Predicting Crack Arrest in Pipelines – Proposal for a Novel Analytical Approach

A novel analytical approach for determination of a required minimum toughness level for prevention of long-running ductile fracture is proposed. Material resistance to crack propagation is quantified via the elastic-plastic toughness parameter J integral. The leading part of crack driving force is considered to be represented by elastic distortion energy accumulated in the pipe-wall due to component stressing by internal pressure. Combining material resistance and component stressing enables to perform a limit state design for prediction of an arrest pressure. Finally, an alternative equation for calculation of a pressure dependent crack velocity is presented.

Within the design of a pipeline transferring gaseous media, prevention of long-running ductile fracture is of major concern. The general strategy is that, for the potential threat of a surface defect penetrating the full pipe wall, and starting to propagate in longitudinal direction, an arrest shall be achieved quickly and after only short propagation length. Therefore, dedicated design codes are requiring certain material properties [1], [2], [3].
Concerning fracture mode, ductile failure behaviour at minimum design temperature has to be proven by drop-weight tear (DWT) testing. The corresponding requirement is that the fracture surface of DWT specimens has to reveal 85% ductile fracture appearance at the specified testing temperature. Resistance against ductile crack propagation then is quantified via the Charpy-V notch (CVN) impact energy representing the main material parameter controlling crack velocity and propagation length. By balancing the pressure dependent crack velocity curve and the decompression velocity curve of the media, a minimum CVN energy can be determined which is required to arrest a running crack. The respective framework is known as Battelle two-curve (BTC) method [4], which has been applied successfully for pipeline design numerous times since it was established in the 1970's.
In the BTC model, minimum arrest pressure at crack velocity zero is determined based on an equation by Kiefner et al. [5]. Considering material toughness, a corresponding maximum sustainable hoop stress can be estimated. Material toughness here is expressed by a correlation to CVN energy. Originally, material resistance to crack extension is quantified via the linear-elastic stress intensity factor K_c. Following a proposal by Hahn et al. [6], a strip-yield plastic zone correction as first proposed by Dugdale [7] is applied trying to extend applicability of the equation also to higher toughness steels and elastic-plastic failure mode, while the involved toughness parameter is maintained. Besides a toughness based criterion for crack extension, Hahn et al. also report that, at high levels of stress corresponding to large-scale yielding conditions, the equation may be reduced to a simpler stress based failure criterion. The latter is reported to be particularly of relevance in case of tough materials and relatively short crack lengths c compared to pipe radius R, where the term short is being closer defined as c smaller than half times R. But for the case of running ductile fracture, the effective crack length c_{eff} is at around 2.4 times R. Hence, the case of a predominately stress controlled failure process in analogy to plastic collapse is regarded to be of minor importance within the context discussed here and will not be further considered.
Experience over the last two decades has shown that, within modern pipeline design, the reliability of the BTC method can come to its limits. A demand for increasing operating pressures requiring higher steel grades as well as more challenging operating conditions, e.g. as for rich gas or CO_2 applications, have lead to uncertainties regarding its applicability. Outcome of full-scale burst testing more frequently failed to match with preceding BTC predictions of ductile fracture arrest. As discussed quite comprehensively by Zhu and Leis [8], up to now several attempts have been undertaken to overcome this shortcoming. But nevertheless, a generally valid and reliable solution is missing yet. In particular, it is the value of CVN energy as involved toughness measure which still is put into question [9], [10], [11], [12]. In the following, an alternative analytical approach for determination of the arrest pressure will be presented.

MINIMUM ARREST PRESSURE AT CRACK VELOCITY ZERO

In an operating pipeline system, stressing by internal pressure generally is strictly limited to the linear-elastic regime. Looking at the cross-section of a pipe in terms of a closed ring, the stressing in hoop direction can be quantified also in terms of accumulated elastic distortion energy U_{el} per pipe length by

$$\breve{U}_{el} = \frac{U_{el}}{\Delta L} = \frac{p^2 \cdot \pi \cdot D_i^3}{8 \cdot t \cdot E} \qquad (1)$$

with:
- length unit ΔL, mm;
- inner pressure p, MPa;
- inner diameter D_i, mm;
- wall-thickness t, mm;
- Young's Modulus E, MPa.

This equation, which is similar to a solution as also discussed e.g. by Greenshields and Leevers [13], quantifies the elastic distortion energy in hoop direction, which is fully recovered during unloading. In case of a propagating through-wall crack, the cross-section of the pipe is disrupted and the ring opens up. Disruption of the pipe ring is equivalent to formation of fracture surface, which involves dissipation of energy.

At the instance of arresting a running ductile fracture, the pressure level in front of the crack typically is far below the level at initiation, which is happening at full operating pressure. Hence, the remaining energy from compressed media then is low compared to the state at initial operating condition. Assuming that the leading part of the driving force now can be governed by the accumulated distortion energy in the just yet closed pipe ring-section in front of the crack, it can be straight related to the energy dissipated in opening of the ring by formation of fracture surface during crack extension. The measure related to energy dissipated in crack extension in the elastic-plastic regime is the toughness parameter J-integral. This assumption leads to the following limit-state equation

$$\breve{U}_{el} \leq J_{mat} \cdot \Delta a = J_{mat,\Delta a} \qquad (2)$$

with: material toughness J_{mat}, N/mm;
length unit Δa, mm.

The material toughness measure J_{mat} is determined in a full-hit instrumented test of a pre-fatigued transverse full thickness $DWT_{(a/W=0.3)}$ specimen at design temperature (details see also [14], [15]):

$$J_{mat} = \frac{\eta \cdot A_{total}}{B \cdot (W - a_0)} \qquad (3)$$

with: $\eta_{pl,LL}$=1.53 (corrected for crack-depth ratio and load span);
total area under load-deflection curve A_{total}, N mm;
DWT specimen thickness B, mm (equivalent to pipe-wall thickness t);
DWT specimen height W, mm (76.2);
initial pre-fatigue crack-depth a_0, mm (target value: 23).

Now setting both ΔL and Δa to 1, a potential arrest pressure $p_{a,J}$ based on material's J value can be determined by:

$$p_{a,J} \leq \sqrt{\frac{J_{mat,\Delta a} \cdot t \cdot E \cdot 8}{\pi \cdot D_i^3}} \qquad (4)$$

Finally, being aware that for the case of an opening pipe ring-section, the mechanical loading system abruptly changes from membrane to bending-dominated stressing, apparently the influence of pipe geometry has to be closer taken into account. In analogy to a cantilever bending beam, it is medium diameter D_m as well as pipe wall-thickness t which then obviously are of relevance. While D_m is representing the span or length being stressed by internal pressure, t is reflecting the stiffness in terms of geometrical resistance to bending of the pipe wall. The following empirically derived geometry correction to $p_{a,J}$ is applied:

$$p_{a,J(geom)} = p_{a,J} \cdot c_{geom} = p_{a,J} \cdot \sqrt{\frac{t_{ref} \cdot D_m^2}{t \cdot D_{m,ref}^2}}$$

$$= \begin{cases} p_{a,J} \cdot \sqrt{\dfrac{t_{ref} \cdot D_m^2}{t \cdot D_{m,ref}^2}} & for\ c_{geom} \leq 1. \\ p_{a,J} \cdot 1 & for\ c_{geom} > 1. \end{cases} \qquad (5)$$

with: t_{ref} = 14.3, mm;
$D_{m,ref}$ = 1052.5, mm.

Eq. 5 is the final version as applied for determination of the J dependent minimum arrest pressure of a pipe at crack velocity zero.

PRESSURE DEPENDENT CRACK VELOCITY

With the aim to derive an equation defining the velocity of a propagating crack in a pipeline system, several reports of public available full-scale burst test results have been reviewed. The underlying data-base used for calibration does contain:

» grades X65 up to X100;
» 48 ≤ D/t≤ 84;
» 16.7 mm ≤ t ≤ 25.4 mm;
» 48" ≤ OD ≤ 56".

All test results considered were achieved in set-ups under soil backfill condition and with natural gas or air only. Within these boundaries, the following relation for crack velocity has been derived:

$$v_{cr,J(geom)} = C_J \cdot \frac{\left(D_{m,ref}/t_{ref}\right)^2}{D_m} \cdot \frac{\breve{U}_{el,0}}{J_{mat,\Delta a}} \cdot \left(\frac{p_{d(v)}}{p_{a,J(geom)}} - 1\right)^{m_J} \qquad (6)$$

with: pressure dependent crack velocity $v_{cr,J(geom)}$, m/s;
constant factor C_J=12 (soil backfill only);
constant exponent m_J=0.343;
$D_{m,ref/tref}$ = 80 (best-fit reference scaling value);
medium diameter D_m, mm;
initial elastic energy $\breve{U}_{el,0}$ at operating pressure p_0, N (see eq. 1);
velocity dependent decompressed pressure $p_{d(v)}$, MPa (e.g. as determined by GASDECOM);
others as defined above.

As the procedure discussed here is based on $DWT_{(a/W=0.3)}$ J integral as toughness measure, which is not generally available, a correlation to standard pressed-notch DWT total energy is applied. The constant parameters C_J and m_J of eq. 6 have been derived involving the following first draft correlation converting pressed-notch DWT total energy, data mainly in the range of 6500 J to 32000 J, to the corresponding measured $DWT_{(a/W=0.3)}$ J integral value in N/mm according to eq. 3 (invalid in the case of abnormal or inverse fracture appearance in pressed-notch DWT testing; stronger deviation towards lower toughness levels to be expected):

$$J_{mat,corr} = k \cdot E_{total}^{n} \qquad (7)$$

with: correlated material toughness $J_{mat,corr}$, N/mm;
constant factor k=282.8;
constant exponent n=0.3386;
total standard pressed-notch DWT energy E_{total}, J.

Eq. 7 is still being further developed and improved so that constant parameters k, n and subsequently also C_J and m_J may have to be adapted. Generally, the J_{mat} value determined with pre-fatigue $DWT_{(a/W=0.3)}$ specimens is to be preferred, also to avoid any issues regarding applicability of the correlation particularly in case of low DWT energy levels (data below 6500 J) and abnormal or inverse fracture appearance in regular pressed-notch DWT testing.

***Table 1**: Example calculations of arrest pressure $p_{a,J(geom)}$ (E=206 GPa)*

D_o, mm	t, mm	DWT_{PN} E_{total}, J	$J_{mat,corr}$, N/mm	c_{geom}	$p_{a,J(geom)}$, MPa
863.6	38.0	25000	8722	0.48	9.1
		50000	11029		10.2
914.4	25.4	12000	6803	0.63	7.5
		24000	8602		8.5
1320.8	20	8000	5930	1.00	5.4
		18000	7804		6.2
1422.4	27.7	12000	6803	0.95	5.9
		24000	8602		6.6
914.4	13.0	6000	5380	0.90	6.5
1219.2	18.4	15000	7337	1.00	6.6

EXAMPLE APPLICATION RESULTS

Example results for the arrest pressure $p_{a,J(geom)}$ calculated via eq. 5 are given in ***Table 1***. To demonstrate the impact of material toughness and geometry, six different dimensions and different levels of DWT pressed-notch total energy are considered. It can be recognized that the effect of an increase in DWT energy on the correlated J value, converted via eq. 7, is low. Therefore, apparently it is best to have J_{mat} as given in eq. 3 available from the outset to have a proper toughness quantification for the prediction of a material's ability to achieve crack arrest. Furthermore it can be seen that the impact of the applied geometry correction can become quite significant, in particular for smaller diameter pipes and in case of a rather thick pipe wall.

A comparison of crack-velocity curves derived with the BTC model and from application of the proposed analytical approach by Salzgitter Mannesmann Forschung (SZMF) is given in ***Figure 1***. The standard BTC model predicts arrest for CVN toughness levels above 121 J, the SZMF approach indicates propagation for 12 kJ and quick arrest for 24 kJ DWT total energy. Main differences between the two prediction tools with regard to shape of the curves are the higher initial velocity as well as a lower deceleration of the crack with decreasing pressure for the SZMF approach. This outcome is also similar to crack velocity curves as predicted by the HLP method [16] proposed by the High-Grade Line-pipe Committee in Japan, which involves DWT energy as toughness parameter too. The range of crack velocity predicted by the SZMF approach does match quite well with measured data from full-scale burst testing of a very similar setup as discussed by Abakumov et al. [17].

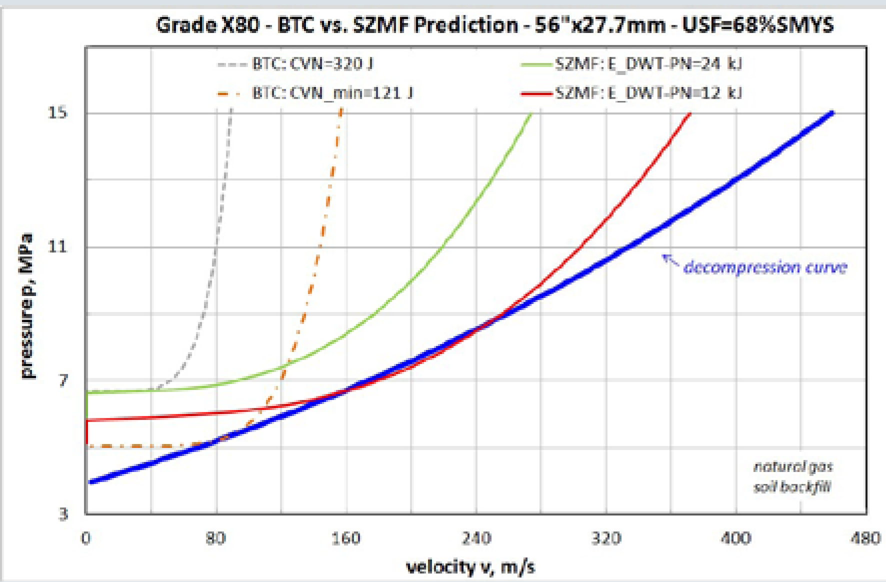

***Figure 1**: Comparison of crack velocity curve from BTC prediction vs. SZMF approach (usage factor 68% SMYS)*

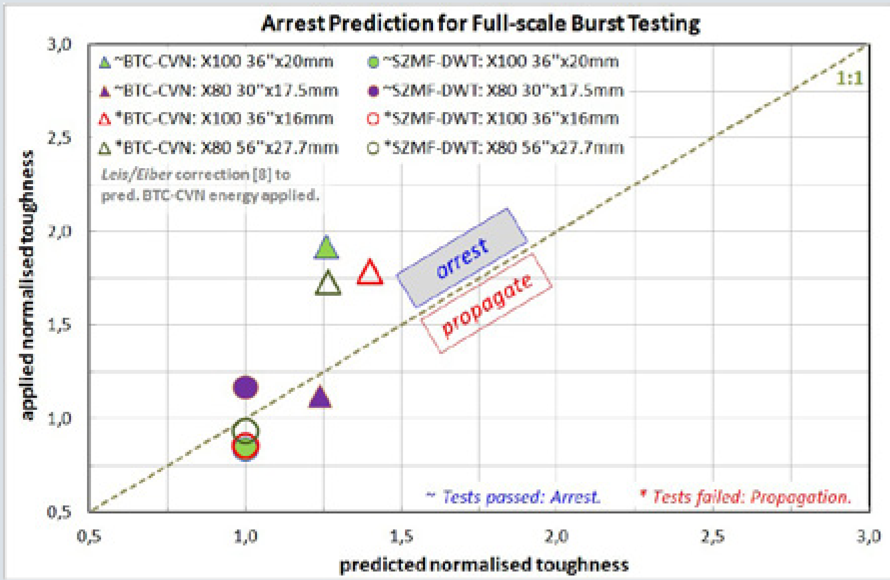

Figure 2: *Prediction results BTC and SZMF approach vs. corresponding test results*

A comparison of prediction results by the BTC model (Leis/Eiber correction [8] applied to predicted CVN value) and the SZMF approach based on internal and public available full-scale burst test data from [18] and [19] is given in ***Figure 2***. For the considered cases, the SZMF approach does show superior prediction reliability, but also yields some over-conservatism in the case of grade X100 with 20 mm wall thickness. The applied toughness level is predicted to be at only 84% of the required toughness to achieve an arrest, though it was confirmed to be sufficient on basis of the results from full-scale burst testing.

SUMMARY AND OUTLOOK

With the aim to provide prediction reliability and support designers with regard to prevention of long-running ductile fracture in pipelines, a novel analytical approach is proposed. The intention is to overcome existing uncertainties related to the applicability of standard prediction tools to modern pipeline design, i.e. for high strength and high toughness grades, elevated operating pressures and severe operating conditions. Core part of this approach is the quantification of material resistance to fracture propagation with the J-integral value. Stressing is quantified in terms of accumulated elastic distortion energy from internal pressure in the pipe wall before rupture. The J value is to be determined in an instrumented test of a DWT specimen pre-fatigued to a crack-depth ratio of 0.3 (crack depth equal to 30% of specimen height). A correlation to standard pressed-notch DWT total energy enables to assess data from full-scale testing for which the $J_{DWT(a/W=0.3)}$ value is not available. On basis of this correlation, relevant constant parameters of an equation defining crack velocity have been determined using public available burst test data. Maintaining the original idea of the BTC method, the regular CVN energy based resistance curve is substituted by the derived J based solution. General applicability of the novel procedure for crack arrest prediction has been demonstrated. It still is in the process of development and verification also as, particularly for high distortion energy levels $U_{el,0}$ prediction of the required toughness level tends to be overly conservative. Origin of this uncertainty may well lie in the applied correlation between DWT pressed-notch energy and J, with the latter being just moderately sensitive even to larger changes in DWT energy. Regarding backfill, yet only soil condition is covered. Also concerning transferred media, a closer investigation on rich gas or CO_2 has not been performed yet. All these aspects are part of ongoing research and will be addressed in future publications.

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