Non-threshold acoustic emission analysis of damage evolution in pipe segments of steel S355J2H under bending load

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Abstract:

Four-point bending tests were carried out to analyze the acoustic characteristics of damage development in pipe segments made of steel, grade S355J2H, being 2.5 m long with an outer diameter of 168 mm and 16 mm wall thickness. To induce stable crack growth, the pipe segments were pre-damaged by a 90° circumferential notch in the middle of the pipe length. While the pipe was quasi-statically loaded, microscopic damage and plastic deformation accumulated to form a macroscopic crack that grew through the pipe wall until leakage. For acoustic emission (AE) monitoring, four broadband sensors of type VS 900 M were mounted close to the notch. Continuous AE signal detection was performed by the non-threshold method. Advantages and disadvantages of the non-threshold AE monitoring compared to a commonly employed method analyzing only signals exceeding a predefined threshold are discussed. The results of AE analysis are compared to additional information on the crack growth detected by the direct current potential drop (DCPD) technique. These studies were carried out in the course of the interdisciplinary research project AGIFAMOR, Ageing infrastructures - distributed acoustic monitoring of pipes at BAM.

1. Introduction

In the course of an interdisciplinary research project at BAM (AGIFAMOR, Ageing Infrastructures – Application of distributed acoustic and fibre optic sensors for continuous monitoring of pipes, 2015-2018), the potential of distributed acoustic fibre optic sensing methods (DAS) in terms of a condition monitoring system for pipelines has been investigated. Therefore, besides studies on the sensitivity of the DAS to noise caused by leakage [1] or to pressure shocks causing dynamic circumferential changes of the pipe, also the sensitivity of the DAS to acoustic emission (AE) caused by crack formation in a pipe wall is investigated. The latter scenario, object of this contribution, was realized by four-point bending tests carried
out on steel pipe segments. Originally, a similar experimental setup was designed at BAM in the 1990’s to study crack initiation and growth on large steel pipes by means of the direct current potential drop (DCPD) and the AE method [2]. To validate the DAS sensitivity, the test is accompanied by accelerometers and AE measurements. The AE during initial tests was monitored using threshold-based approach with threshold settings above 56 dB_AE [3]. Analysis of the continuous data recorded by DAS and accelerometers compared to the AE dataset recorded using threshold-based approach turned out to be insufficient to characterize test progress at the test object as well as to assign sudden deviations and possibly technical artefacts due to the employed extensive monitoring instrumentation. Thus, another test was performed with continuous monitoring by AE, DAS, and accelerometers. First results of AE analysis in comparison to the detection by the DCPD method are presented in the following.

2. Description of work

To investigate the crack initiation and stable growth of a macroscopic crack, a four-point bending test was carried out on a pipe segment made of steel grade S355J2H. The pipe segment was 2.5 m long, had a wall thickness of 16 mm and an outer diameter of 168 mm. Centered at 1.25 m length, a 90° circumferential notch was shaped into the pipe wall by a CNC machine. The notch had an opening angle of 90°, a notch root radius of 0.2 mm and a ratio of wall thicknesses of 0.5. For deflection measurements, six angles were glued to the pipe at the 3 o’clock and 9 o’clock positions as technical aid for the displacement sensors. The bending test was performed with a 4 MN universal testing machine that operates hydraulically. Test was driven displacement controlled with a test speed of 0.25 mm min⁻¹.

The test was monitored by non-threshold acoustic emission (AE) measurement as well as by the method of the Direct Current Potential Drop (DCPD), DAS and accelerometers (Fig.1). Herein, exclusively the results of the AE and the DCPD measurements are focused on. For DCPD, a DC of 300A was injected and the potential drop was measured at five positions close to the notch. The measured potential U is normalized with its output value U₀ and plotted as a function of the deflection (Fig. 2). Then, the potential data are approximated with a fifth degree polynomial in a deflection interval from zero to a freely selectable value between maximum load and load of leakage growth. By doing so, the stable crack growth process is taken into consideration. Based on the first order derivation of the polynomial fit, information on the characteristic development of damage accumulation, crack initiation and stable crack growth are obtained.
The non-threshold AE monitoring was performed with the digital AE equipment AMSY-6 in continuous mode with a sampling rate of 3333333 Hz. Four broadband sensors, sensitive in the range from 100 kHz up to 900 kHz (type VS900-M), were used to ensure the monitoring of crack events. The response of the sensors is characterized by two peaks at 190 kHz and 350 kHz accompanied by two anti-resonances at 200 kHz and 400 kHz. The AE sensors were mounted with magnetic holders. Coupling agent was a reusable adhesive (Bostik Prestik made in South Africa). The four sensors were arranged in a square around the notch with approximately 100 mm distance to the notch. To enable good coupling of all sensors, the corrosion layers were removed by grinding surface at the appropriate areas along the pipe. Teflon sheets were inserted in between the pipe wall and the load bearings. Furthermore, PVC damping plates were assembled into the bearing elements (Fig.1). By this, the acoustic noise was reduced by approximately -10 dB. For AE analysis the near field behavior of the sensors with an attenuation of 9...17 dB must be considered. For the in-plane AE wave propagation a velocity of 5225 m s\(^{-1}\) was estimated.

First step in processing the AE data is to reduce the noise by applying a high pass filter at 150 kHz. For AE hit detection, the moving standard deviation of the measured amplitude values (mV) is calculated with a moving window size of 512 samples. To level low deviations relative to higher ones, the logarithm of the moved standard deviation is employed. Since the noise level increased with increasing load, the AE hits are detected by means of a moving threshold applied to the logarithm from the moved standard deviation of the measured amplitude values. Only AE events detected by all four sensors are evaluated. To determine the time shifts of one signal detected by the four sensors, the cross-correlation algorithm is applied to a time window of 2000 samples comprising the signal's arrival and its peak amplitude. According to the coordinates of the notch (AE source localization) and the AE sensors, the shift of a signal detected in all four sensors must not exceed 2.7E05 s (90 samples) to be assigned to crack events at the notch.
3. Results

The quasi-static bending test of the pipe segment took about 75 minutes (Fig.2). After approximately 2500 s test duration, the piston movement was stopped in order to carry out corrective actions and checks to the setup. In total, a maximum load of 696 kN at deflection of 11.43 mm was yielded (Tab.1). The initial phase of bending test, the pipe segment undergoes an elastic deformation and its cross-section becomes ovalized. With progressive loading, mechanisms of plastic deformation set on; a macroscopic crack initiates and grows in a stable manner in the direction of pipe wall thickness. This is characterized by initial blunting and cross-section necking at the notch, increasing dislocation density as well as by accumulating ductile damage in the metal microstructure. After reaching its maximum, load decreases while the crack finally reaches the state of leakage. With progressing testing time, the leakage opens in a stable manner and the crack continues to grow in circumferential direction of the pipe wall on a low level. At this stage, the load curve stagnates due to equilibrium of strain hardening and crack growth, whereby the deflection increases further.

During the elastic deformation, the DPCD is approximately constant. The significant increase in potential drop indicating the initiation of stable macroscopic crack growth was found at 90% of maximum load (630 kN) and 56% of maximum deflection (6.5 mm). During the leakage grows in circumferential direction of the pipe wall, the potential drop increases with lower slope.

Figure 2. Load-deflection graph of the bending loaded pipe segment of steel (S355J2H). By means of the direct current potential drop (DCPD), the onset of macro cracking at the notch is detected. Leakage usually arises at the marked stage after maximum load.
AE data analysis revealed 1042 AE events (EV) detected by all four sensors, 185 of which are localized (LEV, located event) close to the notch. First LEV is detected within the elastic range at 150 kN after 334 s test duration (Fig. 3). 35 EV and 5 LEV occurred, randomly spread over time, until a significant AE set on. After approximately 1600 s of test duration, the cumulative curves of peak amplitudes significantly increase (Fig.4). Particularly, the increase in cumulative peak amplitude of LEV indicates the accumulation and formation of significant crack events at the notch. The occurrence of distinct AE signals correlates with the crack initiation determined by the DCPD method (Tab. 1). The development of macro-crack and its growth through the pipe wall thickness generates AE with corrected peak amplitudes up to 90 dB\textsubscript{AE}. However, the LEV with the corrected maximum peak amplitude (95 dB\textsubscript{AE}) was not detected close to the maximum load, but shortly before the load stagnated at 585 kN (3500 s) in the course of leakage growth. The formation of the leakage results in a steep increase in cumulated peak amplitude (Fig. 4). The subsequent crack growth in circumferential direction generated AE activity, since the four AE sensors detect approximately 150 EV. However, localization of the EV and, hence, the definite identification of AE source events close to the notch failed.

Table 1. Characteristic values from the DCPD and the AE monitoring of the four-point bending test. Mechanical properties at load peak and deflection peak.

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<tr>
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<th>Crack initiation estimated by</th>
<th>Maximum load</th>
<th>Maximum deflection</th>
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<tbody>
<tr>
<td></td>
<td>DCPD (6 o’clock position)</td>
<td>AE</td>
<td></td>
</tr>
<tr>
<td>Load (kN)</td>
<td>630</td>
<td>626</td>
<td>696</td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>6.5</td>
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<td>11.59</td>
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4. Discussion on AE results

During the test progress, the amplitude of noise in AE data rise with increasing load. This has a main impact on the sensitivity and accuracy of the AE method using “fictive” constant or moving threshold during post-processing of streaming signals, because only AE exceeding are detectable and, furthermore, the estimation of the AE arrival time is affected, too. Noisy signals range up to approximately 150 kHz in frequency. Furthermore, tracking damage processes particularly focuses on AE with higher frequency contents. Thus, setting a high pass at 150 kHz improves the data evaluation. When omitting the de-noising, only 33 LEV with peak amplitudes >60 dB\textsubscript{AE} were identified, which is less than 20% of the herein presented 185 LEV.
Figure 3. Load and corrected peak amplitudes of all detected AE events (1042 EV and 185 LEV) plotted vs. duration of the bending test of a pipe segment of steel. Highlighted characteristic states in the test progress are the crack initiation determined by DCPD, maximum load of 699 kN and leakage formation.

Figure 4. Load and cumulative corrected peak amplitudes of all detected AE events (1042 EV and 185 LEV) plotted vs. duration of the bending test of a pipe segment of steel. Highlighted characteristic states in the test progress are the crack initiation determined by DCPD, maximum load of 699 kN and leakage formation.
By post-processing the non-threshold streamed AE data, the sensitivity of the measurement system was improved. By applying a moving threshold-based on the standard deviation of signal amplitude, LEV with peak amplitudes $>30 \text{ dB}_{AE}$ are identified, even early LEV at low loading levels. The localization of EV of the subsequent crack growth in circumferential direction failed due to the limited AE sensors, their arrangement and the AE wave propagation interrupted by the leakage in the pipe wall.

Determination of the crack initiation by DPCD correlates well with results of the AE analysis. Analogous to the steep increase in DCPD, while crack finally breaks through the wall (leakage reached), also the cumulated AE peak amplitude increases even with a steeper slope. To improve the accuracy in EV localization, more sensors, at least six would be needed. Three sensors are needed on each side of the notch until leakage. Afterwards, as soon as the crack grows in circumferential direction, three sensors should be positioned close to both crack tips in radial direction.

5. Conclusion

AE monitoring by means of non-threshold recording enables true-to-the original replica of the test procedure. This might be particularly beneficial in the case of elaborate experiments, for example, to identify sudden deviations that occurred during the test progress and to clarify technical artefacts and possibly other phenomena retrospectively. The aim of the presented experiment is to investigate the sensitivity of the DAS. Since DAS and accelerometers record the acoustic information continuously during the tests, for comparison purpose, the non-threshold AE monitoring mode provides a sufficient database.

Transient recording with non-threshold mode provides limited information on AE activity in real-time analysis during the test due to the lack of arrival time estimation. The size of recorded datasets essentially depends on number of sensors, sampling rate and test duration. However, compared to the conventional threshold-based recording mode, large data volumes are produced. For example, the monitoring of a single bending test (75 min duration, 4 AE sensors, 3 MHz sampling rate in AE) produces a dataset of 110 GB, but only 10% include relevant information on AE events due to damage mechanisms. The handling of large data volumes and the time-consuming post-processing data analysis are not insignificant. However, most important advantage of the non-threshold AE recording is that almost no information is omitted by digital threshold and frequency filter settings during the active measurement and the measuring system captures and stores the data with its maximum technical performance.
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References:

