Experimental requirements of small and large scale dynamic fracture mechanics testing

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Abstract The paper deals with experimental requirements of dynamic fracture mechanics tests in general with special focus on ductile cast iron materials. This is based on instructions for dynamic measurement techniques provided by the standards ASTM E 1820 and BS 7448-3 which were compared and rated.
The low blow multiple specimen technique using a drop tower was investigated for crack resistance curve determination on SE(B)25x25 specimens. It was shown that no detrimental effects should be expected from the second impact of the rebounded striker. Strain gage instrumentations for direct force measurement according to the standards provided different results. The ASTM position should be preferred. Important conclusions were drawn concerning hidden friction in drop towers from a comparison of electro-optically measured displacement and calculations from force-time record.
Full blow large scale tests on SE(B)140x280 specimens were performed using a servo-hydraulic test system to determine dynamic fracture toughness values. Different strain gage instrumentations were compared with respect to their force measurement capability. For displacement measurement only a non-contact electro-optical camera technique was applicable. An appropriate method of instrumentation was identified whose results show good agreement with numerical simulations of the tests.
It can be concluded that the recommendations of the test standards provide different results. Therefore, they must not simply be transferred to the own specific test requirements. It is regarded absolutely essential for dynamic fracture mechanics tests in general that all measuring techniques are being validated in advance.

Keywords dynamic fracture mechanics testing, ductile cast iron, measurement

1. Introduction

Design and safety assessment of components subjected to high strain rate or impact (dynamic) loading require adequate material data. Therefore, the focus of this paper is on the experimental determination of dynamic fracture mechanics material data.
The problem of how to measure basic quantities like force and displacement correctly and with sufficient precision in dynamic fracture mechanics tests has still been an experimental challenge, although such tests have been performed for at least 40 years. Advice given on that by test standards such as BS 7448-3 [1] or ASTM E 1820 [2] is fairly limited. The ISO standard 26843 [3] on the determination of dynamic fracture toughness using precracked Charpy specimens (PCVN) is still being drafted while comparable contents has recently been included in the very new annex 17 of [2].
A major lesson to be learned from experience is that the first step of experimental dynamic fracture mechanics investigations should always be to establish an appropriate test method. This seems to be trivial only in the first instance. In fact, the material behavior mainly governs the test techniques which are applicable. Many materials - such as the ductile cast iron (DCI) investigated here - substantially change their deformation, damage and fracture behavior from ductile to brittle by increasing loading rate, decreasing temperature and/or increasing stress triaxiality. Unfortunately, this does not happen suddenly so that the corresponding measuring techniques have to be adapted with deliberation.
As will be shown below, transferability of measuring techniques from one lab to another, from small to large scale tests or vice versa and of more or less common advice from standards to the own very special task cannot simply be taken for granted. In contrary, it is of vital importance to validate the basic measured quantities independently before using the data for further analyses and

to establish material characteristics. Basically this should be a matter of course. But it is time and money consuming and studying the literature often reveals an opposite practice.
Usually, conventional techniques as machine load cells and clip-on transducers cannot be applied to measure the true mechanical response of the specimen due to the short duration of dynamic fracture mechanics tests (microseconds up to milliseconds), inertial effects and resulting signal oscillations. The information which is given on that by relevant test standards [1,2] is shortly summarized in Table 1. Table 1 is limited to single edge bend specimens (SE(B)) since this type of specimen is primarily tested under dynamic loading at BAM.

Table 1. Standard information on force and displacement measurement in dynamic fracture mechanics tests on SE(B) specimens with thickness/width-ratios $1 \leq B/W \leq 4$

Information on	BS 7448-3 [1]		ASTM E 1820 [2]		
	Main body	Annex A	Annex A13	Annex A14	Annex A17
loading rate	$3 < \dot{K} < 3000$ MPa√m/s	$\dot{K} > 3000$ MPa√m/s	$\dot{K} > 2{,}75$ MPa√m/s, not for impact or quasi-impact testing (free-falling or swinging masses), minimum loading time 1 ms	$\dot{K} > 2{,}75$ MPa√m/s, minimum test time to be calculated to avoid presence of a significant kinetic energy component in the specimen relative to the internal energy and to assure applicability of static J-integral equations	no restriction on impact velocity provided the time to fracture is greater than the calculated minimum test time
force measurement	machine load cell	resistance strain gages attached to both sides of the specimen, wired as two quarter bridges, positions: W/2 from ligament and at W/2 in width	machine load cell as used for static plane strain fracture toughness test generally suitable, but response characteristic to be checked to avoid inertial effects	on-specimen force measurement recommended (remote load cells allowed if requirements are met), full bridge of 4 strain gages on the specimen midplane at the specimen span quarter points (on upper and lower specimen side)	strain gage instrumented striker
displacement measurement	direct load line displacement via horizontal comparator bar	approximation by test machine ram displacement	the same transducers as used for static plane strain fracture toughness test generally suitable, but response characteristic to be checked to avoid inertial effects	fibre-optic transducers	calculation from force/time record, no measurement
COD measurement	clip gage	-		cantilever beam displacement gages like in static fracture toughness testing down to loading times of 1 ms	-

Table 1 outlines the bottom line for a user when dynamic fracture mechanics tests have to be drafted. The first thing to note about Table 1 is that the recommendations of [1] and [2] regarding strain gage positions for force measurement are very different. This mirrors the status in the literature including for instance early basic studies of Ireland [4, 5] or Trudeau [6] which are still frequently cited. Some own experimental results will be discussed below.
With respect to load line displacement measurement BS [1] does not provide a convenient method for higher loading rates. The recommendation to approximate the test machine ram displacement is rated not sufficient. Compared with this, ASTM [2] at least indicates that non-contact optical methods are suited and inertial effects shall be avoided.

2. Experiments

The paper reports on experimental fracture mechanics impact investigations on bend type specimens of DCI materials. Depending on the DCI's material behavior [7], two types of tests have been investigated: a small scale low blow multiple specimen technique using a drop tower was investigated for crack resistance curve determination as well as large scale full blow tests on SE(B)140 specimens were performed. Different experimental aspects of the test methods are discussed here. Mechanical properties, microstructural aspects and the values of the fracture mechanics characteristics of the materials are not in the focus of this paper. They will be reported elsewhere.

2.1. Small scale low blow tests

When the DCI material exhibits R-curve behavior, it is still first choice to use the low blow multiple specimen technique for dynamic crack resistance curve determination. Unfortunately, single specimen techniques, as the key curve method, have not been proved successfully to be appropriate and to provide enough precision with DCI materials at dynamic loading conditions [8]. Primary goal of the investigations was to setup a multiple specimen test method to determine dynamic crack resistance curves in the temperature range from ambient to -40 °C. Series of small scale low blow tests on SE(B)25 specimens (length 138 mm, width 25 mm, thickness 25 mm, $a_0/W = 0.5$) were performed by use of a drop tower test system (Fig. 1) at stress intensity rates in the linear-elastic range of approximately $3 \cdot 10^5$ MPa√ms^{-1}.

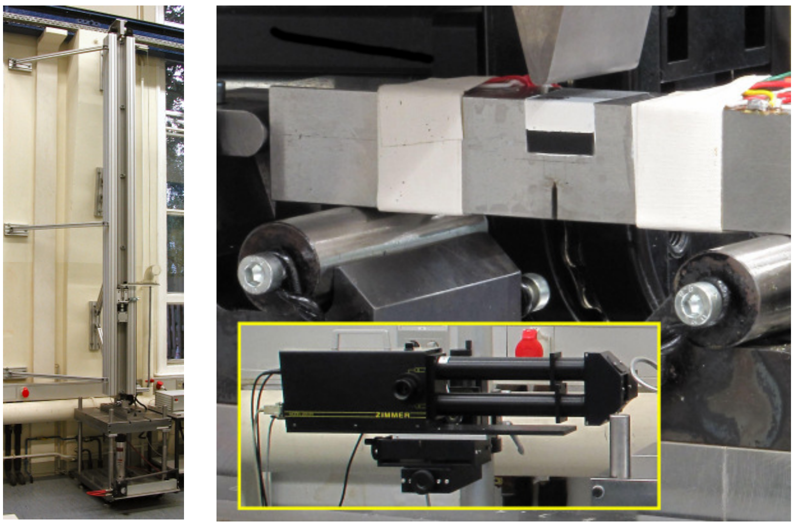

Figure 1. Left: BAM drop tower test system with $v_{0max} \approx 8$ ms^{-1}, max. energy ≈ 300 J, right: test setup with SE(B)25-specimen instrumented for opto-electronic measurement of load line displacement.

Fig. 2 shows different strain gage instrumentations which were compared with respect to their force measurement capability. All strain gages were statically calibrated before the tests.

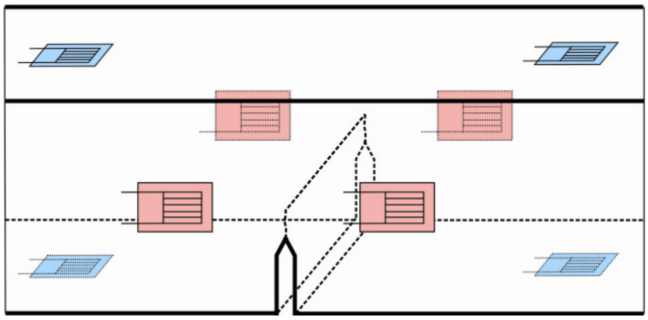

Figure 2. Strain gage instrumentations for direct force measurement on SE(B)25-specimens, blue: ASTM full bridge at specimen quarter points, red: 2 BS half bridges at W/2.

Basic principle of low blow tests is that a defined amount of energy is transferred to the specimen by a single hit of the striker causing deformation and stable crack growth. Therefore, it has either to be realized that second and following hits of the rebounded striker are prevented or that they are of such a magnitude that they will not cause crack growth in the specimen. Catching of the rebounded striker is practically impossible due to the low rebound height and the corresponding short time. Fig. 3 and Fig. 4 show force-time records of a low blow test on a DCI SE(B)25-specimen with $a_0/W = 0.5$ at -40 °C. The first hit of the striker causes the first force peak (low blow test) and the peaks (impulses) 2 to 4 are caused by the successively rebounding striker. After the test a stable crack growth of 0.62 mm was measured on the fracture surface ($a_E/W = 0.52$). As can be seen from comparison of the force signal height with the yield load of the specimen after the first hit ($a_E/W = 0.52$) or even assuming a maximum crack length of $a_{max}/W = 0.55$, the magnitude of the second and following impulses is clearly below the yield loads. This holds for BS- as well as ASTM-strain gage force measurement. The differences between ASTM- and BS-records will be discussed below. For the nonce, it can be concluded that second and following impulses cause only elastic deformation and do not contribute to crack growth so that they can be ignored.

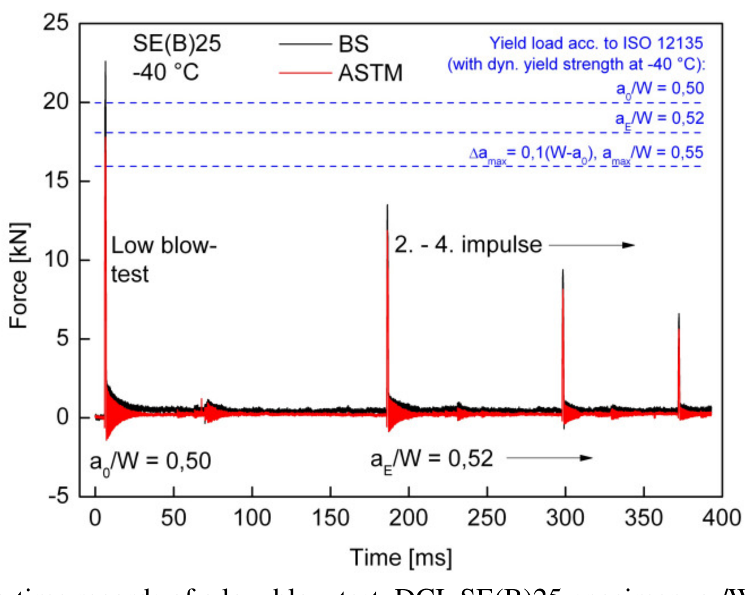

Figure 3. Force-time records of a low blow test, DCI, SE(B)25-specimen, $a_0/W = 0.5$, -40 °C.

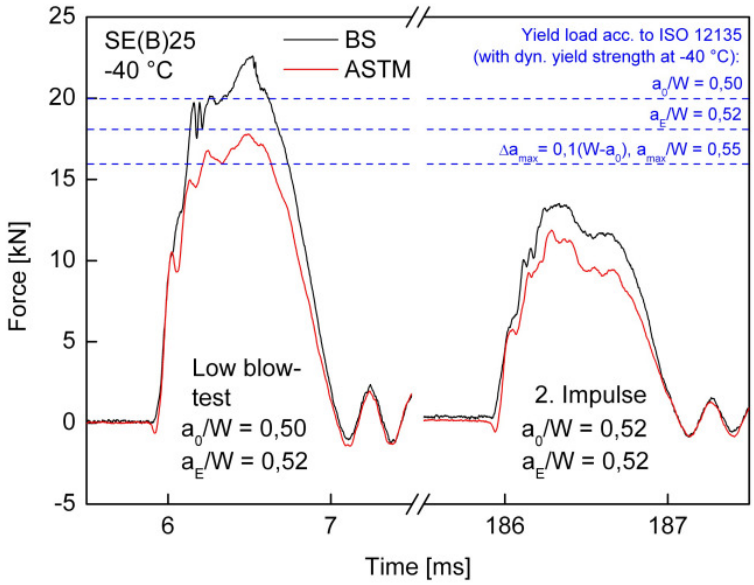

Figure 4. Details of force-time record from Fig. 3, DCI, SE(B)25-specimen, $a_0/W = 0.5$, -40 °C

As already indicated above, strain gage instrumentations according to ASTM and BS provide different results independent from temperature, Fig. 5, left. To clarify this, reference tests under quasistatic loading had been performed with the same instrumentation, Fig. 5, right. They revealed that the ASTM signal widely conforms to the reference while BS significantly differs and displays a remaining tensile force at the end of the test when the specimen is fully unloaded. In order to investigate if plasticity at the BS W/2 positions causes these differences (note: W = B and not W = 2B), a test with BS strain gages at a distance of W from the ligament was performed. A significant improvement could not be achieved. Therefore it is concluded for low blow tests that strain gages at ASTM positions work well with the investigated SE(B)25-specimens while BS positions cannot be recommended.

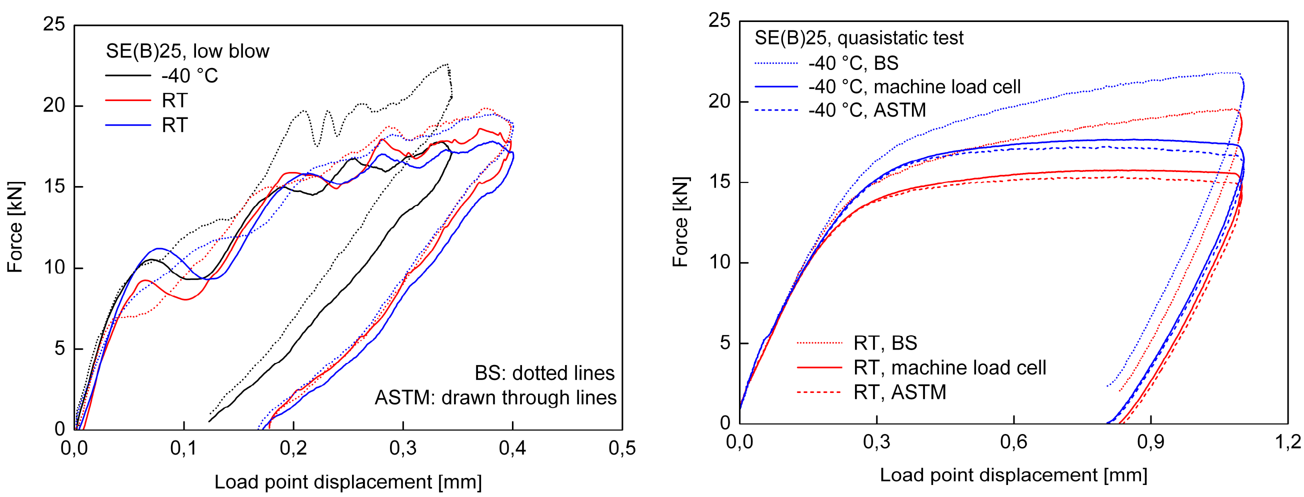

Figure 5. Comparison of ASTM and BS strain gage force measurements on SE(B)25-specimens in low blow tests (left) and quasistatic tests (right).

Basically, the load line displacement in tests using instrumented pendulum impact machines or drop towers can be determined by double integration of the force-time record. This is considered an attractive way to provide displacement data when expensive non-contact measuring equipment is not available or not applicable. However, as can be seen from Fig. 6, left, tremendous differences/errors may occur between the calculated values and the reference measured by an independent and verified method. The errors were due to slight energy losses by hidden friction which may easily occur especially in larger drop towers. Therefore, the drop tower was constructively optimized and the tests were repeated, Fig. 6, right. The calculated and the measured displacement values are now nearly equal so that dynamic fracture mechanics tests could even be performed without having special equipment for displacement measurement available. But it must be considered an absolute essential prerequisite that this procedure can only be followed when the substance of Fig. 6 had been proven in advance. Further technical information on the camera and the validation of the corresponding measurement results is given at the end of chapter 2.2.

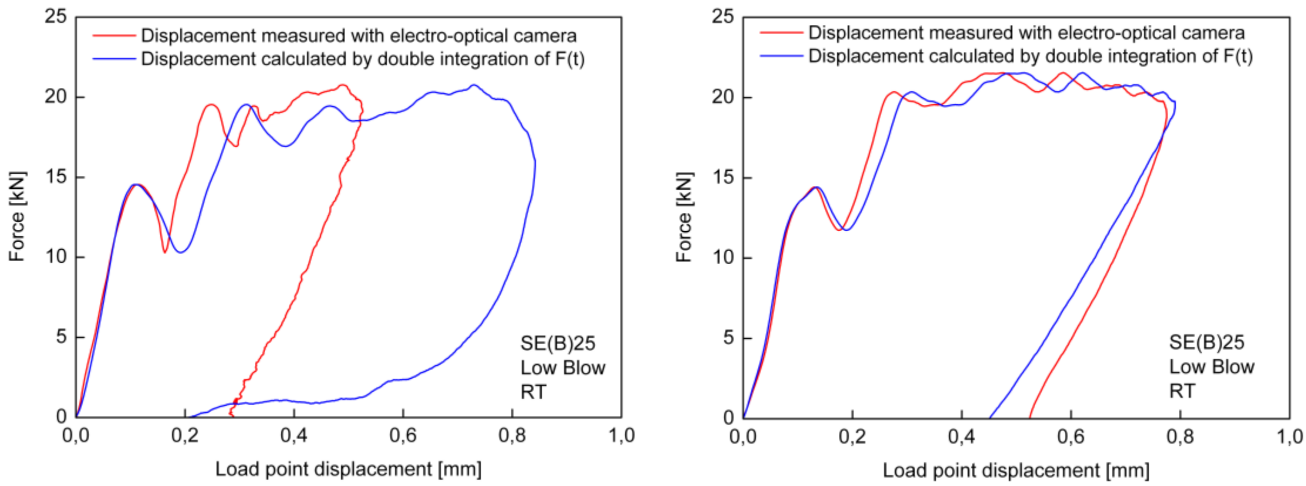

Figure 6. Force vs. calculated and measured displacement,
left: drop tower with friction losses, right: constructively optimized drop tower.

The question of how to detect initiation of stable crack initiation in dynamic fracture mechanics tests has not yet been resolved satisfyingly. Reported techniques like magnetic emission, acoustic emission or near crack tip strain gages seem to work in special cases but cannot be seen as robust methods nor generally be applicable. Additionally, they do not seem to work with DCI reproducibly enough. Therefore, an alternative technique based on the detection of stable crack initiation by failure of strands of a crack propagation sensor attached to the ligament was investigated here, Fig. 7. Two different sensor positions - (1) first strand right in front of the initial crack tip on the specimen surface (Fig. 8, left) as well as (2) sensor at the initial crack tip on the specimen surface (Fig. 8, right) - were investigated. It was observed that in both cases the crack sensors provide discrete signal jumps in quasistatic and dynamic tests on SE(B)25 specimens at RT and -40 °C. Nevertheless, with position (1) there is a large scatter of detected initiation forces F_{ini} of $0.5F_{max} \leq F_{ini} \leq 1.0F_{max}$. Material scatter may be a possible reason. But it seems more likely to

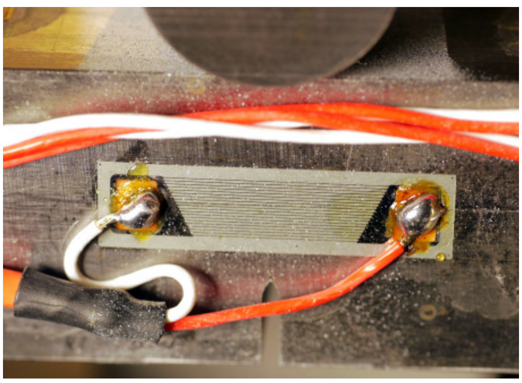

Figure 7. Crack sensor in front of the crack tip of a SE(B)25-specimen.

be due to the sensor position and analysis method. The sensor was placed only based on the nominal position of the precrack tip on the specimen surface. The real, measured initial crack length across the specimen thickness is not taken into consideration. Therefore, sensor position (2) on the crack was investigated. With (2) failure of the n-th strand positioned at the post-test measured mean initial crack length a_0 indicates crack initiation. Scatter of the crack initiation forces F_{ini} can still be observed with this procedure, $0.86F_{max} \leq F_{ini} \leq 1.0F_{max}$. But it is clearly lower than with method (1), although the tests were performed at -40 °C this time. Nevertheless, the data base for method (2) is still too small to finally rate the appropriateness of the technique.

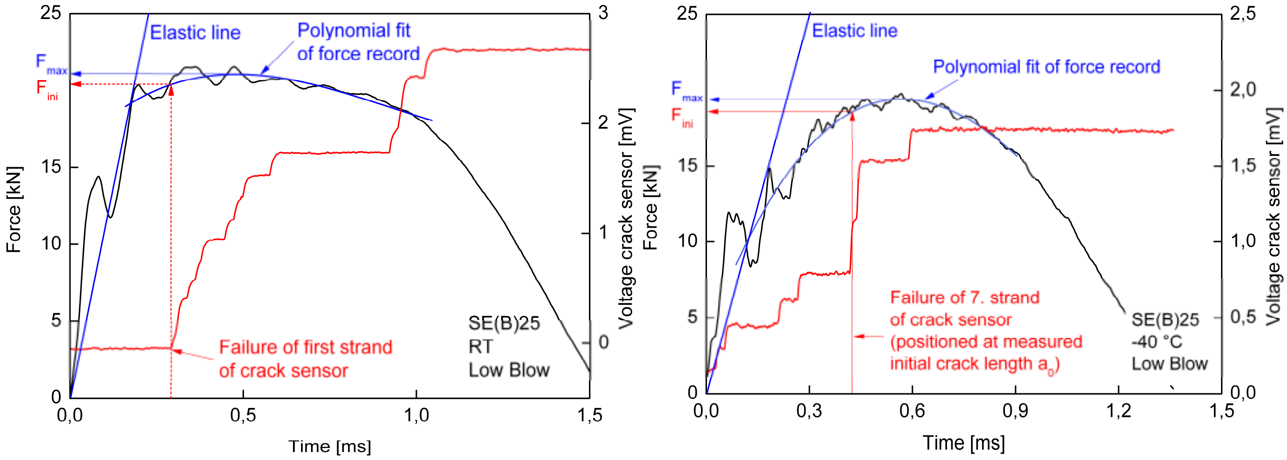

Figure 8. Principle of detection of stable crack initiation by failure of crack sensors, left: (1) crack sensor position at crack tip and failure of the first strand, right: (2) crack sensor position on the crack and failure of the n-th strand positioned at the measured initial crack tip.

2.2. Large scale full blow tests

A large wall thickness is typical for many applications of DCI such as casings or transport and storage cask for radioactive materials. In order to investigate how the fracture mechanics characteristics of small specimens, which could even be determined within quality assurance procedures, correspond to the results of large specimens with component-like thicknesses, series of large scale full blow tests were performed. Since large specimens do not show R-curve behavior under dynamic loading at -40 °C, a test method was developed for determination of dynamic fracture toughness values with SE(B)140 specimens (length 1350 mm, width 280 mm, thickness 140 mm, $a_0/W = 0.5$) at -40 °C by use of a servo-hydraulic impulse loading test system (max. 1 MN and 8 ms^{-1}). As with small scale testing, different strain gage instrumentations (Fig. 9) including as per BS and ASTM were compared with respect to their force measurement capability with SE(B)140 specimens at impact conditions and a stress intensity rate of $5 \cdot 10^4$ MPa$\sqrt{m}s^{-1}$. All strain gages were statically calibrated before the tests. Further details are reported for instance in [9].
Fig. 10 displays an example of force–time records and crack sensor signals. The test can roughly be assorted into 3 phases. During phase I, the rubber mat between striker and specimen is compressed and finally cut. After that, in phase II, the actual loading of the specimen takes place at a significantly higher but nearly constant loading rate compared to phase I. The stress intensity rate which is characteristic for the test is calculated as differential quotient in phase II.
Phase III is characterized by unstable cleavage crack growth until final fracture of the specimen. In phase III, the force signals F1–F4 and F2–F3 are not considered for further analysis with respect to the underlying test goal to determine dynamic fracture toughness at initiation of unstable cleavage fracture. The good agreement of the signals F1–F4 and F2–F3 illustrates the high symmetry of

loading. As expected, the machine load cell only provides a damped and less sensitive force signal which is delayed in time.

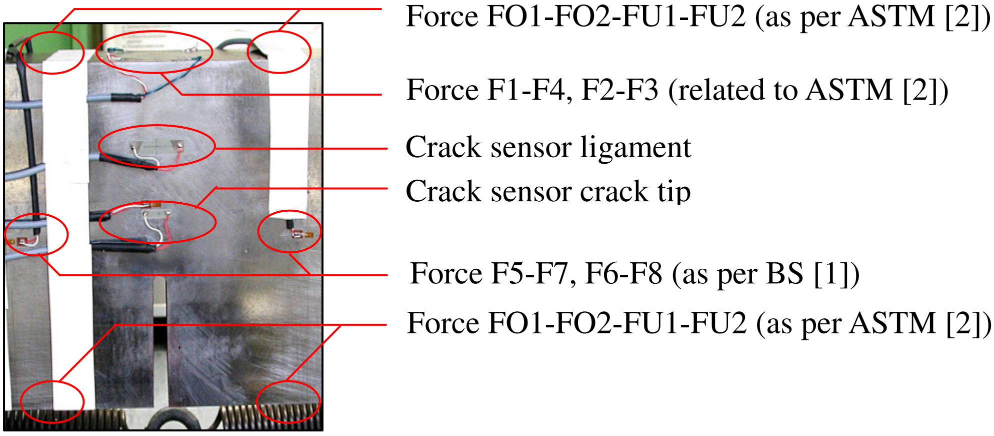

Figure 9. Strain gage instrumentation and crack sensors in and near the ligament of a SE(B)140-specimen.

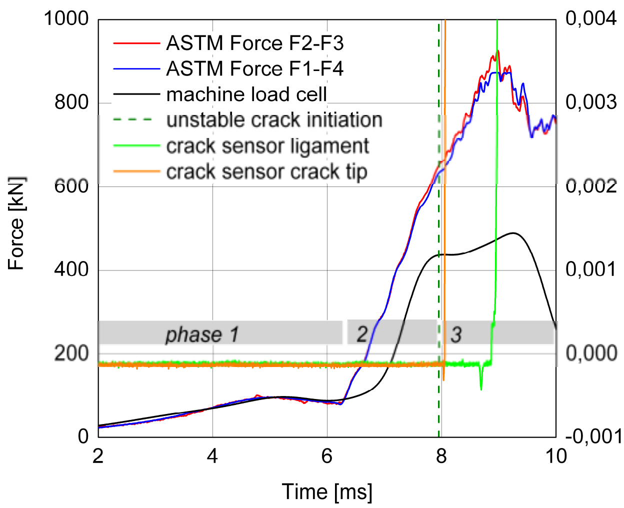

Figure 10, Signals from a dynamic SE(B)140 fracture mechanics test.

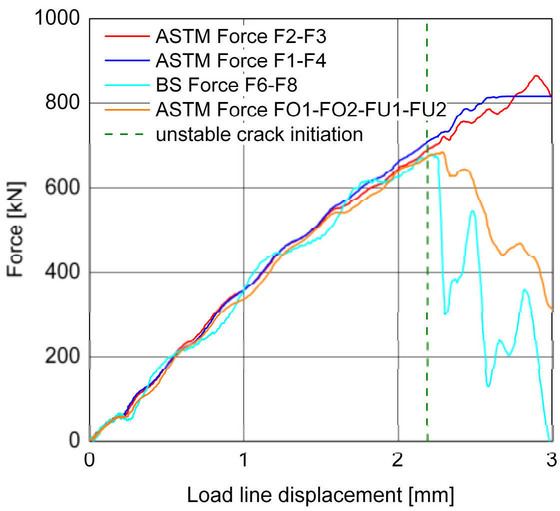

Figure 11a, Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests.

Finite element simulations of the SE(B)140 impact tests in [10] showed a good agreement between time dependent F1–F4 and F2–F3 force signals and numerically determined force-time data. The calculated crack tip loading in terms of K at the experimentally provided time of cleavage crack initiation corresponds very well to the experimental K_{Id} value.

Common feature of all test series is that the ASTM strain gage positions F1-F4 and F2-F3 show smallest dynamic effects, best sensitivity and reproducibility up to unstable crack initiation. Fig. 11 exemplarily shows the responses of different ASTM as well as BS force strain gage instrumentations for several specimens. As Fig. 11a reveals, the signals of ASTM and BS strain gage positions may nearly coincide. But in most of the cases the BS signals are below ASTM and show much more dynamic effects, Figs. 11b and 11c. Mostly, the ASTM half bridges F1-F4 and F2-F3 provide comparable signals to the ASTM full bridge FO1-FO2-FU1-FU2 up to unstable crack initiation. Nevertheless, the F1-F4 and F2-F3 signals show slight advantages in reproducibility and, very important, they offer valuable redundancy of measurement and simultaneously information on loading symmetry.

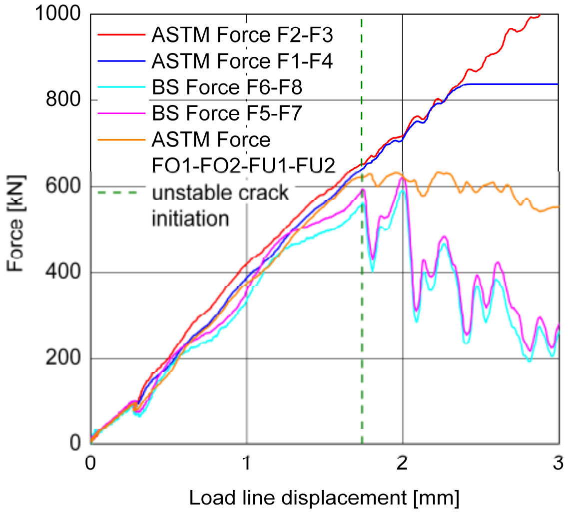

Figure 11b, Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests..

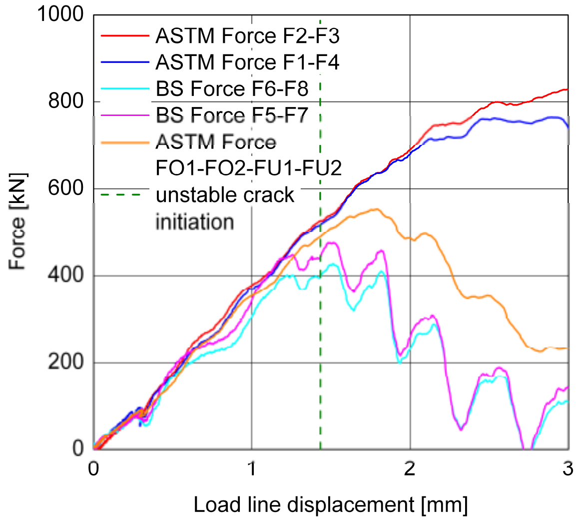

Figure 11c, Examples of force-displacement records of dynamic SE(B)140 fracture mechanics tests.

Generally, the F1-F4 and F2-F3 signals do not instantly show sharp drops at unstable crack initiation as it is known from Type I, II or III brittle behaviour of small PCVN specimens as per Annex 17 of [2] but keep rising until the crack has reached the crack sensor in the ligament, Fig. 10. This is not of concern when stable crack growth is absent and the test is only analyzed until unstable crack initiation. Nevertheless, this underlines the necessity of an adequate experimental method for detection of unstable crack initiation.

In this study, a method was elaborated where the initiation of unstable cleavage crack extension is indicated by fracture of the first strand of a crack sensor (Fig. 9) close to the crack tip (first steep signal rise in Fig. 10). However, since this crack sensor is not positioned at the crack tip directly but some millimeters in front of, a correction of the initiation time is necesssary. This is done by means of the crack velocity which is calculated from the known distance between the two crack sensors and the time measured between their responses. Since the distance between the crack tip and the first crack sensor is known too, the corrected time of unstable cleavage crack initiation can then be calculated. Due to the very limited plasticity in the ligament no problems related to sensors stripping away from the specimen surface were observed.

Since tactile displacement measurement devices are much too slow, the load line displacement was measured using an electro-optical camera, Fig. 12, as practiced with the small scale dynamic tests.

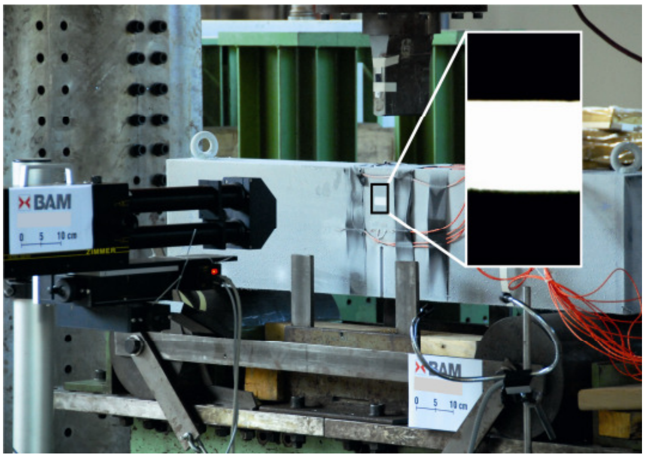

Figure 12. Electro-optical camera for measurement of load line displacement in dynamic SE(B)140-specimen tests.

The camera has two objective lenses, each of which tracing a black-white contrast on the specimen ligament so that two redundant displacement signals can be provided. The camera measurement technique is validated statically by gauge blocks and dynamically by comparison of the results of elongation measurement at rupture in dynamic tensile tests with the corresponding manually determined values.

3. Summary and conclusions

Experimental aspects of dynamic fracture mechanics tests on bend type specimens were discussed and different techniques for the measurement of force, displacement and crack initiation were investigated. It can be concluded that the fairly limited recommendations of the test standards may provide significantly different results. Therefore, they cannot simply be transferred to the own specific experimental tasks. It must be considered an absolute essential prerequisite that the used measuring techniques are validated in advance. The detection of unstable crack initiation by crack sensors in K_{Id} tests works well. Compared to that, the use of crack sensors to detect stable crack initiation in low blow R-curve tests needs further enlargement of the data base to finally rate the technique.

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