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Direct measurement of the resistance to ductile fracture propagation

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ABSTRACT

The resistance to ductile fracture propagation remains a weak point in gas transmission pipelines' safety since the emerging of this risk more than half a century ago. Full-scale burst tests of pressurized gas pipeline sections are performed to verify the ability of pipeline steel to arrest the crack propagation. However, motivated by the commitment to specific predictive models, the main outcome from full-scale burst tests (FSBT) has been in form of a binary "propagation/arrest" metric corresponding to each pipe in the test section. In the absence of a reliable laboratory-scale test demonstrating correlation with the full-scale resistance to ductile fracture propagation, such approach does not appear reasonable since it leaves line pipe manufacturers with very little clue regarding the preferential metallurgical designs. This work aims to better quantify the crack propagation resistance in FSBT providing metallurgists with a target property and facilitating the development of a new laboratory-scale mechanical test that shows reasonable correlation with FSBT. In order to improve FSBT testing methodologies, the pipe wall strain related to the crack propagation should be assessed along the entire test line. This can be implemented by means of modern 3D-measurement technologies that can digitize very large objects with high accuracy at a reasonably low cost. The method is demonstrated in the current work using the results of a recent FSBT carried out on X80 grade pipes. The results indicated that the plastic strain zone in FSBT can spread from the fracture surface over distances equivalent to tens of pipe wall thicknesses, while in the widely adopted drop weight tear test (DWTT) this spread hardly reaches one specimen thickness. Single-edge notched tensile (SENT) configuration provides much larger extent of the plastic zone into the specimen gauge when compared to DWTT whose major deformation mode is bending. Furthermore, the correlations between the strain parameters in different tests are discussed, and conclusions are drawn to promote a new laboratory test method for ductile fracture propagation resistance assessment in high strength steel pipe.

1. Introduction

The efficiency of gas transportation increases with the increase of pipeline diameter and operating pressure [1]. The use of higher-strength line pipes provides opportunities to decrease the amount of steel per unit length of pipeline and thus to reduce the construction cost and the carbon footprint impact on the environment. However, increasing operating pressure and steel strength also increases the risk of the ductile fracture propagation, which can extend over many kilometres all the way to the nearest compressor stations. The assessment methodology of this risk becomes less and less clear with the progress in pipeline steel metallurgy and the emerging demand for carbon dioxide transportation [2–4].

1.1. State of the art

The ductile fracture propagation is a process of longitudinal tearing of a pressurized gas pipeline after its integrity is lost for one reason or

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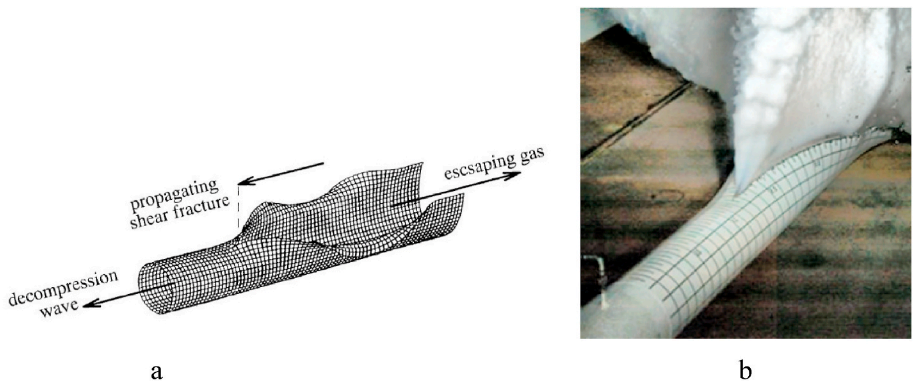


Fig. 1. Running ductile failure in a pressurized gas pipeline. a – schematic, b – high-speed footage frame [5].

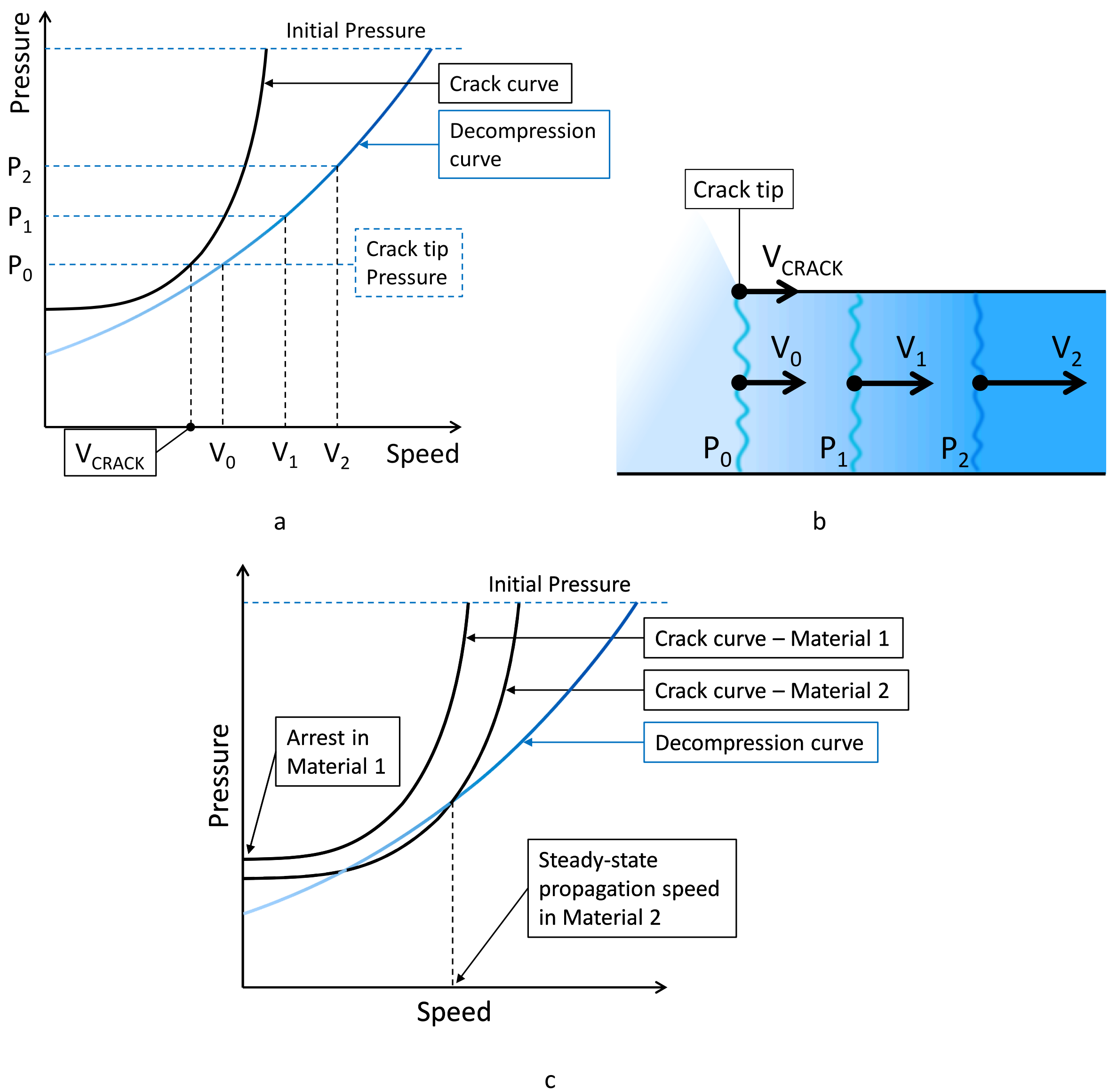


Fig. 2. The two-curve concept. a – arbitrary crack and decompression curves with several pressure and speed values corresponding to the schematic in (b); b – schematic visualization of pressures and speeds inside a pipeline in the vicinity of propagating crack tip; c – different crack curves leading to crack arrest (Material 1) and steady-state crack propagation (Material 2).

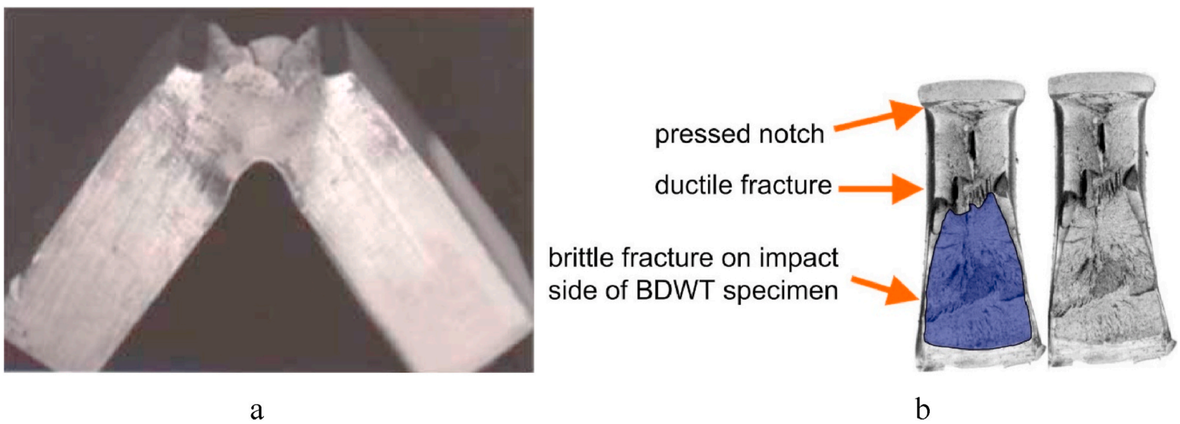


Fig. 3. Unbroken Charpy specimen [10] (a) and the inverse fracture appearance in DWTT [11](b).

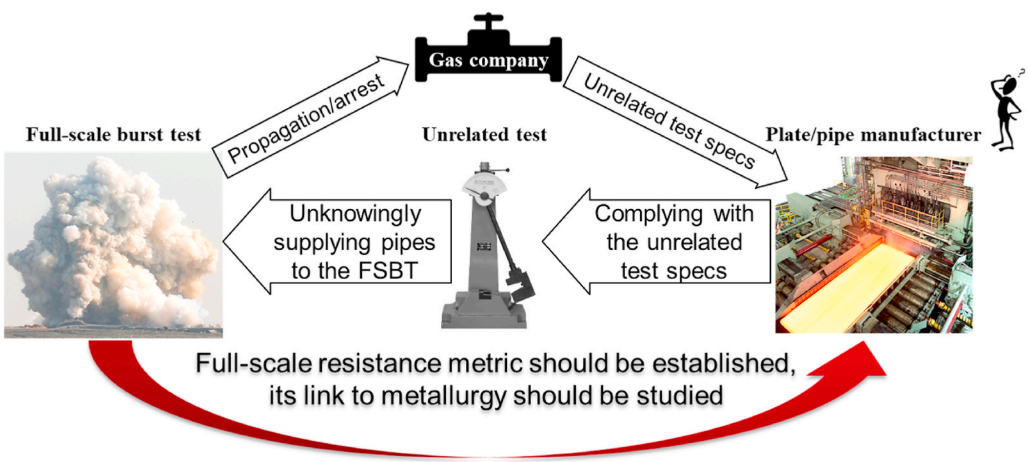


Fig. 4. "Vicious circle" in the communication between pipeline engineers and metallurgists and the need for better assessment of the FSBT.

another (Fig. 1). The gas decompression is not an instantaneous process, so the crack can advance driven by the residual pressure at the crack tip. This is therefore a competition between the crack propagation speed and the gas decompression speed, which can be visualized in the pressure versus speed diagram by means of two curves (Fig. 2, a). The decompression curve illustrates the decompression wave, i.e. the fact that the higher-pressure fronts inside the pipeline run faster than the lower-pressure fronts (e.g. front P2 runs faster than front P1 in Fig. 2a and b). The crack curve shows the relationship between the crack speed and the residual gas pressure corresponding to the position of the running crack tip (crack tip pressure), and therefore it is believed to characterise the material's resistance to ductile fracture propagation. For example, in Fig. 2a and b, crack tip pressure P0 results in crack propagation at speed V_{CRACK}. To be arrested, the crack propagation should always be slower than the decompression, i.e. the crack curve should not intersect the decompression curve in the figure. The intersection point (Fig. 2, c) will indicate the equilibrium between the driving force provided by the residual gas pressure and the resistance force provided by the pipe material. So that the crack will continue to propagate at a constant speed corresponding to this intersection point (given the pipeline wall material stays the same).

The introduction of the two-curve concept in the 70s [6] strongly motivated a continuous effort inputting on predicting the exact appearance of the two curves. While the decompression curve can be predicted reasonably well for a given gas composition compared to experiments, the crack curve has been subject to debate ever since, particularly as pipe strength has increased from typical X52 to now X70/X80 grade pipes.

Most of the crack curve predictions were based on the results of laboratory impact bending tests: Charpy test or drop-weight tear test (DWTT). Besides the fact that the correlation between these bending tests and the full-scale pipe tearing has never been strong [7–9], the tests have become practically inapplicable to modern high-toughness pipeline steels due to their intrinsic methodological artifacts: Charpy specimens often cannot be broken completely in fully ductile mode [10], and DWTT specimens experience the so called "inverse fracture" – embrittlement due to the compressive straining from the impact [11] (Fig. 3).

To date, the only reliable way to reveal line pipes' resistance to ductile fracture propagation is to carry out a full-scale burst test (FSBT), i.e. to construct a pipeline section in a remote area, pressurize it and then breach it to initiate fracture propagation. However, the tradition of choosing material based on a laboratory-scale mechanical test has trapped the communication between pipeline engineers and metallurgists in a vicious circle of unsuccessful attempts to accurately predict the results of FSBT by the results of a standardized laboratory test (Fig. 4). Metallurgists have to design their steel to comply with specifications built around a laboratory test which does not reflect the full-scale performance. Yet their product can still be rejected based on the results of a FSBT. The extremely expensive FSBT has become merely a verification tool for the prediction exercises, with the main output being a binary "propagate/arrest" metric for each pipe [12].

1.2. Means of shifting the paradigm

It appears that in the situation described above a more effective approach would be to quantify the resistance to crack propagation

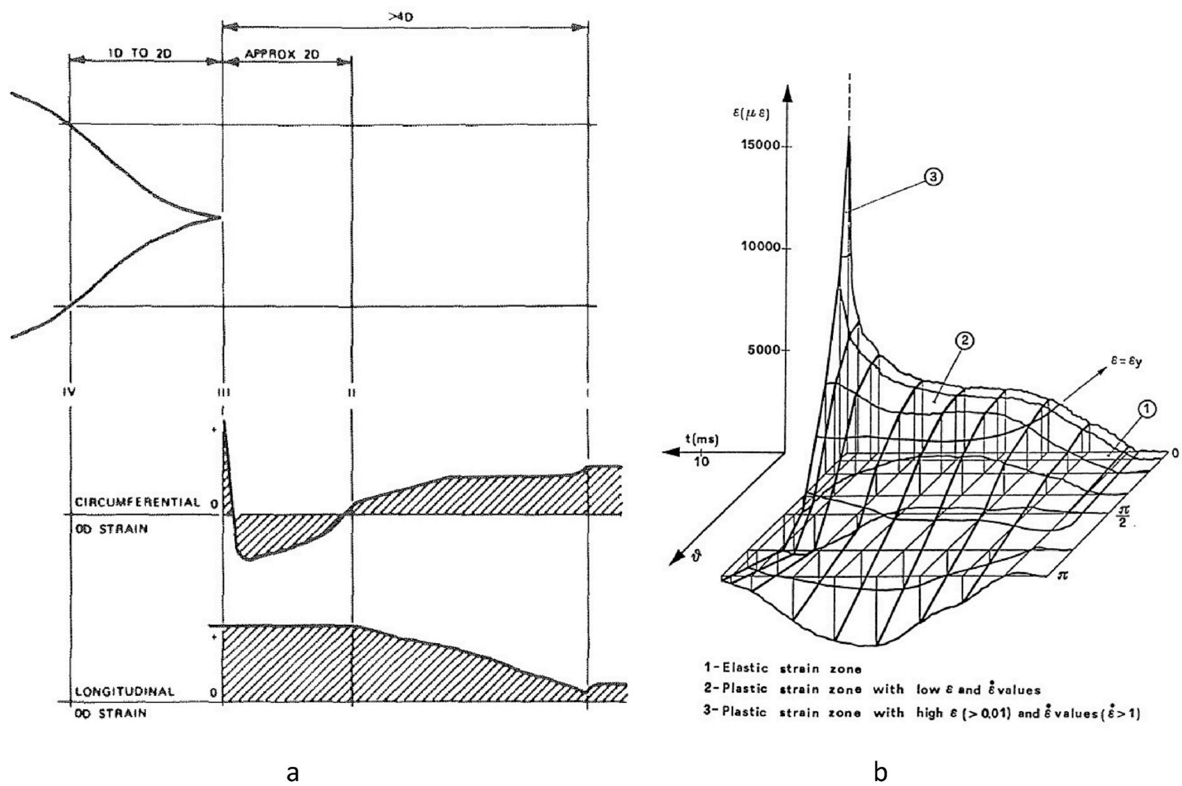


Fig. 5. Distribution of strain ahead of a running ductile crack according to strain gauges readings (a) [13], (b) [14].

directly in the FSBT and to relate it to metallurgical characteristics of steel (Fig. 4). In this way, metallurgists would be provided with the actual target property and could explore how the metallurgical design of pipeline steel affects it. A more thorough examination on the material fracture behaviour in FSBT can also help the development of a new laboratory-scale mechanical test which would show reasonable correlation with FSBT. Having such test as a guidance along with the metallurgical understanding of the resistance to ductile fracture propagation could re-initiate the progress in this stagnating topic.

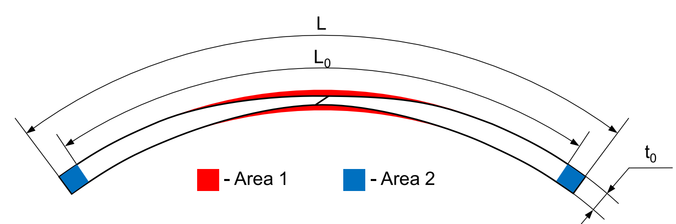
Based on foregoing discussions, it appears reasonable to suggest that the following research directions should be prioritized to gain the necessary knowledge to better address industrial concerns:

1. Development of methodology for the ductile fracture propagation resistance quantification in FSBT.
2. Development of a laboratory-scale testing methodology to reveal the level of the full-scale ductile fracture propagation resistance (at full thickness).
3. Correlation of metallurgical characteristics of modern pipeline steels with respect to full-scale ductile fracture propagation resistance.

These directions are interrelated with the first one being paramount since it is supposed to establish the target property as a foundation. Given the expensiveness of the full-scale tests, attempts should be made to advance in these directions to an optimised extent based on the available and valuable FSBT results and samples. In this article a recent FSBT will be considered, and the above directions #1 and #2 will be discussed based on the results of this test and laboratory mechanical tests for the materials from this test.

1.2.1. Quantification of ductile fracture propagation resistance in FSBT

Evidence has been collected to suggest that the resistance of pipeline steel to ductile crack propagation in a pressurized gas pipeline is related to the amount of energy dissipated by straining of the pipe wall material around the running crack tip. The details of this plastic zone were evaluated reasonably well using data from multiple strain gauges attached to the pipe wall [13,14]. It appeared that the plastic zone extended for several pipe diameters in front of the running crack tip, and the strain magnitude and its principal direction changed in a complex way, as schematically shown in Fig. 5.



$$\frac{\text{Area 1}}{t_0} = \frac{\text{Area 2}}{t_0} = L - L_0 = \Delta$$

Fig. 6. Two-dimensional concept of the plastic zone parameter Δ [15,16].

The strain associated with the crack propagation in pipeline can be quantified by means of the wall thinning measurement in areas adjacent to the fracture surface after the test. The output value can be in a form of equivalent elongation (Fig. 6) or energy, which can be roughly calculated based on strain hardening curve from a standard test [17,18]. However, manual measurement of thinning is inefficient and subject to objectivity. The implementation of a 3D scanning system for conducting strain assessment will be demonstrated in the following sections of this article.

The variations in the magnitude of plastic strain and crack propagation dynamics over short distances are rarely discussed yet hold a potential to reveal the intrinsic material characteristics defining the crack propagation resistance. Transitions of the crack from pipe to pipe and thus the importance of the pipe length and pipe positioning are discussed in Ref. [19], the question of the relationship between the strain and the crack speed is posed in Ref. [20].

Recent advances in modelling of the ductile failure propagation in pressurized pipeline based on modified Bai-Wierzbicki model demonstrated promising results [21–24], however, required very detailed mechanical characterization of the material and significant computational resources. So that might not be applicable for direct industrial application.

Therefore, on the FSBT end, it appears reasonable to improve the methodology of strain assessment and to correlate this strain characteristic to the conventional measurements of the dynamics of crack propagation and gas decompression in FSBT.

1.2.2. New laboratory mechanical test procedure

Single-edge notched tensile (SENT) tests are widely used for various applications. In relation to ductile fracture propagation in pipelines, plate-like SENT specimens were used in conjunction with crack tip opening angle (CTOA) concept development [25,26]. A simplified quasi-static SENT test procedure was proposed by RosNITI upon the analysis of a FSBT series organized by Gazprom [27]. The absorbed energy values in this test demonstrated better correlation with FSBT behaviour than those in any of the conventional bend tests (Charpy/DWTT). This test was recommended as a standard practice for line pipe suppliers [28].

In the work presented in this article, the SENT approach was extended to dynamic conditions. A custom-designed SENT test was employed to illustrate the difference in the plastic zone spread in steels with different level of the full-scale ductile fracture resistance, rather than to analyse parameters used in classical fracture mechanics. In the last section of the article, a new testing procedure is suggested with a potential to be performed in existing drop-weight testing machines.

It appears that a model which will accurately predict the full-scale crack propagation resistance is unlikely to be built based on the knowledge currently available, but this can change as the new FSBT assessment techniques are adopted and a new laboratory test is developed. This work aims mainly at short-term improvements in metallurgical understanding of the full-scale ductile fracture propagation resistance but at the same time points at the fundamental features of the phenomenon which should be considered in future models.

2. Materials and methods

Base metal of API X80 grade line pipes subjected to a FSBT is analysed in this work. The pipes' characteristics are therefore presented in the FSBT description below. The materials were available in pre-test (cut from pipes before the test line construction) and post-test (sections adjacent to the fracture surface with known position along the crack propagation path) conditions.

2.1. Full-scale burst test (FSBT)

2.1.1. Typical FSBT methodology overview

A FSBT is a procedure implemented on a section of pressurized pipeline, specifically built to simulate real pipeline conditions. The pipes being tested are put in the centre of the test line, but the entire line is usually much longer than this test section to ensure that the decompression is not affected by the decompression wave reaching the line ends. Longitudinal crack propagation is usually initiated by an explosive charge in the centre of the test section, which leads to two crack propagation directions.

Often the pipes in the test section are positioned in a way that correlates to their laboratory-scale toughness values. This is because that the values are believed to correlate with the full-scale crack resistance, which increases from pipe to pipe in both directions from the initiation point (so-called "telescoping" of toughness). If the crack is arrested in one of the test pipes, the toughness value of that pipe would then be suggested as the upper bound of minimum required for the arrest. In most cases, the initiation is performed in the centre of a dedicated "initiator" pipe whose resistance to crack propagation can be deliberately reduced to ensure high speed of the crack entering the "first" pipes, so that crack propagation in real situation can be better simulated.

Table 1
FSBT conditions.

Pipe strength grade	X80
Pipe wall thickness (WT), mm	20.6 and 22.9
Pipe outside diameter (OD), mm	1219
Pressure, MPa	15
Design factor	0.8 and 0.72
Pressurizing medium	Rich gas
Ground backfill depth, m	0.8
Test temperature, °C	1.5

The main components of the test instrumentation are:

- Timing wires – girth wires positioned at known distances from the initiation, which break when the running crack crosses their positions. The events of the timing wires failure are recorded to determine the crack speed.
- Pressure transducers positioned inside the pipes at known distances from the initiation, in order to record the dynamic pressure changes upon crack initiation. These data are used to assess the decompression speed of the pressurizing gas medium.

Other measurements can include control of the static pressure inside the test line, temperature of the pressurizing medium and the pipe wall, various atmospheric conditions, strain measurements by means of strain gauges, etc.

As mentioned in the introduction, due to the commitment to build/comply predictive models, main outcomes from FSBT have predominantly been binary "propagation/arrest" metrics corresponding to each pipe involved in the crack propagation.

2.1.2. FSBT analysed in the current work

The test was performed on a test section consisting of 1219 mm outer diameter API X80 pipes. The test section had a different wall thickness either side of the point of initiation. To the east and west of the initiation point the wall thickness was 22.9 mm and 20.6 mm, respectively. The test pressure was 15 MPa at temperature of 1.5 °C using a "rich" (containing less than 95% of methane) natural gas composition – as summarized in Table 1.

The test section contained an initiator pipe and 5 test pipes in both directions. Therefore, the pipes were named in the current work with letter E (East) or W (West) and a number corresponding to the position in the test line, "1" being adjacent to the initiator pipe (Fig. 7). Metallurgy is not discussed in this article but pipes coming from the same heat and having similar microstructural characteristics are marked by colours (Fig. 7).

The FSBT data considered in this work included synchronized recording of timing wire breakages and pressure transducer readings and 3D-measurements of plastic zone areas in post-test pipe sections provided. Positioning of the instrumentation and the post-test pipe sections in each pipe is shown in Fig. 8.

2.2. Standard laboratory mechanical tests

Standard quasi-static tensile tests, Charpy tests, and press-notched drop weight tear tests (DWTT) were carried out by the line pipe supplier as part of the FSBT program. Some of those results are presented here to discuss the correlation between standardized properties and the FSBT results.

2.3. DWTT with strain assessment

Instrumented bending DWTT was performed on a 50 kJ pendulum

WEST DIRECTION PIPES, DESIGN FACTOR 0.80 (wall thickness = 20.6 mm)						EAST DIRECTION PIPES, DESIGN FACTOR 0.72 (wall thickness = 22.9 mm)				
W5	W4	W3	W2	W1	INITIATOR	E1	E2	E3	E4	E5

Fig. 7. Pipe positioning in the test section of the FSBT.

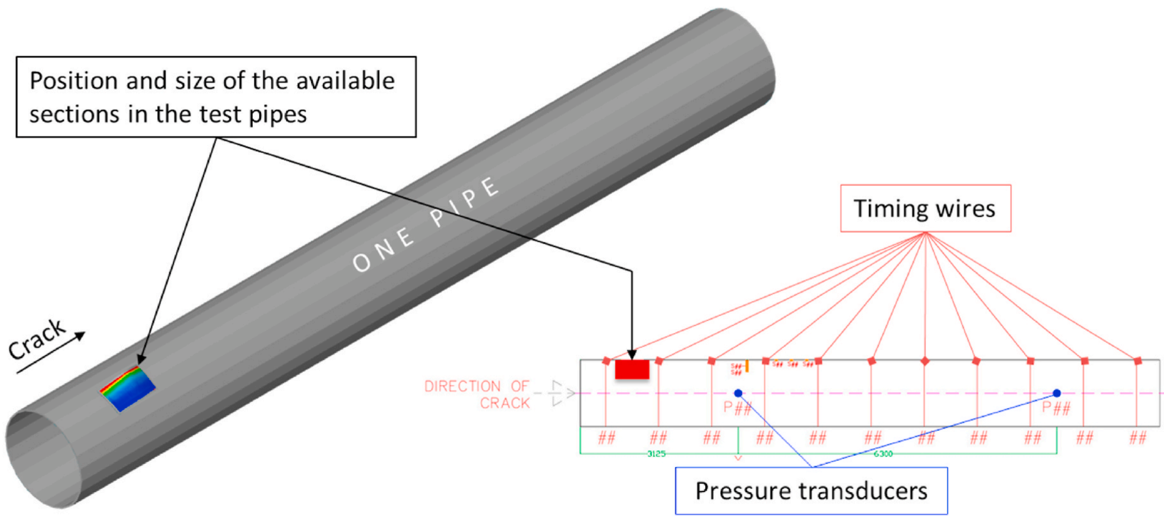


Fig. 8. Plastic zone measurement section and instrumentation positions in the pipes.

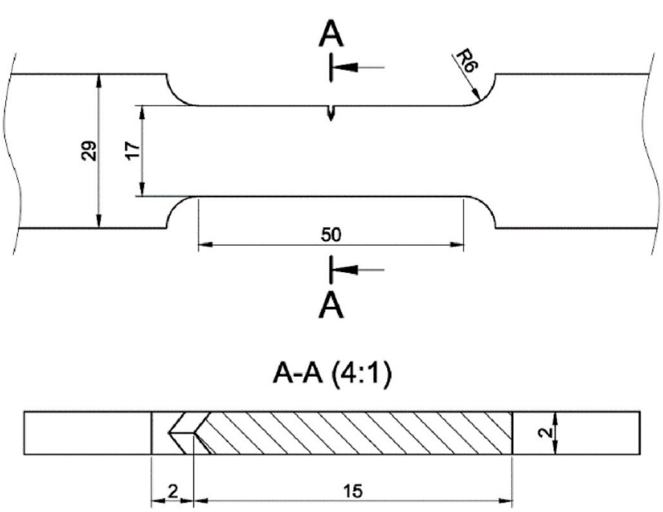


Fig. 9. Main dimensions of the gauge section of dynamic SENT specimen.

type DWTT machine according to API recommended practice [29]. Chevron-notched full-thickness specimens were machined from the pre-FSBT sections of the pipes. The specimens were 3D-scanned before and after the test to assess the strain induced by the test.

2.4. Dynamic SENT test

The test was specifically designed in this work to investigate the effect of loading rate on the resistance to crack propagation and to assess the plastic zone spread with advanced instrumentation. The tests were carried out using a dynamic tensile machine with 60 kN load and 20 m/s crosshead speed capacity. The specimen geometry was chosen to provide clear view of the characteristics of crack propagation, considering the machine requirements (Fig. 9). The test was performed using two target crosshead speeds: 1 m/s and 10 m/s. The actual crosshead speeds varied during the test due to elastic oscillation and were on average around 2 m/s and 8 m/s but consistent from specimen to specimen. Speckle was applied to the gauge section of the specimens, and reference points were put on the grip section to enable digital image correlation (DIC) analysis of the strain field and the crosshead motion using video recorded at 70,000 frames per second. The specimens were also 3D-scanned before and after the test. DIC analysis was performed in GOM Correlate software.

2.5. 3D-measurements

FSBT pipe sections were measured using GOM ATOS Triple Scan. DWTT specimens were measured using Duumm V900 handheld 3D scanner. Dynamic SENT specimens – GOM ATOS Core 80.

The obtained 3D models were analysed in GOM Inspect software.

3. Results and discussion

3.1. Full-scale burst test

To the east, the crack propagated from the initiation pipe, through pipes E1 and E2 before arresting in test pipe E3. The length of failure to the east was 35.91 m axially from the initiation point along the pipe. Travelling west, the crack propagated through all test pipes and arrested after interaction with a crack arrestor on the first reservoir pipe to the west (Fig. 10).

As mentioned in section 2.1.2, the pipes are colour-coded in figures according to their metallurgical characteristics. The variation of the crack propagation speed (Fig. 11, a) suggests that the “green” steel possesses higher crack resistance than the others. It provided arrest in 0.72 design factor and deceleration in 0.8 design factor.

The circles in Fig. 11, a show the available pressure transducers’ readings at the time of crack arrival to their positions, i.e. the experimental values of the crack tip pressure. While higher crack tip pressure corresponds to higher crack speed, the absolute variation in the crack tip pressure values is not very large (Fig. 11, b). Two pressure transducers

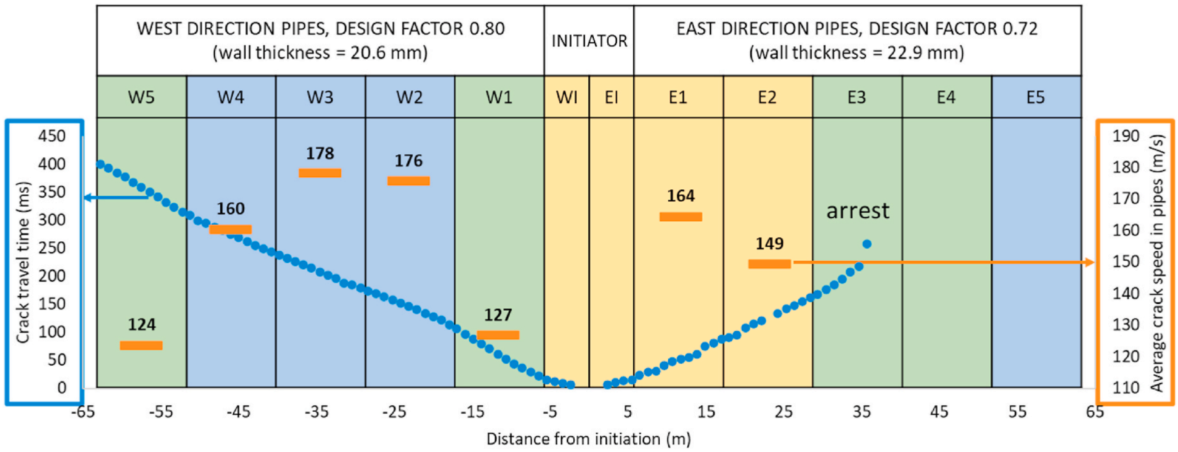


Fig. 10. Crack motion and positioning of pipes in the FSBT.

per pipe provide rather rough information about the crack tip pressure variation along the crack propagation path, but FSBT setups rarely include larger number of pressure transducers per pipe. Adjustments of the FSBT instrumentation can be considered in the future to improve the crack tip pressure variation assessment.

The crack curve concept suggests that there is always one possible crack propagation speed for a given combination of material and crack tip pressure, which appeared not to be in line with our experimental observations. Few available critical reviews on the applicability of this concept were only focusing on pipe-to-pipe transitions from higher to lower crack resistance sections [19]. In the current FSBT analysis the short-distance crack speed variations within each pipe, which were revealed in the west direction pipes with exceptional clarity (Fig. 11, a), do not appear to associate with corresponding variations in the crack tip pressure. For example, the extreme acceleration of the crack in the beginning of the second west pipe was not associated with a drastic increase of the crack tip pressure. More importantly, these dynamic crack speed variations occur not only upon a transition of the crack to a next pipe, but also in the middle of pipes (e.g. see accelerations and decelerations in pipes W3 and W4). These observations imply that the same material being torn with the same force can demonstrate different resistance to the crack propagation depending on other factors (that were not considered in the two-curve predictive model). Considerable amount of speed variations observed in the experiments would logically lead to a hypothesis, that this effect is related to the strain rate sensitivity which in this context is controlled by the incoming crack speed. Higher incoming crack speed leads to high strain rate, and therefore triggers different crack resistance performance for the same line pipe steel materials. Therefore, the equilibrium built in the existing predictive model could be made invalid, because that the model uses single-valued material resistance parameter obtained from tests with a given strain rate.

As foregoing discussions, it might be more reasonable to use a load-displacement approach to measure the resistance to ductile fracture propagation. While there is no clear way to record a load-displacement curve in FSBT, there might be ways to determine the equivalents of maximum load and total displacement for a given pipe, especially if it is a propagation pipe and has more than one pressure transducer installed inside it in FSBT. The equivalent of load can be derived from an average crack tip pressure, and the equivalent of total displacement – from strain measurements along the entire length of the pipe. The resulting energy parameter related to the crack propagation speed could be used as the resistance metric.

In this work the strain measurements represent only a small portion of the pipe length due to logistics requirements. The pipe sections containing the plastic zone region were cut from the same position of each pipe and were approximately 650 mm along the crack path. This means that only a single value of crack speed corresponds to each of the sections, since the sections' positions were between two neighbouring timing wires (see Fig. 8). The sections were 3D-scanned, and thickness maps were plotted on the obtained 3D-models. Results of 3D-measurements in Fig. 12 suggest that the plastic zone spread can vary significantly even within this small portion of the pipe (most pronounced in the sections of pipes W1 and W5), and the width of the plastic zone often exceeded the circumferential dimension of the available pipe sections.

The precise timing wires data in the west direction provide opportunity to analyse the crack motion even in the short parts of the pipes corresponding to the plastic zone measurement sections. The results in Fig. 13 suggest that the strain correlates with the crack acceleration, rather than the speed. The least plastic zone spread corresponds to the highest acceleration in pipe W2, and the deceleration in the first and the last western pipes corresponds to larger plastic zone spread. If the correlation between the crack acceleration and strain is true for the rest of the test line, the strain distribution and therefore the energy absorption should be uneven along the length of each pipe. The crack propagation rarely reaches steady state (constant speed) in propagation pipes even when it is three very similar pipes in a row (W2, W3, W4).

The strain has not been quantified in this work because of the limited size of the plastic zone sections provided. Fundamental fracture mechanics work such as [30] might provide solutions for strain quantifications, however, that is out of the current scope. Scanning of the entire test line before and after FSBT is technically possible and is recommended to be employed in future tests to further investigate the relationship between the crack propagation dynamics and the crack propagation resistance of steel. The complete 3D-measurements will allow easy strain assessment not only by the thickness mapping but also by measuring length changes in any direction using reference points.

3.2. Correlation between FSBT and laboratory test results

As discussed above, the variation of driving force (crack tip pressure) in the FSBT was relatively small, and the strain measurement was possible only across a very limited area. An average propagation speed (the distance between the first and the last timing wire in each pipe divided by the time between their breakages) in propagation pipes will be used as the resistance parameter; and this is because that the crack speed is qualitatively linked to the materials resistance in a very general sense: the slower the crack the better the material resistance.

The results of mechanical tests widely used in pipeline specifications are plotted against the average crack propagation speed in Fig. 14 (only west-direction pipes were considered). Expectedly, there is virtually no correlation with Charpy tests results (Fig. 14, a), and the correlation with DWTT results (Fig. 14b and c) is rather weak. Interestingly, the best

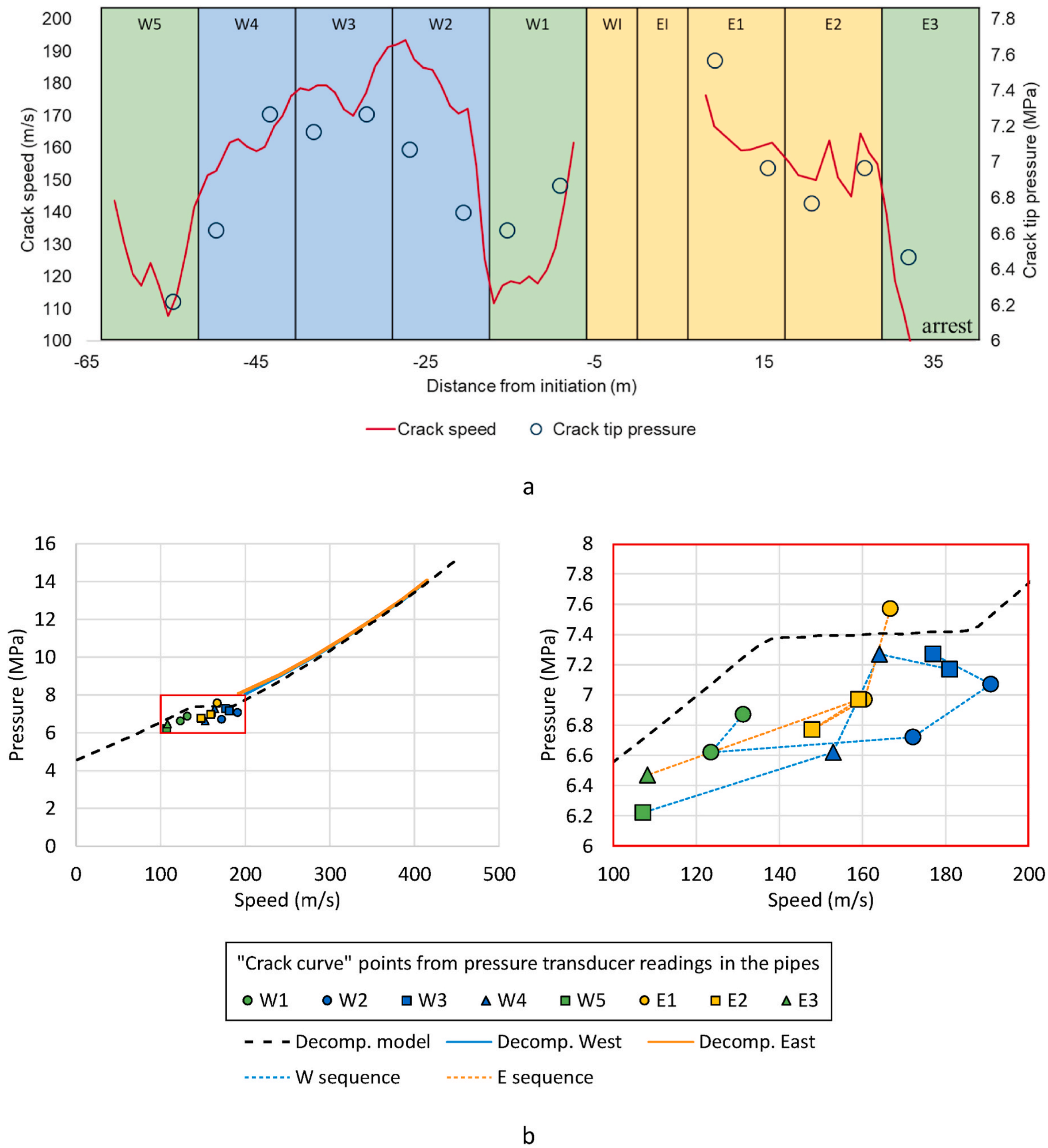


Fig. 11. Crack speed and crack tip pressure in the FSBT. a – plotted against the distance from initiation, b – in pressure vs speed coordinates along with the decompression curve.

correlation was demonstrated with the uniform elongation in the longitudinal direction (Fig. 14, d). Cheng Lu et al. [31] proposed yield-to-tensile ratio (which in most cases correlates well with the uniform elongation) as a new basis for the prediction models but this property was considered in the transverse direction. Importance of the longitudinal ductility for the fracture propagation resistance might be related to the fact that the strain in the most part of the running plastic zone ahead of the propagating crack tip is longitudinal, as briefly discussed in the introduction.

3.3. *Dynamic single-edge notched test*

Two pipes with clearly distinguishable full-scale crack resistance were chosen for this test: the first and the second pipe from the west direction of the FSBT (W1 and W2). Under nearly identical conditions in the FSBT the crack was strongly decelerated in W1 and then was drastically accelerated in W2. Therefore, the full-scale crack resistance of W1 is undoubtedly higher than crack resistance of W2. The list of specimens is presented in Table 2.

The results suggest that with the same crosshead speed the lower fracture resistant pipe material W2 fails earlier than the higher fracture resistant pipe material W1 (Fig. 15). This is because that the less strain were distributed across the gauge section of W2 specimen than it was in W1 specimen, which was confirmed by strain field analysis (Fig. 16). Therefore, this test demonstrates the evidence of the relationship between strain and crack speed and thus fracture resistance.

The total strain can be described in this case by the total crosshead displacement to failure which was accurately measured by means of motion analysis of the grip section in the high-speed footage of the test. Since the crosshead speed was not perfectly constant during the tests,

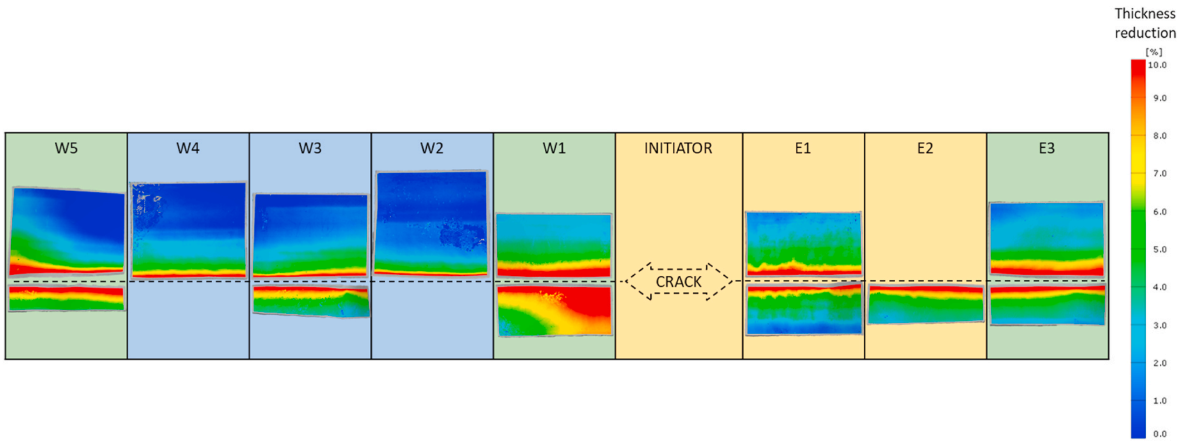


Fig. 12. Thickness mapping of the plastic zone sections.

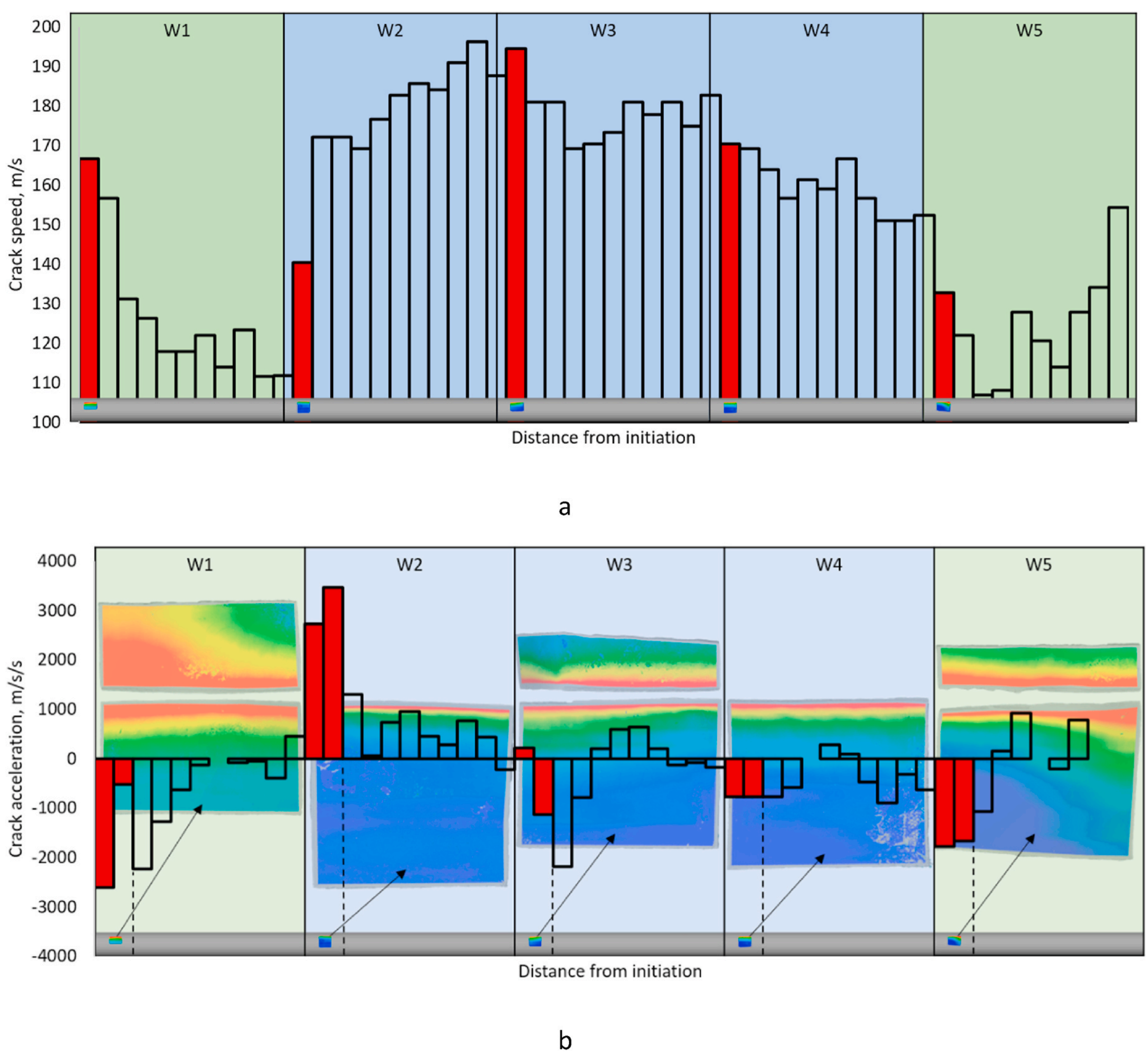


Fig. 13. Crack speed (a) and acceleration (b) in the west direction of Spectra FSBT with the values corresponding to the plastic zone measurements highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

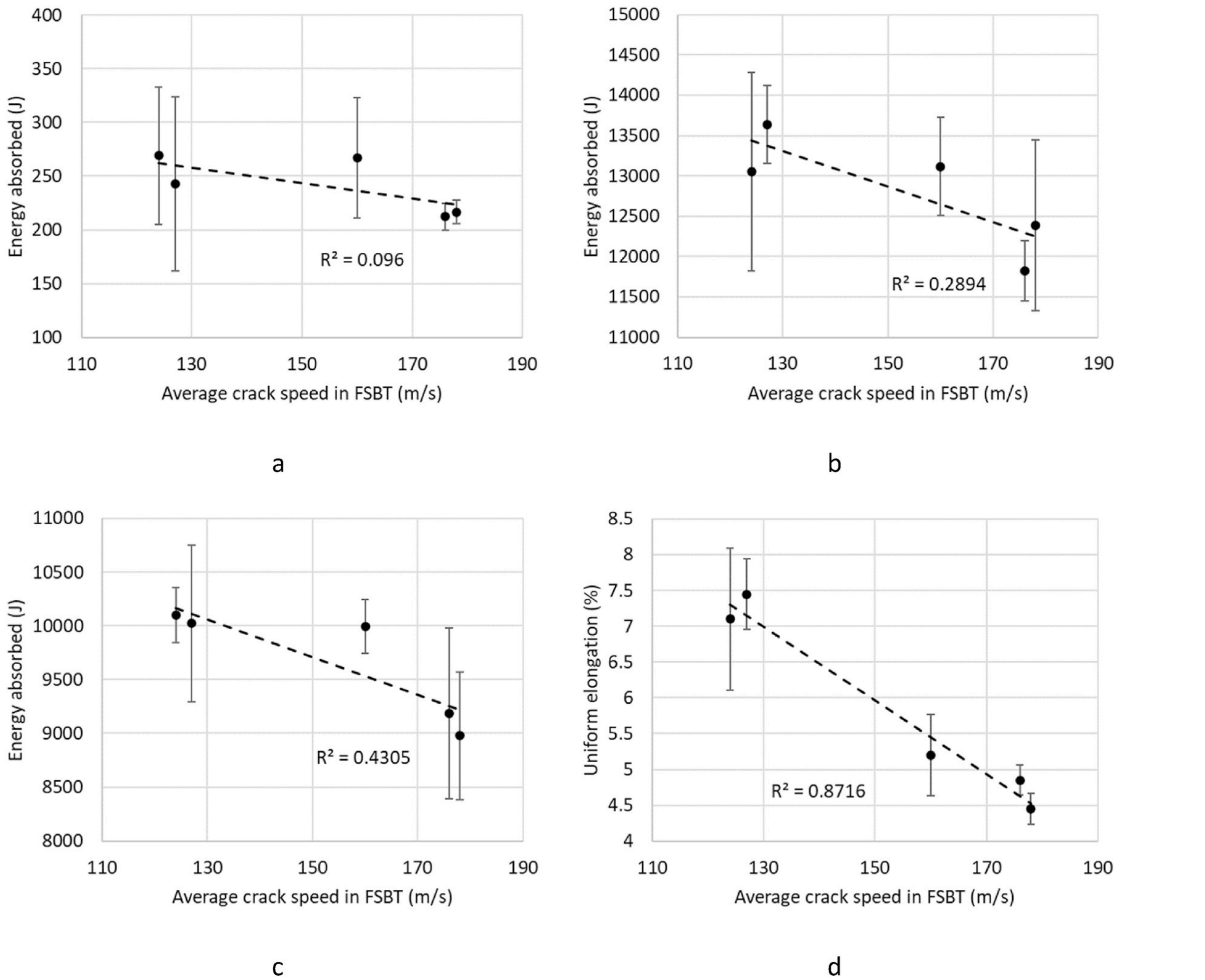


Fig. 14. Absorbed energy in ¾ Charpy test at −5 °C (a), press-notched DWTT at −5 °C (b), chevron-notched DWTT at room temperature (c), and uniform elongation in longitudinal full-thickness flat tensile specimens (d) correlation with the average crack speed in west direction pipes in the FSBT. Error bars show+/-Standard Deviation.

Table 2
List of specimens for the dynamic SENT test.

	Pipe W1	Pipe W2
Higher crosshead speed	2 specimens	2 specimens
Lower crosshead speed	3 specimens	2 specimens

the crack speed should be evaluated in relation to the crosshead speed, i.e.:

$$Speed\ parameter = \frac{Crack\ speed}{Crosshead\ speed} = \frac{Crack\ length}{Crosshead\ displacement}$$

The total crack length was a constant, and therefore the total crosshead displacement can also be used as a single-valued parameter describing the crack speed in this test.

The total crosshead displacement was larger in W1 than in W2 and increased for both materials with the increase of the crosshead speed (Fig. 17, a) indicating that the resistance to crack propagation in this test correlates with FSBT and is sensitive to the crosshead speed which could be considered an analogue of the "incoming speed" in the FSBT. That said, the absorbed energy (calculated from load-displacement curves) was very close for both materials but clearly increased with the increase of the crosshead speed (Fig. 17, b). This can be explained by the higher strength of the low-resistant pipe W2 and the increase of strength with the increase of strain rate.

The crosshead speed affected the steels' resistance to crack propagation, even though the range of the crack speed achieved in this test (10 … 30 m/s) was still an order of magnitude lower than the range of speed in FSBT (100 … 200 m/s). This implies that the relationship between the crack speed and the crack resistance cannot be ignored, and thus a new laboratory-scale test should be performed in (variable) dynamic conditions.

3.4. Comparison of strain distribution in different tests

In summary, the FSBT results discussed above indicate that the mechanism of the ductile fracture propagation resistance is based on the ductility associated with this propagation or the ability of the material to spread the plastic zone. Bending DWTT and dynamic SENT samples were 3D-measured to evaluate the spread of the plastic zone. Results are shown in Fig. 18. The first point to be observed is that in the bending test the spread of the plastic zone is constrained and can hardly reach one wall thickness. SENT configuration provides much deeper penetration of the plastic zone into the specimen gauge resembling the FSBT plastic zone. Therefore, SENT test appears more promising as a laboratory-scale evaluation of the full-scale resistance to ductile fracture propagation.

The thinning profiles in different tests of the lower and higher crack

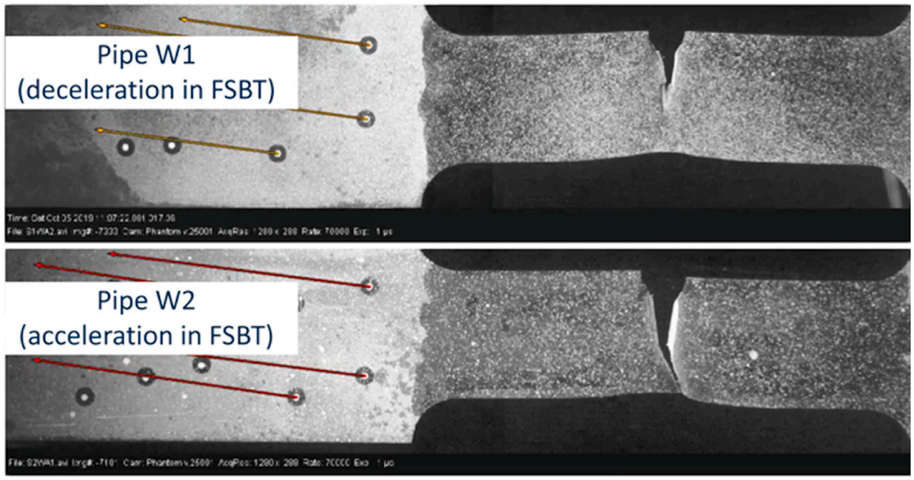


Fig. 15. High-speed video frame showing materials with different full-scale crack propagation resistance under the same dynamic SENT test conditions. Both frames correspond to the same time and crosshead displacement from the onset of loading (video is provided in supplementary material).

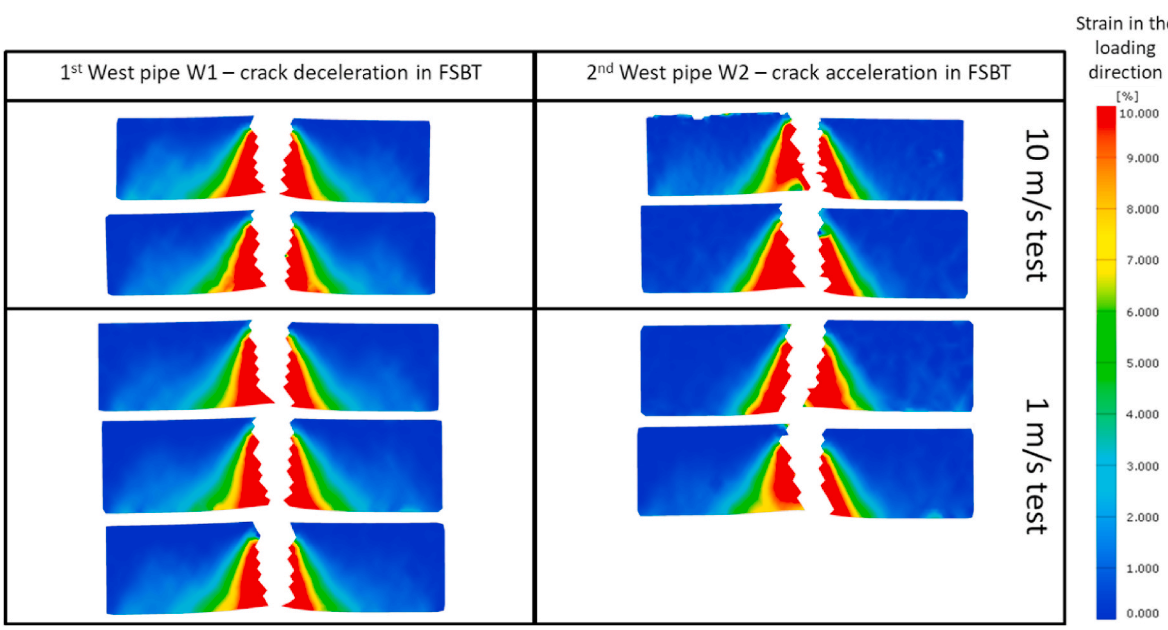


Fig. 16. Strain fields across the gauge section of the dynamic SENT specimen after the test (derived from DIC, video of the strain field development during the test is provided in supplementary material).

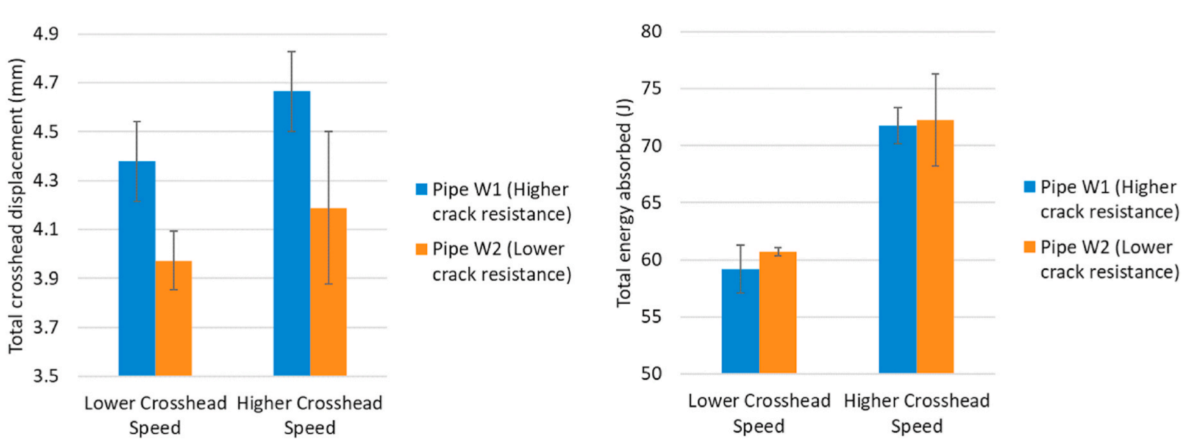


Fig. 17. Influence of the crosshead speed on the strain (a) and absorbed energy (b) in steels tested. Error bars show± Standard Deviation.

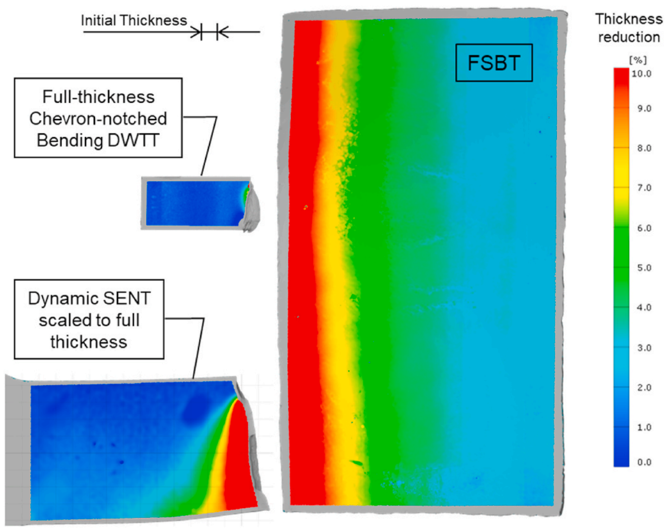


Fig. 18. Comparison of the plastic zone spread in different tests.

resistance steels are compared in Fig. 19. The bending DWTT test demonstrates the least plastic zone spread, also compared to the standard round bar tensile test carried out on 10 mm diameter, 50 mm gauge length specimens.

A laboratory-scale test that closely simulates the material's response in the real situation (FSBT) can be crucial for more reliable analysis. Foregoing discussions indicate that existing small scale tests are not sufficiently optimised for the topic.

It is logical to suggest that the experimental activities presented above should be extended to other FSBT materials. However, without a universal measure of the crack propagation resistance in FSBT it is virtually impossible to compare materials from different FSBTs. This also renders FSBTs with almost immediate arrest in both first pipes useless for this kind of investigation. That said, it would still be valuable to perform similar analysis on other FSBTs incorporating propagation pipes with different level of resistance if sufficient data and material will be provided.

4. New test design

Since line pipes can have a significant gradient of microstructure through the wall thickness, the dynamic SENT test should be scaled-up to full-thickness. A high speed pneumatic or hydraulic system used in dynamic tensile machines provides high precision of initial loading velocity but limited total impact energy and peak force. Cost and safety can also be of concern for testing machines of this type.

A drop-weight test design is much simpler in realisation. Nowadays, the drop-weight test is used predominantly for compression or bending and not for tension, but tensile loading can be implemented in this test by introduction of a load reverser. Load reversers were widely used in early quasistatic tensile testing machines and custom-built drop-weight rigs [32–34].

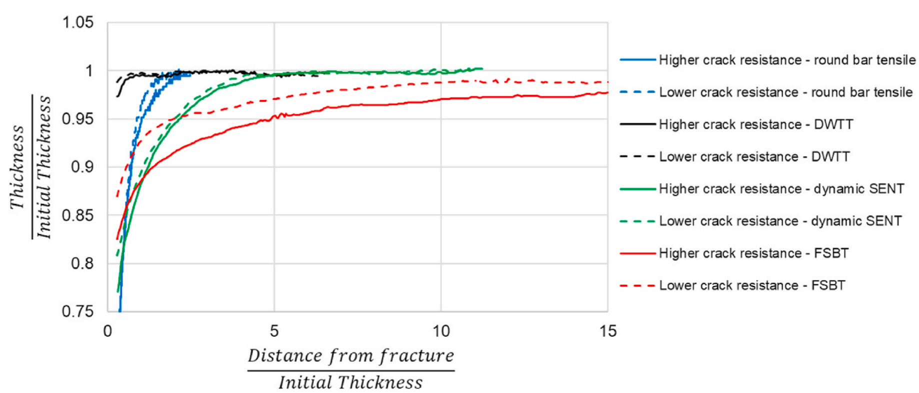


Fig. 19. Thinning profiles in different tests.

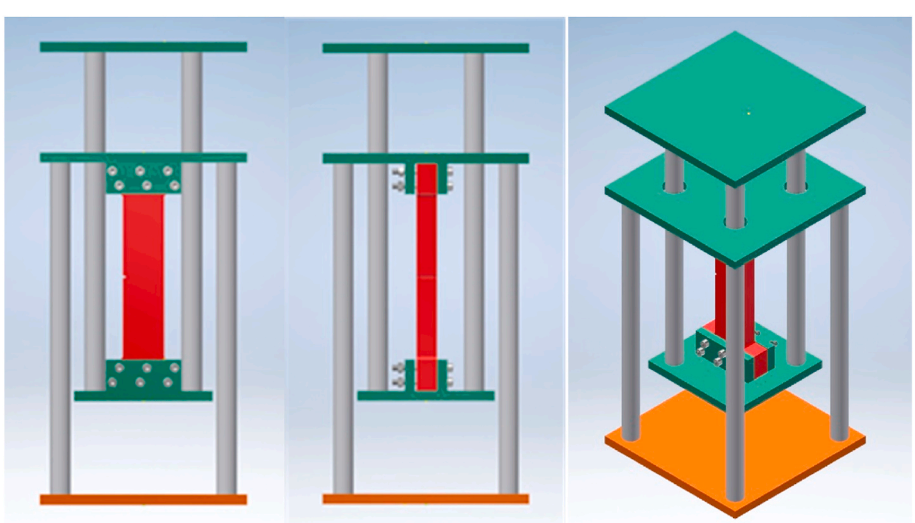


Fig. 20. Load inversion device principle.

Table 3
Comparison of experimental (impact bending) and modelling (impact tension) results for X80 steel.

	Charpy V Sample			DWTT Sample		
	Impact Bending test	Impact Tensile Load FEM Simulation	max/min	Impact Bending test	Impact Tensile Loading FEM Simulation	max/min
Peak Force	18 kN	66 kN	3.60	300 kN	1000 kN	3.33
Fracture Energy	240J	450J	1.86	6000J	20200J	3.36

In our case a combination of an existing drop weight test machine and a load reverser can be taken as a basis for the test development. This solution would provide access to very high (up to 100 kJ) impact energies which can be reached in modern drop-weight machines. Therefore, the load reverser should be designed to fit those machines and ensure their safe operation.

A 200 J-capacity prototype drop weight tensile testing rig was designed as the first step (Fig. 20). The prototype was successfully built and used for dynamic tensile tests on 1.5 mm aluminium sheets (video is provided in supplementary materials). The instrumentation of tests (load-displacement measurement) was not performed. Only stability and functionality of the prototype were tested.

As the second step a preliminary geometry of the full-thickness drop-weight tensile test specimen was chosen based on a 20 mm-thick X80 bending DWTT specimen according to API specifications [29]. FEM modelling with simple damage mechanics approach (a model with constant critical strain until fracture, which correspond to the ultimate strain of material) was performed to estimate the fracture energy. Charpy geometry was also modelled for reference. The results suggest (Table 3) that breaking the DWTT specimen by tension would require 3.36 times more energy than breaking it by bending. If the actual ratio is close to this, it should be possible to break most of the full-thickness specimens by tension in the existing drop-weight machines.

The results of prototype test and the modelling estimations provide a solid basis for further development of the full-thickness drop weight tensile test.

5. Conclusions

The resistance to ductile fracture propagation must be quantified based on the FSBT results to enable the development of new metallurgical solutions and laboratory-scale mechanical test procedures. It is suggested that the details of the crack propagation and gas decompression dynamics should be related to the corresponding straining of the pipe wall to better understand the dynamic changes in crack propagation resistance.

Complete strain assessment along the entire failure length in the FSBT can be implemented by means of precise 3D-measurements before and after the test.

The width of the plastic zone associated with the ductile fracture propagation in a pipe can reach tens of pipe wall thicknesses, and, therefore, most of the energy is absorbed by a relatively small level of deformation over a large volume of metal, rather than by relatively large deformations in the shear lip zone. Standardized impact-bending tests constrain the plastic zone spread and thus are phenomenologically too different from FSBT.

A new dynamic SENT test based on drop-weight principle has been proposed.

Credit author statement

Alexey Gervasyev: Investigation, Methodology, Writing – original draft. **Jingsi Jiao**: Investigation, Methodology, Writing – review & editing. **Maina Portela Garcia**: Conceptualization, Writing – review & editing. **Frank Barbaro**: Conceptualization, Resources, Writing – review & editing. **Chunyong Huo**: Supervision, Resources. **Denis Novokshanov**: Methodology, Writing – review & editing. **Stephen Rapp**: Investigation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpvp.2022.104816.

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