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REVIEW AND EVALUATION OF ALTERNATIVE CHARACTERIZATION METHODS FOR THE FRACTURE RESISTANCE MEASUREMENT OF HIGH TOUGHNESS LINE PIPE STEELS

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ABSTRACT

Semi-empirical methods such as the Battelle Two Curves Model (BTCM), which are based on the Charpy V-notch energy, have been established in the 1970's to predict the propagation or arrest of running ductile fracture in natural gas transportation pipelines. However, the development in the recent years of high toughness steels leads to the loss of validity of these models and to the absence of reliable methods to design pipelines against running ductile fracture.
In this context, in the presented work, the reasons for the loss of validity of the semi-empirical methods have been determined to be the discrepancy between the crack tip loading conditions in the Charpy V-notch test and in a bursting line pipe. The loading conditions acting on the crack tip during running ductile failure have been therefore identified and alternative test methods able to reproduce these conditions at the lab-scale have been selected based on non-subjective criteria. These investigations revealed that the Modified Double Cantilever Beam/Modified Compact Tension and the In-Plane Stretching tests as well as the Back-Slot Drop Weight Tear Test might enable to measure the fracture resistance of the line pipe materials in relevant loading conditions. Furthermore, the critical Crack Tip Opening Angle ($CTOA_c$) has been selected as a quantity likely to characterize in a reliable manner the fracture resistance of the new line pipe steels. Based on these conclusions, a strategy is proposed to quantify the sensitivity of the $CTOA_c$ to various parameters such as the crack tip velocity or the specimen geometry in order to define guidelines for the reliable measurement of the fracture resistance.

DISCLAIMER

1. INTRODUCTION

1.1 Context and objectives

Running ductile fracture is a failure mechanism which can lead to a catastrophic crack propagation at high speeds, in the range of several hundred meters per second, in line pipes transporting natural gas. It is therefore crucial to integrate the criterion of running ductile fracture resistance into the design of pipelines. The definition and application of this criterion requires both a quantitative measurement of the fracture resistance and a method to determine if this value is sufficient to ensure the integrity of the pipeline during use. In the mid-1970 and for the steel grades available at that time, the Charpy V-notch (CVN) and/or Drop Weight Tear Test (DWTT) were considered to be tests delivering reliable values of the fracture resistance and these values were used for example in the Battelle Two-Curve Model (BTCM), a semi-empirical method based on a set of full-scale burst tests [1]. With this method, crack propagation or arrest could be predicted successfully based on the values for the CVN energy in a range of up to approximately 100 J.

However, with the development of modern and tougher steels (CVN fracture energy higher than 200 J) featuring different stress-strain behaviors, critical discrepancies have been observed between the predictions of the BTCM and experimental full-scale burst tests: crack propagations were observed in steels assumed to feature a sufficiently high fracture resistance to arrest the crack [2]. Investigations on the origin of this discrepancy have enabled to identify that the CVN tests exhibit, for high toughness steels, a large amount of plastic deformation (and therefore energy dissipation) in the specimen [3]. This energy dissipation which is not representative for the mechanism involved in a running ductile fracture led to an overestimated fracture resistance.

In general terms various parameters has been reported in the literature to influence the fracture resistance. These parameters are amongst others: the specimen geometry, the loading conditions (as presented in Figure 1) [4, 5, 6] or the loading rate [7].

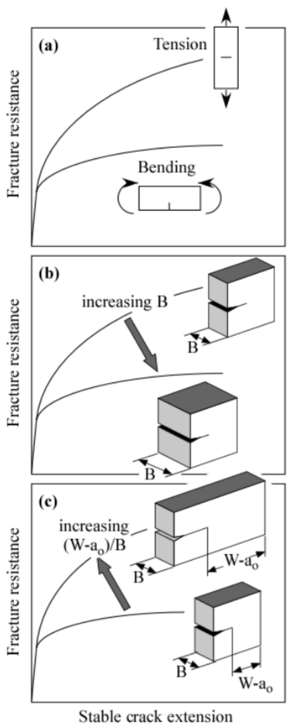


Figure 1: Influence of the parameters: loading condition, specimen thickness and crack or ligament length on the fracture resistance in metallic specimens [7].

Based on these observations, the determination of a relevant value of fracture resistance regarding running ductile fracture for high toughness line pipe steels requires addressing the following points:

- A relevant criterion needs to be defined to enable a quantitative comparison of the specimen loading conditions reachable at lab-scale with the crack tip loading conditions acting during a pipeline burst. This criterion would ensure the transferability of the fracture resistance measured at the lab-scale to the full-scale.
- A relevant quantity needs to be defined which enables to measure in a reliable manner the fracture resistance. This quantity should only consider energy dissipation due to crack propagation, be as much as possible independent of the loading conditions and should be easily measurable (in particular in a view of an industrial use of the test method).
- An experimental test method inducing crack tip loading conditions similar to the ones at work during pipeline burst should be determined.
- An experimental campaign should be designed to validate the suggestions made based on the literature

1.2 Influence of constraint on the fracture resistance

As mentioned in various scientific publications [4, 5, 6, 7], the fracture resistance is sensitive to parameters such as the loading conditions, the specimen geometry and the loading rate. As the specimen geometry (specimen thickness, ligament length) and the loading rate can be easily determined and measured, the major issue when comparing the loading conditions applied during two fracture mechanical test is to compare quantitatively the loading conditions. In fact, Mode I fracture can be obtained through purely tensile loads perpendicular to the crack propagation direction, in-plane bending loads or a combination of both. These remote loads lead to different loads at the crack tip and different amounts of dissipated energy due to the plastic deformation of the specimen.

In the framework of fracture mechanics, the concept of constraint is used to quantify the differences in terms of loading conditions between two configurations. Amongst the various quantities proposed to describe the constraint effects, the T-stress has been identified as an interesting quantity to compare quantitatively different testing conditions [8].

The T-stress is defined in the William's asymptotic extension describing the stress field in the vicinity of a crack as stress acting in the crack propagation direction for purely elastic materials [9]. For very small values of r (the distance between the considered position and the crack tip), and for a value of $\theta = 0$ (i.e. on a line aligned with the crack propagation direction), the T-stress can be expressed as defined in Equation (1).

$$T = \sigma_{xx} - \sigma_{yy}|_{r \to 0, \theta = 0} \tag{1}$$

As it can be seen in Equation (1), the T-stress can be calculated as the difference between the stress acting in the crack propagation direction (σ_{xx}) and the stress acting in the perpendicular direction (σ_{yy}) at the vicinity of the crack tip. This concept has been extended to elastic-plastic materials by considering the value of the T-stress at the edge of the fracture process zone [10, 11].

From a physical point of view the value of the T-stress has been reported to influence the size and shape of the plastic zone surrounding the crack tip as highlighted in Figure 2 [12]. The variations of the plastically deformed area around the crack tip explains therefore the influence of the constraint on the fracture resistance. Additionally, the sign of the T-stress has been reported to play a significant role on the path of the crack [13, 9]. Positive T-stress values have been shown to induce a deviation of the crack propagation direction, while a negative T-stress tends to ensure a straight crack growth.

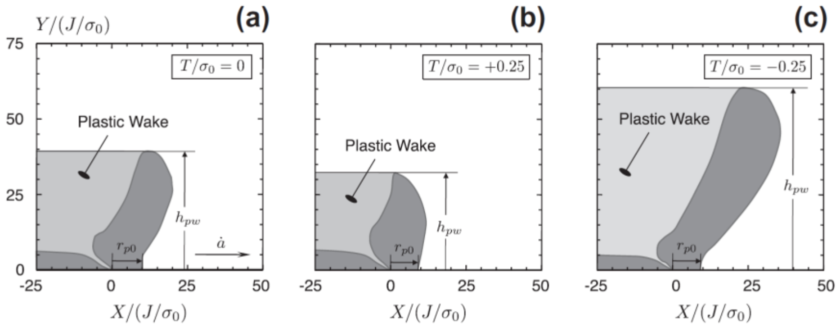


Figure 2: Influence of the sign and value of the T-stress on the size of the plastically deformed zone at the edges of the crack [12].

Therefore, the T-stress or at least the difference between σ_{xx} and σ_{yy}, which can be calculated or determined independently of any theoretical framework or material behavior, appears to provide interesting quantitative information on the plastically deformed zone around the crack tip and thus on the fracture resistance. It can be consequently seen as a promising criterion in order to ensure comparable loading conditions and thus transferability between the lab-scale and full-scale testing conditions. This conclusion is confirmed by the work of Sumpter [8]. In the present work, the notion of T-stress is further used to compare the loading conditions of the reference test methods. This is enabled by the existence of compendiums of the T-stress realized under the assumption of purely elastic material behavior for various fracture mechanical tests [14]. These calculations are used as a first approximation in order to determine if the specimen geometries are likely to generate the desired loading conditions on the crack tip. The exact loading conditions at the crack tip should be verified during experimental tests in order to determine the influence of the plastic behavior of the material.

In the frame of this work, the value of the T-stress (or $\sigma_{xx} - \sigma_{yy}$) acting on the crack tip during running ductile failure has been estimated in order to deliver a goal value for the experimental methods. To do so, the remote stresses acting on the line pipe have been estimated using the classical equations for the calculation of the hoop ($\sigma_h = \frac{Pr}{t}$) and axial ($\sigma_a = \frac{Pr}{2t}$) stresses in a cylinder subjected to internal pressure. It is additionally assumed that the relevant fracture resistance should be determined either at the onset of crack propagation or in a configuration in which the crack is propagating in an increasing or constant speed as these conditions are relevant to estimate if the fracture resistance of the material will enable initiating a reduction of the crack speed. In these conditions, the internal pressure of the gas ahead of the crack tip has not the time to decrease and the line pipe section ahead of the crack tip is therefore still subjected to the reference loading conditions. This gives a biaxiality ratio of $\eta = \sigma_{xx}/\sigma_{yy}$= 0.3 to 0.5 depending if the line pipe is buried or not. Using the work of Shlyannikov and Zakharov [15], a value of normalized T-stress $\overline{T} = T/\sigma_{yy}$ in the range of -0.4 to -0.5 can be estimated based on the remote stresses given by the biaxiality ratio. This negative value is in good agreement with the observed straight crack propagation during running ductile fracture.

1.3 Crack Tip Opening Angle to measure the fracture resistance

Various quantities have been proposed in the literature to quantify the fracture resistance of a material [4, 16, 17, 18]. However, in the recent years and in the context of the characterization of the line pipe materials, the Crack Tip Opening Angle (CTOA) and in particular the critical CTOA ($CTOA_c$) - the CTOA at the onset of crack propagation - is reported to be the most promising quantity [4, 19, 20, 21]. As for the other quantities to describe the fracture resistance, higher values $CTOA_c$ imply higher values of fracture resistance. Figure 3 presents the concept of CTOA and the difference to the Crack Tip Opening Displacement (CTOD).

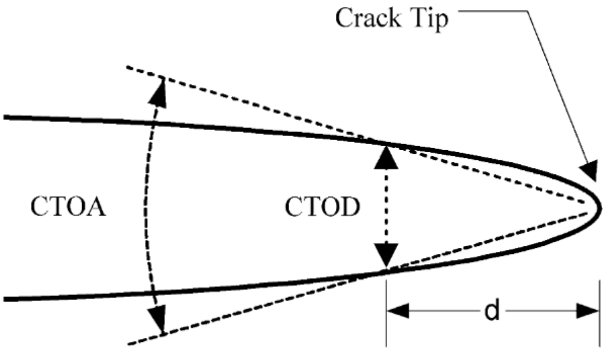


Figure 3: Relation between the CTOD and the CTOA [25].

The methods to measure optically the $CTOA_c$ have been standardized in the standards ISO 22889 and ASTM E2472. The local measurement of the CTOA is a major advantage which provides information on the complex plastic deformation around the crack tip. The fact, that the measurement is local, is also an advantage as for particular specimen geometries energy dissipative mechanisms, not associated with crack propagation could be at work during crack propagation and might influence global measurements.

Additionally, a method dedicated to Drop Weight Tear Tests (DWTT) has been standardized in ASTM E3039 based on the use of the force-displacement curve obtained from the tests and analytical equations [21].

Finally, it can be noticed that the CTOA can be used numerically either directly as a criterion to release nodes initially merged [19, 22] or to calibrate the traction separation low of a cohesive zone model [22, 23].

The $CTOA_c$ has been reported to be independent of the loading conditions and specimen dimensions in [21, 24], however, attention should be paid to several points in order to ensure the transferability of this quantity from lab-scale testing conditions to full-scale:

- Crack length

  It is important to ensure that the CTOA reaches a constant value during the test as the $CTOA_c$ in the initial and final portions of the ligament are mostly affected by edge effects [6, 25].

- Specimen thickness

  Contradictory results can be found in the literature regarding the influence of the specimen thickness on the $CTOA_c$ [26, 27, 28]. For this reason, tests on full-thickness specimens are encouraged in order to access relevant values of fracture resistance.

- Specimen dimensions, geometry and loading conditions

  Contradictory results can be found in the literature regarding the influence of the specimen dimensions, geometry or loading conditions. Authors reported various values of $CTOA_c$ for the same material tested with different loading conditions or specimen geometries [4, 5, 6]. On the other hand, similar values of CTOA were obtained from DWTT and form filmed burst tests

[24]. Finally, authors reported that the CTOA should be independent of the (tensile or bending) loading conditions for crack length and ligament length longer that four times the thickness of the specimen [18]. These contradictory results would require an investigation of the constraint effects acting in the different tests in order to determine in which extent the loading conditions acting on the crack tip were different and if the CTOA is practically independent of the specimen dimensions.

- Loading rate

The majority of the scientific publications read by the authors tended to affirm that the $CTOA_c$ does not feature a sensitivity to the loading rate. Several studies conducted in the range of velocities comprised respectively between 0.05 mm/s and 1 mm/s (test speed) [27], 0.002mm/s and 8 m/s (test speed) [29] and 100 and 200 m/s (crack speed) [25] did not observe changes in the values of CTOA. In the later study, comparisons with DWTT featuring a crack speed of 20 m/s provided similar values of CTOA. However, a study conducted using various geometries of Back-Slot Drop Weight Tear Tests (BS DWTT) (Table 1) and reaching crack speeds in the range of 20 to 150 m/s reported a strong change in measured $CTOA_c$. This study tends to encourage a verification of the influence of the loading rate on the $CTOA_c$ and in particular to verify that the measured changes in $CTOA_c$ for the various crack speeds are not due to the change in specimen geometry.

As a conclusion, the $CTOA_c$ is a promising quantity to determine the fracture resistance of the line pipe steels. However, preliminary investigations on the sensitivity of this quantity to the parameters: specimen dimensions, geometry and loading conditions as well as loading rate should be conducted.

2. PRE-SELECTED TEST METHODS

Based on a preliminary study using qualitative criteria (EPRG-project 216 – 2019, Report I- 18/20), six test methods likely to enable reproducing the loading conditions at work during running ductile fracture have been investigated. The aim of the presented work is to define and apply non-subjective criteria to determine which of these methods is the most likely to enable a relevant measurement of the fracture resistance of the material using the $CTOA_c$.

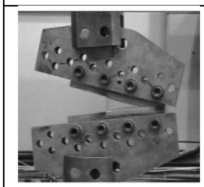
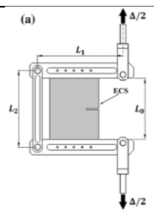
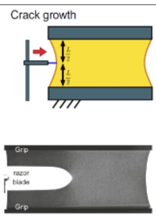
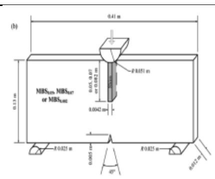
MDCB/MCT	IPS	CCS	WLDCB	USETT	BS DWTT
 Modified Double Cantilever Beam / Modified Compact Tension [13]	 In-plane stretching [30]	 Center crack specimen [31]	 Wedge Loaded Double Cantilever Beam [32]	 Unstable Single Edge Tensile Test [33]	 Back-Slot Drop Weight Tear Test [7]

Table 1: Six reference test methods investigated in this work.

The six test methods are:

- Modified Double Cantilever Beam/Modified Compact tension (MDCB/MCT)

  This test method is derived from the classical compact tension test. The test setup has been adapted in the way that the opening force is applied not only on one single hole in the specimen but on four holes along the crack propagation direction.

- In-Plane Stretching (IPS)

  The in-plane stretching specimen is similar to MDCB/MCT specimen but differs in the way that a beam is connecting two rotation axes at the outer edge of the specimen leading to tensile load (with varying intensity) over the whole length of the ligament.

- Center Crack Specimen (CCS)

  The center crack specimen consists in a sheet of the tested material in which a slot has been machined. The sheet is subjected to a tensile load perpendicularly to the slot.

- Wedge Loaded Double Cantilever Beam (WLDCB)

  The particularity of this double cantilever beam test is the introduction of the opening forces with a wedge. This enables for the high strength steels tested in [32] to induce unstable crack propagation at high speeds trough the ligament.

- Unstable Single Edge Tensile Test (USETT)

  This test is inspired from the experimental method presented in [33] in which a wide elastomer membrane is subjected to a tensile load and in which an unstable crack is initiated by inducing a crack at the edge of the specimen. This test induces for elastomers high crack velocities.

- Back-Slot Drop Weight Tear Test (BS DWTT)

  This test method is inspired from the classical DWTT with the difference that a high strength shim is introduced in a slot created at the back of the specimen. The load of the impactor is applied directly to the shim which transfers it to the middle of the specimen. This test setup has been reported to enable high crack speeds (in the range of 20m/s to 150m/s).

3. EVALUATION OF THE TEST METHODS

3.1 Definition of the evaluation criteria

The evaluation criteria are defined as follows:

- Crack propagation at a remote (hoop) stress below the yield stress of the material

  In order to reproduce, in an accurate manner, the loading conditions at work during crack propagation, the remote stress applied on the specimen to propagate the crack should not be larger than the yield stress of the material as this is not allowed by the design of the pipeline. This criterion also ensures that no plastic deformation of the whole area of the ligament occurs, which would not be representative for the real crack propagation conditions.

- Normalized T-stress at the crack tip in the range of -0.4 to -0.5

  According to the estimations presented in Section 1.2, the loading conditions and specimen geometry should ensure a normalized T-stress value in the range of -0.4 to -0.5.

- Full line pipe thickness

  Due to the contradicting trends given in the literature on the influence of the specimen thickness on the $CTOA_c$, the test method should enable the testing of specimens featuring the full thickness of the future pipeline wall thickness [26, 27, 28].

- Fast crack growth

  As introduced in Section 1.1, the crack speed during running ductile failure is in the range of several hundred meters per second [Tagawa]. In so far as the influence of the test speed on the $CTOA_c$ value could not be determined with certainty, the highest possible loading rates should be applied to the specimens. In this context, unstable crack growth would be preferred as they ensure crack propagations in the desired range of crack speeds. High rate tests with stable crack propagation are also acceptable.

- Force and $CTOA_c$ measurement

  In order to access the largest possible amount of information, the test should enable both loading force and $CTOA_c$ recording.

3.2 Evaluation

For the sake of brevity, in this section, only the critical criteria for each of the test methods are detailed. The criteria not mentioned have also been evaluated and they have been considered to be satisfied.

- Modified Double Cantilever Beam/Modified Compact tension (MDCB/MCT)

  For the MDCB/MCT tests, two criteria: on T-stress and on full wall thickness, could not be validated explicitly from the literature review. However, the following suggests that the criteria are likely to be satisfied. Regarding the T-stress, Ben Amara obtained in [11] negative values of T-stress for the MDCB specimen over the complete length of the ligament. A sensitivity analysis should be conducted in order to determine the extent the geometry can be adjusted to ensure that the normalized value of T-stress can fit the desired range of -0.4 to -0.5. Regarding the testing of specimens with full wall thickness, no proof of such tests should be found in the literature, however, such tests could be possible with loading blocks welded to the specimens in order to enable the transmission of the force at the edges of the holes without risking damage to the specimens.

- In-Plane Stretching (IPS)

  For the IPS tests, two criteria: on T-stress and on the high rate tests, could not be validated explicitly from the literature review. However, the following suggests that the criteria are likely to be satisfied. Regarding the T-stress, no study could be found in the literature investigating the T-stress induced by the IPS loading conditions, however, the similarity with the MDCB/MCT loading conditions is promising that the desired range of -0.4 to -0.5 can be reached. In this context, the addition of the vertical bar between the two loading bars can be seen as an option to adjust the T-stress if it cannot be reached with the MDCB/MCT setup. Regarding the high rate testing, no proof of high rate IPS test was reported in the literature. However, high-rate IPS tests could be conducted similarly to the high-rate MDCB/MCT tests [29].

- Center Crack Specimen (CCS)

  Based on the T-stress calculations made in [14], the normalized T-stress for the CCS test is below -1 and therefore out of the range of desired normalized T-stress values.

- Wedge Loaded DCB (WLDCB)

  Due to the vertical compression load applied by the wedge on the arms of the double cantilever beam, the biaxiality stress ratio has to be negative. Based on the work of Shlyannikov and Zakharov [15] this implies a normalized T-stress value less than -0.8 and therefore out of the range of the desired normalized T-stresses. Additionally, the test setup does not enable a proper measurement of the opening force applied to the arms of the specimen.

- Unstable Single Edge Tensile Test (USETT)

  In order for the USETT specimen to feature the desired unstable crack propagation, a sufficient amount of elastic energy needs to be stored in the specimen and the machine prior to the crack initiation. Due to the large plastic domain featured by the current line pipe steels, the amount of elastic energy that can be stored in order to reach unstable crack growth has been estimated to be too small. A plastic deformation of the whole specimen would therefore be necessary to reach the required state of loading and this disagrees with the criterion on the remote stress which should be maintained below the yield stress of the material.

- Back-Slot Drop Weight Tear Test (BS DWTT)

  No evaluation of the T-stress has been conducted for DWTT specimens featuring a high-strength shim on the back side. However, as the DWTT covers a wide range of T-stress values [14], it can be assumed that, based on a sensitivity analysis of the specimen characteristics as per [14], the T-stress can be adjusted to reach the desired range of -0.4 to -0.5.

As a conclusion, the MDCB/MCT, the IPS and the BS DWTT tests are the most promising to measure a relevant value of fracture resistance.

4. CONCLUSION AND PERSPECTIVES

The goal of the presented work was to identify a way to measure under relevant conditions the fracture resistance of high toughness steels which behavior regarding running ductile fracture cannot be predicted with the classical methods such as the BTCM. In this context, the loss of validity of the BTCM has been investigated and attributed to the too large difference between the CVN loading conditions and real pipeline bursting conditions. Starting from this statement, a criterion enabling a quantitative comparison of the testing conditions has been identified. This criterion is the difference between σ_{xx}, the stress acting in the crack propagation direction at the vicinity of the crack tip and σ_{yy} the stress in the direction perpendicular to the crack tip propagation at the vicinity of the crack tip (called T-stress in the framework of the fracture mechanics of purely elastic materials). A range of values of T-stress relevant for the real pipe line burst could be defined.
Furthermore, the $CTOA_c$ has been identified as a relevant quantity for the fracture resistance of the material. This quantity features the advantage to be local (and therefore to be applicable to methods

in which other dissipative mechanisms than the energy dissipation due to crack propagation are at work). However, the sensitivity of the $CTOA_c$ to the loading conditions and to the loading rate could not be clearly determined which would require additional investigations supported by experiments. Finally, six experimental test methods have been evaluated using non-subjective criteria to determine the ones which should be the most appropriate to reproduce the loading conditions acting on the crack tip during running ductile failure. The MDCB/MCT, the IPS and the BS DWTT have been found to be the most promising.

The following is recommended in order to confirm the results obtained, based on the presented literature review. The first step would be to evaluate the capacity of the T-stress to serve as a criterion to ensure the transferability of the measured CTOA. The CTOA could be measured for three specimen geometries and testing configurations from which two (ideally different types of tests as MDCB and DWTT) would feature a similar T-stress value in the range of the one desired (-0.4 to -0.5) and one would feature a different T-stress value. If the two tests featuring the same T-stress generate the same $CTOA_c$, the transferability would be confirmed and the value of CTOA obtained for the third configuration would indicate the sensitivity of the CTOA to the T-stress. If three different values of $CTOA_c$ are obtained, further investigations would be required. A similar procedure should be applied for the sensitivity analysis of the loading rate on the $CTOA_c$ using various DWTT and BS DWTT specimens. The high-rate tests based on the BS DWTT might additionally serve as basis for an industrial test method. Finally, a reliable method to predict crack propagation or arrest based on the $CTOA_c$ should be developed and validated.

5. ACKNOWLEDGMENTS

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