simpler than fracture analysis, the discussion to this point indicates that it is best to consider the phenomenology of propagating shear from the earliest records available. Accordingly, archival records that included high-speed films taken of the early full-scale experiments have been gathered and evaluated, as have related data on the steels used and the testing conditions.

The phenomenology of propagating shear for 1960s line pipe steel

Segments of the film archive for key tests done in the late 1960s and early 1970s were located and digitized

for purposes of other reporting while the author was employed by Battelle. Image-capture software was used to extract images of incipient shear propagation from those films and analyzed sequentially as the basis to characterize the phenomenology that underlay the BTCM.

The image introduced earlier as Fig. 7 (see no. 1, 2015) has been extracted as just outlined and is instructive for present purposes. This image came from film of what became known as a 'West-Jefferson' (WJ) test. The process used to initiate failure in this WJ test is comparable to that used to initiate propagating shear in the early full-scale tests. While this trigger event for full-scale propagating shear tests has changed over time, the outcome of all such tests regardless of how they are initiated is a propagating shear failure. The only differences between a full-scale test and a WJ test is that 1) a shorter length end-capped pup is used, and it is not axially restrained by thrust-blocks as is typical for most full-scale test setups. On this basis, the phenomenology local to the shear process zone prior to axial instability of the defect in Fig. 7 (see no. 1, 2015) is comparable to the usual outcome in a full-scale propagating shear test. The resulting shear process zone translates down the pipe as it forms in the wake of the propagating plastic wave that is triggered by the rupture. Accordingly, once the pipe ruptures there is little difference between these process zones, aside from minor differences in the dynamic nature of the stress-strain field in the full-scale test. Such dynamic response could diminish the magnitude of the stretch in the shear process zone relative to that in the quasi-static situation prior to rupture in a WJ test.

The key feature of interest in Fig. 7 (see no. 1, 2015), aside from the crack extension from 3.3 inches (84 mm) in total length up to about 5.6 inches (142 mm) as discussed earlier, is the presence of the axial through-wall (TW) thinning (strip-yield/necking) evident in the plane of the defect. This view shows the damage state at this TWD well prior to 'instability' in terms of axial growth, as the length of TWD evident in this image extended still further via stable tearing. This image is one of 100s captured from the digitized films. Sequentially stepping through these images from the start of the pressurization shows that the initial TWD extends stably along the axis of the pipe. This stable extension develops as a consequence of TW (plastic) collapse (TWC), which as noted above is evident as necking – which creates a strip-yield zone. As the pressure rises, the incipient shear failure lengthens, until axial instability ensues when the TWC zone reaches its critical length. Once shear failure initiates, the shear failure extends axially in the wake of this TWC zone, which advances along the pipe in the wake of the propagating plastic wave. For the WJ result illustrated in Fig. 7 (see no. 1, 2015), the total TWC zone length (i.e., notch plus the stable tearing plus the TWC zone) increased up to 10.6 inches (269 mm) prior to shear instability. This critical length TWC zone then extended dynamically, via shear, along the length of the test pipe or until the conditions for arrest were satisfied. When needed, the energy to sustain axial growth in these early tests came from a 'gas cap' that filled a few percent of the pipe's capacity.

The flow properties for the pipe used in Test 18-8 were typical of the NG-18 TWD database and much of the line pipe then in service, as evident in the ratios of AYS/SMYS = 1.165 and Y/T = 0.75. The CVN response for this pipe steel is presented in Fig. 14, with part *a* being in US units, while part *b* is in SI units. At the test temperature of 26 °F (3.3 °C) Fig. 14 indicates that the TWD in this

pipe was operating well below its 85-percent CVN SATT (~120 °F {48.9 °C}). However, because this pipe has a relatively high CVP energy, in spite of being well below the SATT, related analysis using the Pipe Axial Flaw Failure Criterion [2] (PAFFC) at the resistance for the test temperature remains sufficient to ensure collapse controlled failure. The tendency to fail via plastic collapse evident in Fig. 7 (see no. 1, 2015) thus is not a surprise.

Asequence of images like that in Fig. 7 (see no. 1, 2015) shows a TWC zone that developed to a critical length and then became axially unstable, such that a propagating shear failure ensued – even for this 1964 vintage line-pipe steel operating well below its SATT. As such, failure occurred by a plastic collapse mechanism, not a fracture-controlled process. Significant in this context is that the same phenomenology is evident for modern high-toughness high-strength steels so long as collapse controls failure. This is evident in Fig. 15, reproduced from the work of Prof. Alexandr Glebov [3], as presented at the 'Fracture Roundtable' held in conjunction with the 2013 Microalloyed Steels Symposium in Moscow.

Fig. 15 when compared to the image presented in Fig. 7 (see no. 1, 2015) shows the same tendency to form a TWC zone in a large-diameter post-Millennial Grade 551 (X80) pipe whose wall is more than an inch (2.54 mm) thick. Because of the heavy wall, plane strain develops for the case shown in Fig. 15 as compared to plane stress for the thin-wall pipe shown in Fig. 7 (see no. 1, 2015). As discussed later in detail, this means that the TWC zone in the heavy-wall pipe is much smaller and so dissipates much less energy as compared to Fig. 7 (see no. 1, 2015) – were all else equal. In this context, the TWC concept provides a bridge from the lower grades and FSE CVN energies of the 1970s into the post-Millennial scenario involving higher-strength grades and much FSE CVN energy levels. This bridge appears relevant so long as the governing mechanism is largely ductile and leads to shear propagation.



Fig. 14. FSE CVN transition curves for the pipe in Test 18-8: a - US units; b - SI units



Fig. 15. TWC-controlled propagating shear evident in heavy-wall post-Millennial Grade 551 (X80) pipe

The just-discussed TWC zone continues to deepen and lengthen as the pressure increases toward the limit pressure. The pipe ruptures once this TWC zone reaches its critical length and depth, and thereafter propagates in the wake of the plastic wave that is triggered by rupture of the pipe. Failure through the net ligament via unstable shear gives rise to its axial propagation along the pipe. Conversely, arrest occurs when the ligament remains stable, either because the steel has sufficient strain capacity to support the imposed deformation, which can occur if sufficient dissipation has slowed the plastic wave speed, or the steel's inherent strain capacity exceeds the imposed strain demand.

Because the TWC zone and unstable shear propagate in the wake of the axial plastic wave, the speed of that wave controls the maximum speed of the propagating shear, which in turn is a function of the plastic dissipation that develops as that wave propagates. That dissipation develops in a 3-D strain field that grows in and ahead of the TWC zone and around the pipe – spreading all the more as the TWC zone slows until arrest occurs. Fig. 16 schematically captures this TWC-controlled propagating shear failure mechanism.

Implications of TWC-controlled propagating shear

In view of Fig. 7 (see no. 1, 2015) and the above discussion, propagating shear continues until the speed of the decompression front exceeds the speed of the propagating shear instability, which depressurizes the pipe below a critical level, leading to arrest. Propagating shear failure occurs through plastic collapse, with the through-thickness flow properties of the steel controlling the resistance to TW shear. The in-plane properties affect the spread of plasticity, which dissipates energy that slows the speed of the plastic wave, and the speed of the TWC zone that grows in its wake.

What has been considered a 'crack' in the context of fracture mechanics thus is the separation due to failure in the wake of the propagating shear process zone. Under this concept, fracture parameters that relate to a 'crack-tip' process zone do not control failure nor affect it in any way. This is because the 'crack' forms in the wake of the TWC shear process zone and is a consequence of the collapse-controlled failure process, rather than a driver for the process. Control is affected in the context of plastic collapse, which in turn depends on the 3-D strength and flow properties of the steel. This TWC zone develops well ahead of what is considered in a fracture mechanics setting "the crack-tip field" – in which case crack-growth resistance is a secondary consideration.

In contrast to TWC control, if the dissipation remote to the crack-tip field diminishes because the inherent resistance to strain for the steels involved decreases, then a transition to fracture control occurs – with transitional response occurring between the limits of TWC and Fracture control. In such cases, the resistance to crack advance is dictated by the energy dissipated in creating new crack surface. In the limit, this scenario tends to brittle fracture.

Where increasing "toughness" is a surrogate for increasing through-wall strain capacity and resistance to TWC, dissipation remote to the crack-tip field becomes dominant. Thus, for TWC controlled propagation the usual fracture parameters are not consequential, nor is an understanding



Fig. 16. TWC-controlled propagating shear failure mechanism

of their role essential to quantify propagating shear under this alternative TWC view of the phenomenology¹. This observation opens to two critical questions. First, if fracture does not control, how or why has a fracture-based formulation like the BTCM proven successful in predicting fracture arrest requirements – albeit with scatter and errors that require correction factors? Second, if collapse controls, what are the steps to formulate a first-order model, and what parameters appear relevant in quantifying resistance to propagating shear? These questions are considered next.

While issues with the fracture-based approach to quantify propagating shear were apparent before the BTCM was published in 1974 [4], and a sequence of images for Test 18-8 similar to that in Fig. 7 (see no. 1, 2015) had been published and discussed by Battelle authors [e.g., 5], the view that fracture controlled the process was never questioned - at least in writing. Successfully resolving brittle propagation in the late 1950s through use of fracture concepts appears to have cemented fracture concepts as the basis for their analysis of propagating shear. The absence of a significant role of plasticity as was apparent for the CVN data in Fig. 14 likely also was a factor. Against this backdrop, it remains to address the first of the critical questions: how or why a fracture-based formulation like the BTCM could prove successful in predicting 'fracture-arrest requirements' if fracture did not control the process? Thereafter the second critical question is addressed.

How/why has the BTCM successeded if fracture does not control?

One plausible explanation for the continued 'successful' use of the BTCM is that its success was more perception that reality, with predictive scatter and/or errors that required correction factors invoked in support of this assertion. Fig. 5 and 6, as well as Fig. 9 and 11 (see no. 1, 2015), make clear that scatter has been an issue from the outset. As the scatter evident in laboratory CVN testing can contribute much of the scatter evident in those figures, one might argue that scatter masks potentially significant model errors, like that discussed in regard to Fig. 8 (see no. 1, 2015). One could equally argue that because of the scatter evident in any laboratory fracture test, it is difficult to quantify the extent to which the BTCM errs in predicting arrest toughness. On this basis it is difficult to invoke scatter as a compelling explanation for the success of the BTCM.

The need for correction factors to correctly predict arrest toughness has been evident for the BTCM since the mid-1970s. Successful predictions using the BTCM coupled with the LCF might be viewed by some as proof of the shortcomings evident for the BTCM. In contrast, others could view it as support for the use of fracture concepts, because that correction is explicitly coupled to fracturebased energy dissipation in a CVN test. Thus, as for scatter, the need for correction factors must be discounted as the explanation for how the fracture-based BTCM could be perceived as successful since its introduction in the 1970s.

With the assertion of perceived success in the use of the BTCM since the 1970s discounted, rational alternatives for its continued use and apparent successes were sought. One pragmatic view for its continued use lies in the absence of a simple/practical alternative - but that does not address the question of how a fracture-based model correctly predicts if collapse controls shear propagation. A simple, answer for its successful predictions follows directly in regard to Eq. 3 (see no. 1, 2015), and its related assumptions [4, 6-8]. This equation is central to the BTCM, as it quantifies 'fracture velocity' - one of the 'two curves' in this two-curve model. As noted in earlier discussion, Eq. 3 modifies the plastic wave speed in regard to the flow properties of the steel, and the steel's resistance to propagating shear. If collapse controls rather than fracture and 'fracture velocity' was correlated through Eq. 3 to CVN energy as a metric of 'fracture resistance', then the CVN energy must be a surrogate for flow properties that quantify the resistance to plastic collapse.

Addressing how or why the BTCM could prove successful thus can be established by demonstrating that the CVN energy correlates with metrics of plastic collapse. Fig. 17, *a* explores this possibility in regard to true-fracture ductility, ε_f , while Fig. 17, *b* considers surrogacy relative to true-fracture toughness, $\varepsilon_f \cdot \sigma_f$, approximated as $\varepsilon_f \cdot UTS$.

Fig. 17, *a* presents literature data as trended by Gray [9] in the early 1980s. As the symbol key indicates, these results cover a broad range of steel types and processing histories, and include materials comparable to line pipe steels – all on one plot. While the data are scattered, which reflects the inclusion of a broad range of steels, the bounding trends on linear scales indicate that true-fracture ductility, ε_f , varies with CVP in a manner consistent with a power-law or logarithmic relationship.

The results Fig. 17, b involve data subsequently developed and trended by Leis [10], in the early 1990s. While that work focused on the energy trending discussed earlier in regard to Fig. 10 (see no. 1, 2015), it also assessed the interdependence of the flow and fracture properties of line pipe steels. Properties were developed for Grade 482 (X70) and Grade 551 (X80) produced in heavier-wall sections in the late 1980s and early 1990s, as well as a series of lowerstrength pipe grades that were produced back into the early 1960s. The results shown in Fig. 17, b indicate a clear logarithmic dependence of true-fracture toughness, approximated as ε_f UTS, on the CVP energy, and indicate that processing can strongly affect that relationship. The anomalous results developed for the case of X80 pipe that had been produced from plate that had been controlled rolled but not accelerated cooled.

¹ Clearly, a fully general NLFM formulation could be developed that embeds this remote dissipation. However, as NLFM solutions are much more complex than collapse solutions where nominal plasticity occurs, and the energy dissipated within the usual view of the crack-tip field is a small fraction of the total in such cases, the virtue of a collapse-based approach becomes transparent.



Fig. 17. CVN surrogacy for the plastic-flow response of many steels: $a - \text{for } \varepsilon_f$; $b - \text{for } \varepsilon_f$ ·UTS; $\blacktriangle - 0.20 \text{ C}$, 1.2 Mn, 0.07 V Plate 1" & 2" Thick; $\blacklozenge - 0.02/0.05 \text{ C}$ Cb–Mo–B 1/2" Plate–Acicular Ferrite; $\square - 0.02/0.05 \text{ C}$ Cb–Mo–B 1/2" Plate–Polygonal Ferrite; $\bigcirc - \text{No}-\text{Cr}-\text{Mo}$ (HY 130) –Various Thick; $\blacksquare - \text{Mn}-\text{Ni}-\text{Cb}$ 1/2" Plate; $\nabla - \text{Low C}-\text{Cb}$ 1/2" Plate; $\triangle - 18$ Different Steels

It follows in view of Fig. 17 that the CVN energy used to represent the resistance to propagating shear in the BTCM functions as a surrogate for flow properties in a collapse-controlled model of propagating shear. In this context, empirically calibrating what was considered to be a 'fracture' velocity relative to CVN energy is no different than calibrating the speed of propagating shear relative to the flow properties. Given that the phenomenology evident in Fig. 7 (see no. 1, 2015) indicates collapse controls rather than fracture, Fig. 17 indicates that the BTCM should succeed in correctly predicting 'fracture' arrest. Success in this context is not fracture based, but collapse based. Not coincidental in this context is the observation that the nonlinear bent-over trend evident in Fig. 9 (see no. 1, 2015) for the AISI model, which is characteristic for all CVN-based 'arrest' models [11], closely matches the same bent-over trend evident for the flow properties in Fig. 17. The same is true, although not illustrated here in regard to the trend for the LCF as a function of CVN energy. Thus, success for the BTCM in conjunction with the LCF is anticipated because the BTCM quantified arrest resistance using CVN energy – which correlates with metrics of plastic collapse (and strain-based design).

The observation that the BTCM coupled with LCF led to successful arrest predictions for a wide range of data in Fig. 11 (see no. 1, 2015) using CVN energy as the measure of 'fracture resistance' suggests that the same conclusion might be drawn if the drop-weight tear test (DWTT) had been used in lieu of the CVN test. Fig. 18, which shows DWTT energy as a function of the CVN energy, suggests this is unlikely – as 'fracture' energy appears badly scattered between these two test practices. Significant in this context is the fact that the DWTT practice was developed to indicate fracture mode, not fracture energy, whereas the CVN practice had emerged many decades earlier and has been standardized to quantify fracture resistance relative to the observed shear area.

Which parameters quantify resistance to propagating shear?

The answer to the first of the two critical questions posed earlier, as just discussed, provides insight into the answer to the second critical question: which parameters quantify the resistance to propagating shear? Because plastic dissipation acts to slow the TWC zone and the plastic wave speed, high values of true-fracture toughness approximated as ε_f . UTS provide a win-win combination to resist the TW collapse-



Fig. 18. DWTT energy as a function of CVN energy (100 % shear-area): $\Delta - X52$ and lower; $+ - X60 \& X65; \diamondsuit - X70 \& X75; \divideontimes - X80;$ $\bigcirc - X90; \blacksquare$ – Throw Energy

controlled failure, and to dissipate energy as the means to arrest propagating shear, as follows. Earlier discussion regarding Fig. 13 (see no. 1, 2015) also shows that Y/T, or more specifically the strain-hardening exponent, is an important metric in discriminating response.

Delaying TWC is equivalent to reducing the speed of propagating shear, which ultimately leads to its arrest. Thus, parameters that relate directly to delaying TWC are first-order metrics of the resistance to propagating shear.

The phenomenology and alternative TWC concept indicate that collapse through-wall is delayed by the ability to sustain circumferential strain, ε_c . The isochoric (constant volume) requirement of plasticity theory [e.g., 12] (viz, no plastic work is done by the spherical component of the stress tensor) is critical in this context. That requirement means that the amount of circumferential strain is limited if deformation that occurs in the other orthogonal directions is accommodated other than by plastic flow, the extent to which depends on the local stress state. Thus, what have been termed 'splits' or 'laminations' - which can accommodate the through-thickness thinning prior to TWC by physical separations² rather than by homogeneous deformation – act to limit ε_{a} . As illustrated in Fig. 19, such splits can be evident in fracture tests as well as mechanical properties tests. The images in Fig. 19, a and b are full-thickness views of separations in different mid-1990s vintage X70

pipes with 0.560 nominal wall thickness. The images in Fig. 20, a and b are views of separations in different post-millennial heavy-wall X70 pipes.

The larger the volume occupied by the separations, where volume is integrated across the size (length and width) of the splits and the number of splits formed, the smaller the circumferential stretch – all else being equal. This limit in circumferential strain reflects a mechanics-driven limitation to flow, which applies in spite of the steel's potential capacity to sustain further hoop strain. Accordingly, a high value of true-fracture ductility (uniform strain capacity) in the through-thickness direction, ε_{tf} , is equal or possibly more important in delaying TWC to slow propagating shear than is a high value of true-fracture ductility (uniform strain capacity) in the circumferential direction ε_{cf} . It follows that eliminating splits is essential to propagating shear resistance within a plastic-collapse framework. While not new insight for those that develop steels, the practical benefits that derive from eliminating or significantly reducing the frequency and size of splits now can be quantified directly.

The ability to strain uniformly in the through-thickness direction to develop a large value of ε_c provides time for the spread of plasticity around and ahead of the shear process zone – which affects dissipation and acts to slow the TWC zone such that arrest can occur. The ability to sustain uniform strain in the axial direction (i.e. sustain large ε_l) is also important, as the length of this zone in contrast to that forming circumferentially is large, which indicates that ε_l also is important. The length of the plastic zone that forms at the TWD in the wake of the plastic wave cannot become



Fig. 19. Ductile separations in full-scale tests: different mid-1990s X70 pipes; t = 0.560'' (14.2 mm): a -on a shear plane, in a full-scale test; b - perspective view on a shear plane in test pipe

² Separations, splits, laminations, as they have been called have been cited as limiting fracture resistance in that literature for decades, so this mechanics-based outcome provides a rationale that cross-cuts both technologies.



Fig. 20. Illustrations of ductile separations in standard properties test specimens: a -on the failure plane in full-size CVN tests; b -on the failure plane in tensile tests, t = 0.750'' (19 mm)

a

large unless the strains in the other two orthogonal directions also become large – so the uniform strain capacity the axial direction is secondary. However, because the length of the axial plastic appears to be very large, even though the longitudinal strain is small compared to the through thickness and circumferential components, it can contribute significantly to the dissipation that slows the TWC zone, such that arrest can occur.

High values of the UTS work in complement to the through thickness and circumferential strains, as increased hoop stress capacity provides increased pressure capacity prior to local shear instability - all else being equal. High values of the UTS thus facilitate the role of high hoop and through-thickness strain capacity to spread plasticity. It follows that a high value of true-fracture toughness approximated as ε_f UTS is a win-win scenario where the focus is energy dissipation – as this combination directly resists collapse-controlled failure and so the arrest of propagating shear - with due consideration of the directional dependence of this metric. In regard to the UTS, its value relative to that of SMYS depends on the strain-hardening exponent, n. Values of n that lead to a lower value of Y/T reflect increased strain hardening and promote increased stress relative to the same total strain, such that more energy is dissipated all else being equal. In this regard, a high value of the exponent 'n' coupled with a high value of ε_{ϵ} . UTS is an even better scenario.

Several aspects bear emphasis regarding the trend in Fig. 17, b and its implications relative to collapse-controlled arrest of propagating shear. First, while a correlation is clearly evident, there is scatter - with microalloying and processing that can affect both separations and the inherent directional strain capacity potential causes that must be understood. This is true both for the flow and fracture properties as measured in laboratory tests relative to Fig. 16, 18, and 20, and for the full-scale testing. Second, the mechanical properties that underlie Fig. 17, b reflect the quasi-static transverse (T) round-bar uniaxial tension stress-strain response, while fracture is represented by the transverse-long (TL) CVP energy - each of which open to several related aspects. Clearly round-bar uniaxial T response is not indicative of the behavior in the other two orthogonal directions, with significant differences possible depending on the steel involved. This is particularly the case in the through-thickness direction, which is a topic for later discussion. Likewise, round-bar response is not indicative of the full-thickness response, not only in terms of the volume or location of the steel it samples but also in regard to the orthogonal response. The use of the full thickness tensile tests would lead to higher through-thickness stress that could promote separations³, which in a shear propagation context would limit the thinning process and the spread of plasticity that promotes dissipation leading to arrest.

A third aspect of concern is that the strain rate in the usual tension test is orders of magnitude less than that in the through-thickness or circumferential directions within the shear process zone, which could act to localize or change the mode of failure, and so alter the specific data that develop from such testing. It is for this and related reasons like the role of splitting on the local mechanics that can limit stretch – that attempts to develop correlations between DWTT and CVN test results become scattered and so difficult to establish. Fourth, as the ability to sustain throughthickness strain increases in association with certain processing practices, the extent of stretch in the orthogonal directions increases. While this 3-D aspect is not assessed in the context of Fig. 17, b, it is critical to shear propagation as it promotes increased the in-plane stretch around and ahead of the shear zone, which promotes dissipation leading to arrest. Finally, in light of the results in Fig. 10 (see no. 1, 2015) and the plastic-collapse controlled phenomenology evident in Fig. 7 (see no. 1, 2015) (and schematically in Fig. 16), the CVN energy was an effective surrogate for the flow response because it increasingly reflects the role of plastic flow as the toughness increases. In light of the scatter between CVN energy and pressed-notch DWTT energy evident in Fig. 18, it is not clear that such would be the case for DWTT energy. Using notch treatments to affect reduced plasticity and initiation (or deformation) energy in the DWTT diminishes the role of plasticity that otherwise makes the CVN test a viable surrogate for collapse-control. It follows that such notch treatments could not improve the predictive outcome of the BTCM were it based initially on DWTT results.

Stress state and wall thickness are key aspects

As noted above, stress state can influence the role played by splits via the isochoric assumption, which is a direct indication of the role of stress state. If fracture mechanics can be taken as an analog for the circumstances that exist in the wake of the propagating plastic wave and TWC zone, then one can further infer that stress state will play a role in the scale of the plastic field that contains the shear process zone. An equally critical role for pipe wall thickness also emerges in this context. Fracture mechanics texts generally present images such as those shown in Fig. 21 as the basis to illustrate the role of stress state. Because the concepts in Fig. 21 are widely considered in textbooks, suffice it here to simply highlight the important aspects.

First, plane stress develops under local conditions that favor unconstrained flow, which occurs at the free surfaces and so favors thin-walled pipe applications. Plane stress develops on shear planes that form symmetrically at 45° through the thickness of the pipe wall, which gives rise to axial through-wall thinning local to the TWD that initiates propagating shear. In contrast, the other idealized

³ This is not to imply that only full-thickness strap specimens are prone to separations, because they also form under the stressing conditions in round bars – and will in any setting where the stress perpendicular to the rolling direction exceeds the interfacial strength of the local microstructure.



Fig. 21. Schematic fracture perspective for the effect of stress-state

state termed plane strain develops under local conditions that constrain flow, as occurs in thicker sections that limit through-wall thinning. This promotes the formation of an in-plane deformation fan that develops with axial symmetry and promotes the formation of a hinge-like local response. As such, plane strain favors heavier-walled pipe applications and gives rise to a symmetric deformation fan in the plane of the pipe wall. As evident from the Mohr's circle analysis shown in Fig. 21, failure occurs at a much lower shear stress in the context of plane strain.

To the extent that fracture serves as an analog, one can infer that the areal size of the shear process zone that develops in the wake of the plastic wave and the TWC zone is, in the simplest scenario, three times larger for plane stress than for plane strain [13]. As such, one infers that where plane stress controls the rate of dissipation is the order of three times faster for plane stress than for plane strain scenarios – all else being equal. Considering general circumstances the value of the maximum shear stress is much reduced in plane strain from that in plane stress with such Mohr's circle analysis indicating that for plane stress being ~1.5 times that for plane strain [13]. One can also infer in view of the Mohr's circle analysis that lower strength thinner wall pipes will arrest propagating shear faster than would higher strength heavier wall pipes.

Given that the above results are relevant to present purposes, the Mohr's circle analysis leads to a factor on the maximum stress the order of 1.5 for plane stress relative to plane strain, and a factor of on the order of 3 on the scale of the plastic zone. On such basis one can infer that the coupled effects of stress state on the rate of dissipation is significant. However, formal analysis is needed in a plastic collapse context to adequately quantify this aspect. Until such work is completed, the role of stress state will remain uncertain – beyond its clear influence in the context of separations.

Test geometries

Dissipation in the pipe versus that in current laboratory tests

As discussed in regard to the phenomenology and its interpretation in terms of collapse controlled failure, dissipation that slows the propagation speed of the TWC zone occurs through 1) in-plane stretch and 2) through-wall collapse in the thinner walled pipes. For thicker walled line pipe, dissipation that slows the speed of the TWC zone involves in-plane stretch but, as Fig. 21 indicates the contribution of the through-wall collapse component will be diminished. Regardless of whether the wall is thin or thick, the deformation local to the plastic wave front and the dissipation in its wake in the TWC process zone leading to arrest does not involve global bending. While it varies depending on the test circumstances and the steel involved, the speed of this plastic-wave front can be inferred from that of the propagating shear that forms in its wake. On that basis the speed of the TWC zone is on the order of 50 to 100 m/s (~150 to 300 f/s) approaching arrest, such that the plastic wave speed is at least that order, whereas its initial speed depends on the test conditions.

The circumstances developed in the CVN and DWTT specimens respectively used to quantify the resistance to propagating shear and the mode of failure as ductile versus brittle are quite different from just outlined for the line pipe. Each test practice leads to global bending developed by impact loading on the face of the specimen opposite the notch, which is cut or pressed into a beam subject to simple bending (3-point loading). While their loading is similar, their sizes differ, as do their proportions in regard to 1) span length relative to beam depth and 2) notch depth relative to the remaining ligament.

Viewed in elevation, the span, S, between load-reaction points for a CVN specimen is 40 mm (1.56 inch) whereas its

beam depth, d, is 10 mm (0.39 inch), while the notch depth, denoted a, is 2 mm (0.79 inch). In contrast, the span between load reaction points for a DWTT specimen is 254 mm (10 inches) whereas the beam depth is \sim 76 mm (3.00 inch), while the pressed-notch depth is ~ 0.5 mm (0.2 inch). On this basis, the ratio of S/d for the CVN specimen is 4, while the notch depth relative to the beam depth is 0.2. The corresponding parameters for the DWTT lead to S/d = 3.33and a relative notch depth of just 0.067. While in comparison to the CVN specimen the DWTT specimen creates the impression of deep beam, which opens to unique consideration of its shear distribution, for simple spans a deep beam has $S/d \le 1.25$ – so this is not a major concern for either geometry. The remaining ligament (net depth) for the CVN sample is just 8 mm (~ 0.32 inch) in contrast to ~ 71 mm (2.8 inch) in the DWTT specimen – which is almost a factor of 10. This difference is significant if the desire is to characterize crack morphology, but it is counterproductive if the desire is to emphasize plastic deformation metrics in regard to dissipated energy, as is the case where plastic collapse controls propagating shear.

The global bending that develops in both specimens induces a stretch zone across the notch, with lateral contraction developing through the thickness along the notch root, and compression and thickening occurring at the back face and support points. At lower toughness levels, including the range considered in calibrating the BTCM, both tests lead to crack initiation at the notch root, and a crack-tip "process zone" that propagates through the remaining ligament of the specimen. While less a concern at lower toughness levels, as the toughness increased continued propagation through that ligament at a high rate was conditional on 1) the excess energy supplied in comparison to that dissipated in failing the specimen, and 2) the existence of a small initial plastic zone due to high-speed impact. In this context, the size⁴ of the plastic zone that formed below the notch and at the loading points prior to 'initiation' differed depended on the specimen geometry used, and the speed of the hammer at contact, as well as the excess energy required to propagate that plastic zone through the ligament. While hammer speed is noted as relevant to the test outcome for both specimens, the speed of the hammer in the laboratory test varies with the setup but at best is typically 1/10th of that occurring for propagating shear in full-scale testing.

Test geometries for collapse-controlled propagating shear

The prior section has contrasted the line-pipe situation to the geometries used historically, with the outcome clear that alternative geometries are required to better capture the phenomenology of propagating shear. This is so whether you choose to persist with a 'fracture view' – but is essential if the collapse controlled view is a compelling alternative to the historic approach.

Realizing that the fracture view has been with us since the 1960s, the need for alternative geometries has been a priority development for some time. Early work tied to CTOA opened the door to develop a unique test practice more consistent with the field scenario. Although the opportunity was there, that work built on an adaptation of the DWTT geometry - which possibly constrained its evolution into a simple concept like the BTCM. Alternate fracture mechanics geometries such as the single edge-notch tensile 'SENT' geometry have been explored, with varying degrees of local bending developing depending on the length between the grips and end fixity. While many fracture-mechanics-based test geometries and loadings could be adopted – any change from the historical approach that develops without a correlating bridge to the past means that hundreds of full-scale tests become useless in testing the broad utility of the new test, or its ability to quantify resistance. In modern parlance - this is a slippery slope - that once on will be hard to return from.

The phenomenology and metrics of resistance discussed to this point in regard to the alternative collapse-controlled propagating shear perspective make clear that the historically used practices must be abandoned. Different test methods and geometries must be used to quantify collapsecontrolled resistance in terms of metrics like ε_f , UTS, and *n*, all of which are directional. But, while different geometries and test protocols and procedures are required, these are not new concepts. There is a wealth of experience and a set of basic standards on which to build. More critically, the observations made in regard to Fig. 17 suggest that it will be possible to correlate those parameters to CVN energy - at least in the context of a given class of steels. In that way, a bridge can be built back to the historic full-scale test database, with the collapse controlled predictive basis for arrest made back-compatible. As such the transition to the collapse controlled alternative technology has an already established basis to judge its utility.

It will be necessary to quantify the full-thickness response, in all three orthogonal directions. While this calls for some adaptation of currently used practices and techniques, again much exists to build on. And given such test methods are already implemented in the mills, managing a shift from fracture to collapse-controlled failure offers hope for a smooth transition.

While resistance in terms of plastic flow parameters should not pose issues, developing the test to ensure ductile response will be more challenging. The geometry should emulate the wake of a propagating TWC zone, where shear instability initiates and propagates. Because the high speed shear wave leads to high rate deformation in its wake, which can reduce the size of the shear zone and promote less-ductile response, this test must involve impact loading. Because a reasonable length of propagating shear must be simulated, the specimen must provide sufficient width for

⁴ Because the yield stress varies with strain rate under dynamic conditions, the 'size' of the zone depends on the rate, while the relative size varies with the grade of the steel, being relatively smaller in theory as grade increases.

the shear to run – such as a wide-plate test that is oriented axially rather than circumferentially. Symmetry is desirable, as it has the potential to initially minimize bending, and emphasize tension akin to the hoop tension that drives the propagation.

Finally, there is a need to trigger the propagating shear instability – which could be created and guided initially through deep but diminishing side grooves that function until the shear instability is triggered through the full thickness under the increasing impact loading and runs the width of the sample. Thereafter, inspection of the fracture features provides the basis to judge the fracture morphology. Unlike current concerns with the DWTT practice due to initially ductile response, which traces to concepts built around much less tough steels, because the test targets collapse controlled failure fully ductile response is expected. Fig. 22 illustrates one test concept that satisfies this generic test concept to validate in-pipe ductile response.

Clearly the outcome of this test practice is not as simple or as quick and cheap to produce and compete in a mill as was the DWTT. But, if steel-making and processing can be codified for a given order, and the related process parameters controlled adequately, and recorded/evaluated on-line in a digital framework, such testing could be done prior to full production and periodically thereafter – leading to a practical as well as technically viable mill practice.

Through-thickness properties

Prior discussion of the phenomenology and alternative concept to quantify propagating shear in a pipeline as collapse-controlled failure identified the true fracture ductility, the strain-hardening exponent, and the UTS as parameters to characterize resistance. The mechanics further indicate that the through-thickness properties are critical in this context. Given the strong properties-microstructure tie, it is useful to consider the potentially strong dependence of such properties on the steel chemistry and processing, as follows. While propagating shear and lamellar tearing have much different consequences, they both depend on the properties in the through-thickness (short-transverse, ST) direction. The properties developed in that direction quantify the resistance perpendicular to the plane that is affected by the orientation created in the concast process and in the rolling/finishing of the slabs. Depending on the temperatures during rolling/finishing, those properties also reflect the effects of the mechanical work done. As such, any resulting weakness on planes parallel to the surface of the product are evident as poor through thickness strength and ductility.

Fig. 23, which was developed in regard to lamellar tearing in structural Carbon Manganese (C-Mn) steels and adapted from Reference 38, is useful as the basis for discussion in this context. The *x*-axis in this figure is the true strain to failure, which is the same as what earlier was termed true fracture ductility. The *y*-axis is a metric of ductility termed the ductility index (DI), which depends on the inclusion density and their mean length [14]. The paper concludes with the view that the inclusion distribution offers a metallographic basis to establish mechanical properties.

The outcome of the paper and the trends in Fig. 23 are not new. However, the existence of a threshold in the DI is significant for present purposes, as is the fact that this threshold develops at quite low values of ε_f , with widely scattered results above that threshold.

In contrast to the trend in Fig. 23, excluding Grades that rely on less ductile microstructures, as for example X120, modern higher strength steels have values of ε_f in the axial or circumferential direction that are the order of five times larger than the bounding strain noted in the figure. This underscores the need to broadly consider both the chemistry and processing. While this is intuitive, its influence is now crystal clear in the context of collapse control of propagating shear. Major gains in propagation resistance can be affected in this regard.



net width = $\sim 10x$ thickness (NTS)

Fig. 22. One implementation of the generic test to validate failure mode



Fig. 23. Apparent threshold in inclusion density and ductility in the ST direction (adapted from [14]): ● – data for three C–Mn steels [12]

The observation that *ef* is increasing without correlation to the DI above the DI threshold is relevant, as this implies that the gain in ε_{f} develops for reasons other than reduced inclusion content. Gray has held the view that the absence of strong (100) texture is central to good through-thickness properties in the context of propagating shear since the 70s [e.g., 14]. Clearly the presence or absence of such texture could explain much of the scatter for the data shown in Fig. 23. This ill-characterized aspect is now the focus of ongoing work, which in the context of the alternative TWC characterization for propagating shear should bear fruit. In addition work is needed to quantify dissipation as a function of the steel's directional properties and their influence on the speed of the TWC zone as a function of pressure and other operational aspects. This too is the subject of just initiated work. These are major gaps in the current understanding and so key points along the critical path to formalize the TWC concept.

Implications concerninng inertial flap effects and arrestors

Over the years inertial effects were fundamental to analytical modeling of dynamic fracture as a route to quantify arrest toughness. Given the high-rate of the circumferential separation that forms in the wake of the TWC zone coupled with the mass of the "flaps" that results in flattening what began as a cylinder it is easy to understand the concern for this inertial driver for continued propagation in a fracture-based approach. Credence for the role of the flaps followed in the context of experiments that showed restraining the flaps using a ring or a sleeve (i.e., a hoop) around the pipe led to arrest of the 'fracture'. Significantly, successfully arresting 'fracture' in this context depended on misfit or clearance between the pipe and the 'fracture arrestor' prior to the test - with close fit-up needed for propagating shear and a tight-wrap required for brittle propagation. The length of the arrestor also was a consideration which follows from the time lag of the arrestor to react the driving force for propagation.

As support for fracture control of propagating shear develops in regard to non-integral fracture arrestors in regard to retrofit rings and/or sleeves, it is important to simply rationalize their apparent success in light of this alternative collapse-controlled approach, as follows. Any hoop around the pipe acts to restrain flap formation, depending on the extent to which the flaps open. Loose-fitting arrestors will contain flap formation, such that if fracture controlled then the restraint of flap opening over some length would limit the inertial feedback to the crack tip and lead to arrest. However, it was found that the effectiveness of hoop arrestors required close to tight circumferential fit-up - from zero to 2 % of the pipe's radius (typically). On this basis, in addition to restraining flap formation the arrestors also were constraining the circumferential stretch, thereby reducing the hoop strain.

Arrest occurs in the TWC zone when the steel can sustain the imposed local 3-D stretch, such that the success of hoop arrestors is anticipated within a plastic-collapse controlled TWC zone. Significant in this context is the observation that arresting brittle fracture required a tight fit-up in such experiments whereas a somewhat looser fit-up could be effective in the case of propagating shear. Equally significant is the observation that the fracture resistance quantified by CVN energy did not consistently correlate the arrest versus propagate results for such hoop arrestors. Quite simply, arrest in a TWC context is not characterized by the true fracture strain in just the hoop direction: rather, the TWC approach depends on the 3-D dependence on strength and flow properties. Thus, the surrogacy of CVN energy for true fracture toughness evident in Fig. 17, b in a one-dimensional setting indicates that CVN energy as historically measured in the LT direction is an inadequate surrogate in regard to hoop arrestors, and more generally.

The dependence of the TWC concept on the 3-D strength and flow properties implies that the design of an 'arrestor' dealing with brittle fracture propagation involves different concepts and success metrics as compared to when dealing with propagating shear, as follows. As noted in the context of Fig. 2 (see no. 1, 2015) the extent of plastic dissipation associated with brittle fracture is minimal at the micro-scale as well as at the macro-scale. Cleavage governs the formation of new fracture surface, which because this occurs at relative low stress limits the extent of flow remote to the fracture. The extent of the plastic flow and dissipation associated with propagating shear depends on the 3-D strength and flow properties. Where these properties support high stretch in all three directions, the dissipation local to the TWC zone is large, which opens to the spread of dissipation remote to this zone. In contrast, where the hoop and TW strain capacity is limited either by properties or the formation of splits, the dissipation local to the TWC zone is limited, which limits the spread of dissipation remote to this zone. On this basis it is possible to incur large hoop expansion, or virtually no hoop expansion, during propagating shear. Transitional states that mix brittle fracture with ductile response, due for example to the effects of stress state and wall thickness or 3-D differences in properties, likewise open to a range of response in regard to hoop expansion, although such scenarios tend toward virtually no hoop expansion.

On this basis, hoop-arrestor design for propagating shear should quantify the hoop expansion based on likely 3-D strength and flow properties specific to the application involved, and then limit hoop expansion to limit TWC. The length of the arrestor in this context depends on the speed of propagation, the time-lag inherent in the arrestor, and the amount of expansion relative to the critical value for TWC. Propagation in steels whose 3-D properties support significant hoop expansion is logically much easier to arrest than those that do not. In contrast, the design of arrestors for brittle fracture remains unchanged – as the TWC concept is specific to ductile response.

Summary and conclusions

This paper first reviewed the historical background and related developments that represent almost 40 years invested in fracture-based approaches to quantify propagating shear in pipelines. Thereafter, using graphical evidence of the full-scale failure process and related phenomenology an alternative hypothesis was presented to quantify this process based on a collapse-based view of this failure process. Finally, aspects of the historical fracture-based approach are related to the collapse-based concept as the basis to rationalize the success that at times has been achieved using such approaches.

It was evident that the phenomenology did not support fracture-control, and that metrics for arrest resistance should be based on the directional flow properties of the steel. It was shown that CVN energy correlates well with ε_f ·UTS, such that in a TWC view of propagating shear the success of the Battelle two-curve model coupled reflects CVN energy serving as a surrogate for key flow properties of the steel. Finally, remaining gaps and issues are addressed. The role of texture and its process dependence was identified in this context as was the need to quantify dissipation as a function of the steel's directional properties and their influence on the TWC zone and the plastic wave speed as a function of pressure and other operational aspects.

Many important conclusions were identified in the course of this paper, with the more significant ones including:

- the phenomenology associated with 'ductile propagating fracture' is that of propagating shear and is controlled by plastic collapse in a TWC zone that forms in the wake of a propagating plastic wave triggered by rupture of the pipe –
 - apparent for X52 (but likely lower) up through X80 (and likely higher), for CVN energy from ~20 ft-lb (~27 J) up to well above 200 ft-lb (~270 J);
 - the through-wall flow properties control failure, as do the in-plane flow properties, which together act to dissipate energy and so slow the TWC zone until decompression offloads the hoop stress, and arrest occurs;
- metrics of the resistance to propagating shear were identified in the context of the ε_{f} ·UTS and *n*, all of which are directionally dependent;
- the isochoric (constant volume) assumption of plasticity theory provides a quantitative link between reduced resistance to propagating shear and the existence and extent of splits (separations);
- simple established test practices exist that can be adapted as mill-tests to quantify the resistance of line-pipe steels to plastic-collapse controlled propa-

gating shear, whereas some effort will be needed to develop a mill-test practice to ensure the propagation process will be ductile;

- CVN energy historically used as a metric for the resistance to 'ductile propagating fracture' correlates with metrics of plastic collapse and strain-based failure, specifically as εf and ε_c ·UTS;
- success with use of the BTCM reflects its formulation relative to the plastic wave speed and its empirical calibration of that speed with CVN energy – which correlates to collapse metrics;
- the correlation between CVN energy and $\varepsilon_f \cdot UTS$ suggests that a bridge can be built between a collapse-controlled model of propagating shear and the extensive full-scale test database that has been largely based on CVN energy as such the predictive technology based on plastic collapse concepts can be 'back-compatible';
- the occurrence of texture and other aspects with metallurgy (which are tied to steel chemistry and processing) is ill-characterized but is fundamental to high resistance to propagating shear, which is a focus of ongoing work;
- work is needed to quantify dissipation as a function of the steel's directional properties and their influence on the TWC zone and plastic wave speed as a function of pressure and other operational aspects; with related work soon to be initiated.

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ПРИОСТАНОВЛЕНИЕ РАСПРОСТРАНЕНИЯ ДЕФОРМАЦИИ В МАГИСТРАЛЬНОМ ТРУБОПРОВОДЕ

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Аннотация. Для проявления распространяющегося пластического разрушения требуется, чтобы трубопроводы были спроектированы с учетом недопущения распространения трещин. Подходы, описывающие поведение трубопровода, его устойчивость и гарантированную остановку в случае сбоев в работе, основаны на полуэмпирических моделях, получивших свое развитие в середине 1970-х годов. Эти модели, которые калибровались на сегментах трубопровода в производственном масштабе (в натуральную величину), используются и сейчас, и включают три нелинейные характеристики: пластическую деформацию и винтовую неустойчивость; влияние структуры (состава) почв и увеличение волновой отдачи, а также декомпрессию в нагнетающей среде. Рассматривается более чем 40-летняя история расчета распространения деформации в трубопроводе, основанного на трещинах (механическом разрушении). Графические свидетельства полномасштабных сбоев в процессе работы обусловили появление гипотезы о сбоях, возникших в связи и пластическим разрушением.

Ключевые слова: распространение деформации, трещина, приостанавливать, вязкая сталь, степень пластичности, сталь, разделения/расщепления, разработка модели.

Список литературы см. выше.

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