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# Predicting Crack Arrest in Line Pipes

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## ABSTRACT

As predicted ductile fracture arrest in line pipes more and more failed to match with the outcome of full-scale tests within the last decade, the applicability of standard prediction tools to modern pipeline design is put into question. To overcome this shortcoming, research at SZMF is focused on deriving a novel approach to crack-arrest prediction. Two independent routes are being followed. An analytical, energy based criteria shall allow for arrest pressure predictions involving a material toughness value. In a numerical approach by FEM, material damage is covered by an energy based cohesive zone model representing material resistance. The characteristic mechanical material quantities are determined by DWT testing involving pre-fatigued specimens.

KEY WORDS: Toughness; crack-resistance curve; ductile crack growth; DWT testing; J-integral; cohesive zone model; crack arrest.

## INTRODUCTION

Responding to market demands, strength and toughness properties of pipeline steels have been continuously increased as outcome of research and development within the steel industry over the last decades. At the same time, well established and more than 35 years old prediction tools for arrest of long-running ductile fracture have lost their reliability with respect to new steel grades for pipeline systems. As result of a first pragmatic solution by applying safety factors on a predicted minimum Charpy value, stringent toughness requirements have been established in terms of high Charpy impact energy. This issue brought up the question about the significance of the Charpy value as indicator for material toughness and input parameter for crack arrest predictions.

Over the last years, researchers all over the globe started to quest for alternative testing methods and different characteristic values to measure toughness of a material. Drop-weight tear (DWT) testing, originally developed only for determination of a transition temperature via fracture surface appearance, came naturally into the focus of ongoing research. Recent developments were mainly dealing with specimen modifications and notching procedures influencing crack initiation, propagation velocity and a toughness parameter as testing result. The latter relates to energy, measured by load-time plot from instrumented DWT testing, and crack-tip opening angle, e.g. determined in high-speed camera observation of specimen failure. Following standard fracture mechanics approaches, work within that scope at Salzgitter Mannesmann Forschung (SZMF) is focused on derivation of energy parameters in DWT testing representing ductile failure behaviour in terms of a dynamic crack-resistance curve $J_d$-$\Delta a$.

## TOUGHNESS BY J-INTEGRAL

In fracture mechanics, the J-integral is a well established parameter. It is a measure of material resistance to crack-growth or quantifies the crack-tip loading in terms of a local component stressing. Testing procedures for its determination as characteristic material value are well defined in different standards, e.g. ISO 12135, BS7448 Part 1 or ASTM E 1820. The latter provides a most recent procedure for determination of resistance curves involving J values corrected for crack-growth. This incremental procedure for J derivation, originally limited to single specimen compliance testing, is adapted to determine crack-resistance curves for dynamic loading condition in a DWT testing setup. The specimen type is chosen to be close to standard DWT specimen dimensions. Main difference is a pre-fatigue crack at a ratio of initial crack-depth $a_0$ to specimen height W of 0,3. This value is taken for two reasons. First of all, compared to a regular DWT configuration, the loading condition of the specimen is shifted more towards bending due to the lower ligament. Second, a preceding numerical study by finite-element (FE) simulation did show that, at relevant crack-tip loadings, the constraint at $a_0/W=0,3$ is in the range as found in a pipe exposed to inner pressure with longitudinal through-thickness flaw.

To be able to derive the J-integral from three-point bend testing according to ASTM E 1820, either crack-mouth opening CMOD or load-line displacement $v_{LL}$ is to be recorded. To apply the equations as given in the ASTM standard, the difference in crack-depth ratio as well as loading span compared to standard SEN(B) specimen still has to be covered. In the SZMF procedure, measurement of $v_{LL}$ is accomplished in an indirect manner. The position of the tup is recorded continuously during testing. This signal is taken to represent the specimen deflection. A derivation with respect to time also gives the tup velocity V. Combined with the recorded force signal at the tup, it enables to plot load F and V vs. $v_{LL}$, e.g. as given in **Figure 1**.

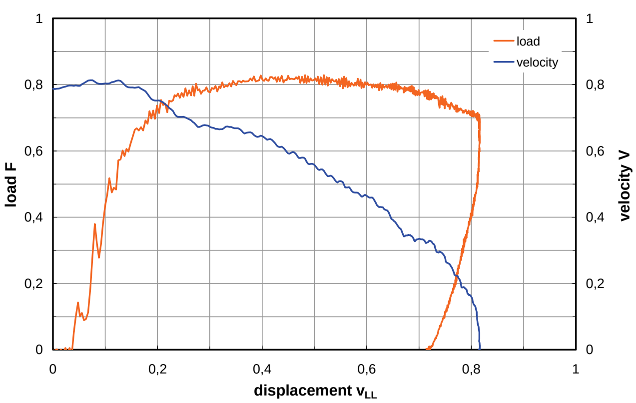

Figure 1: Norm.load and tup-velocity vs. displacement, low energy.

## CRACK-RESISTANCE CURVE DERIVATION

By exposing the pre-fatigued DWT specimens to different amounts of energy, varying levels of crack-growth are induced. A similar procedure for dynamic J-R curve determination was also applied by Böhme and Schmitt (1991). After testing, the ductile fracture area is marked by heat-tinting. The fracture surface is finally revealed in cleavage mode. Typical fracture surface appearances are shown in **Figure 2**.


low energy　　medium energy　　higher energy

Figure 2: Example fracture surfaces at different energy levels.

From a series of specimens, the amount of ductile crack-growth Δa and the corresponding J-integral values are determined. Ideal for derivation of the crack-resistance curve would be a data set giving evenly spaced values of ductile crack-growth. In particular, this is of major importance when applying the correction routine to consider crack-growth in determination of the J values. An exemplary result in normalized form is given in **Figure 3**. Alongside results for J from the basic approach and the corresponding potential fit, also the potential fit derived from J values corrected for crack-growth is shown. Towards larger amounts of Δa, the difference between the basic and the incremental procedure becomes more and more significant. The basic procedure leads to very high toughness values. Due to the fact that the influence of crack-growth on specimen failure is omitted here, toughness values by the basic procedure have to be taken with caution. Especially towards the upper region of the J-Δa curve, material resistance to crack growth is substantially overestimated.

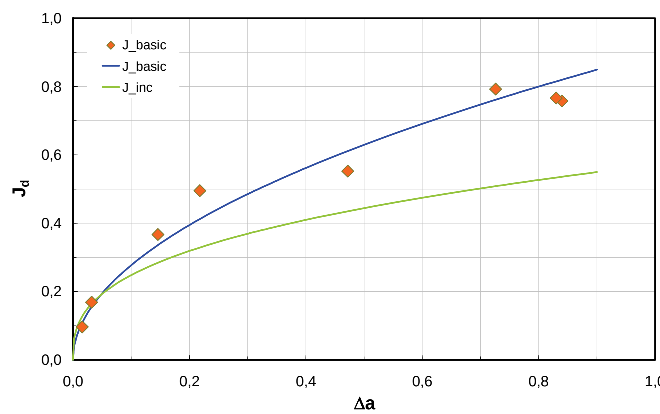

Figure 3: Normalized dynamic crack-resistance curve $J_d$-Δa.

## SMALL-SCALE NUMERICAL APPROACH

With the aim to cover DWT testing in a numerical approach, an appropriate FE model is designed. Material damage in terms of ductile crack-growth is considered by including a cohesive zone model (CZM). The CZM is a phenomenological approach in damage mechanics which is applicable to various modes of damage. It is defined by characteristic material values which are determined in small-scale laboratory testing. The amount of tests required for parameter determination is very limited. Compared to other damage mechanics models, it is a rather facile approach with limited expenses for calibration. Numerically, the CZM has proven to be a robust and efficient procedure. A comprehensive overview on theory and application of the CZM is given by Schwalbe et. al (2009).

At SZMF, a CZM provided by Scheider (2006) is employed. Damage behaviour is defined via characteristic material values. Two specific parameters have to be quantified, namely the separation strength $T_0$ and the cohesive energy $\Gamma_0$. This is done on basis of small-scale laboratory tests. The result of a first dynamic FE simulation is compared to laboratory DWT testing data in normalized form in **Figure 4**. Whereas the shape of the F-$v_{LL}$ curve is in close agreement, the overall load level of the FE model is too low. The deceleration of the tup between $v_{LL}$ of about 0,15 and 0,5 is very well represented. Towards the end of the test, the tup velocity in the FE model is too high and deviation to the testing data rises. These issues are expected to be improved in the second attempt with a FE model considering strain-rate effects. Including strain-rate dependence also involves recalibration of $T_0$ and $\Gamma_0$ so that the agreement of the curves is expected to be enhanced.

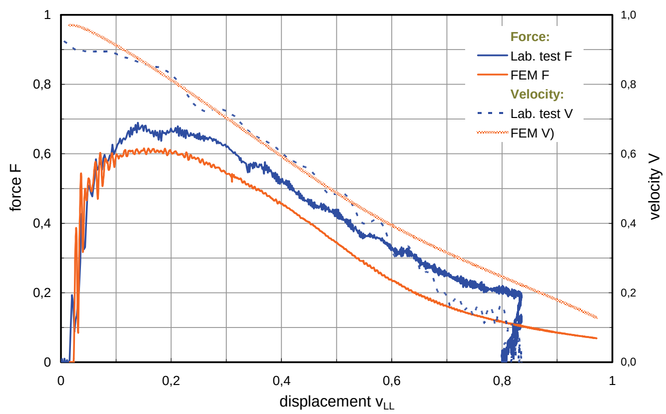


Figure 4: Norm.load and tup-velocity vs.displacement,test and FEM.

## CONSIDERING STRAIN-RATE SENSITIVITY

To cover effects of elevated strain-rates, a series of high-rate tensile tests is performed. A comparison of the characteristic values brought up that, as result of increasing strain-rate, it is mainly a higher strength level which is recognized. Concerning the numerical model, this can be covered by an upward shift of the flow-curve. The amount of strength increase is defined on basis of the approach derived by Cowper and Symonds (1957). Normalized yield-strength depending on strain-rate determined at five different rate levels is shown in **Figure 5**. The blue curve gives the result of applying the Cowper-Symonds equation.

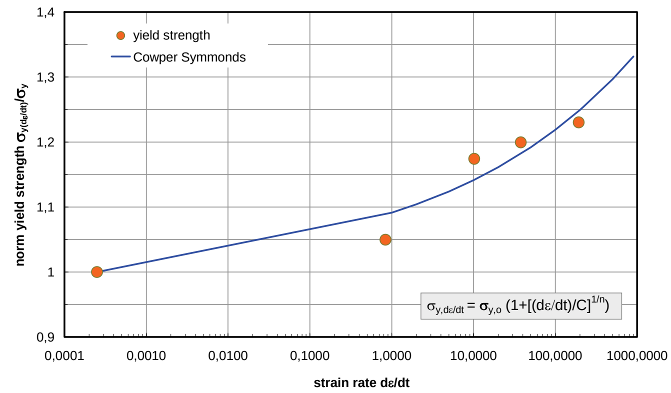


Figure 5: Normalized yield-strength in dependence on strain-rate.

## OUTLOOK

On basis of the procedures outlined above, two complementary routes for crack arrest prediction in line pipes are being elaborated.

From the dynamic crack-resistance curve $J_d$-$\Delta a$, a characteristic toughness value is derived which represents the material resistance to crack-growth $R_{(J)}$ in an analytical approach. This material resistance is balanced with a component stressing $S_{(D,t,p,\sigma)}$ which is determined involving specific pipe dimensions, pressure and material strength. In terms of a limit state design, the arrest pressure can be predicted by solving

$$S_{(D,t,p,\sigma)} \leq R_{(J)}.$$

In a FE model of the pipe component, crack propagation in terms of material damage is fully covered by the CZM approach. The specific parameters, which, as described above, have been determined and verified by small-scale testing, are applied to the component. Therefore, the material resistance to crack-growth R is well-defined. The crucial part is to apply the component stressing S. The driving force of crack-propagation is the inner pressure p. Its local distribution in longitudinal direction, especially backwards the crack-tip, and in circumferential direction has to be specified. Furthermore, this has to be done in correspondence to the global pipe deformation. As the crack propagates and depressurisation continues, it is of course a transient process. This is a highly complex issue. Target at SZMF is to cover all the above mentioned aspects in a simplified expression representing the pipe stressing. This is part of ongoing research.

Further details and results from the analytical and numerical approach to crack arrest prediction derived by SZMF are being published elsewhere in the near future.

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