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Dynamic impact tests on materials & components of RAM packages - Advanced experimental and measurement methods

Juergen Auster **Karsten Mueller**

Klaus-Peter Gruender

Bundesanstalt für Materialforschung und -prüfung (BAM)
12200 Berlin, Germany

ABSTRACT

In accident scenarios of transport packages or hypothetical crashes of containers in a storage facility or repository, the materials resistance against dynamic failure of the involved components is a deciding factor for package and container integrity during the handling, transport and storage for each type of radioactive material. For example, different dynamic impact tests on containers and components like lid sealing systems and specimens made of ductile cast iron and shock-absorbing materials are carried out by BAM. In order to perform dynamic impact tests with packages and its parts BAM operates two free-fall drop test facilities with maximum capacities of 200 t and 55 t, and a test bench for guided drop tests. This latter drop test machine enables a clearly specified component loading by a precisely positioned test object or drop weight and has been used recently for numerous investigations. The paper gives an overview of the wide range of experimental testing methods carried out within guided impact and bending tests. Examples of methodological challenges are presented, especially such experimental analysis of dynamic impact conditions. In addition to known applied methods of dynamic, non-contact displacement measurements like high-speed 3-D surface deformation a recently patented 2-D tracking method is presented. By means of in-situ determination of fracture parameters with relevance to the materials stress intensity factor, the method has been successfully applied for a typical specimen geometry. Also shown are the possibility of detecting in-situ He-leakage rates on laterally impact loaded lid sealing systems as well as a method of acceleration sensor-temperature control under test conditions in the low temperature range.

INTRODUCTION

In the context of approval procedure tests of containers for the transport of radioactive material, mechanical stress tests under dynamic loading conditions are carried out to verify the structural and material resistance under hypothetical accident conditions. In contrast to quasi-static or cyclic mechanical loads, the force acting under impact-like mechanical stresses lead to special test devices and measurement equipment by means of sensory specialties. Tactile measuring methods, in particular for displacement measurement, are just as important as low-scanning force measuring methods. The actual load events often last only a few milliseconds and are partly superimposed by mechanical natural frequencies of the test sample, the sensor or the test apparatus. In addition, specific test conditions, such as the test temperature of e.g. -40 °C, which limits the use of sensors, or additional equipment.

In the following, some special test methodical applications of the test bench for guided drop tests are presented with implementation of new technical solutions developed and practiced by BAM.

The experimental methods and methodical features presented here are sometimes used in the context of ongoing approval or type examination programs. Thus, the respective methodological specialties are explained.

BAM TEST BENCH FOR GUIDED DROP TESTS

Since the construction of a large 200 t drop test facility in 2004 at the Test Site Technical Safety of the Federal Institute for Materials Research and Testing (BAM TTS), the test bench for guided drop tests have been used for component and materials tests under dynamic loading conditions belonging to package design approval procedure of containers for radioactive materials as well as for the simulation of other safety applications too.

In recent years, research projects and investigations have been deeply focused on the dynamic resistance of components and materials since a wide range of industrial applications need those data collections also for general safety evaluations. For example, drop tests on loaded Polyethylen containers and Li-ion battery packs as well as three-point bending tests on selectively rolled crash barriers and truck underride protection elements have been performed by BAM.

Technical Data

Max. Height:	14.2 m
Max. Drop Height:	12.0 m
Max. Drop Weight:	1,000 kg
Max. Impact Energy:	118 kJ
Max. Impact Velocity:	15.3 m/s
Impact target	
Weight of foundation incl. steel slap:	18,000 kg
Impact Area:	2 m x 2 m

Test Methods

Guided Drop Tests
Shock and Impact Tests
Dynamic Three-Point Bending Tests
Crash- und Crush Tests
Dynamic Compression Tests
Penetration Testing

Figure 1. Assembly parts of BAM's Test Bench for Guided Drop Tests

Depending on the component test as ordered, the setup of the test machine is adapted according to the respective task. In the following, the technical possibilities of the test bench for guided drop tests is shown by exemplary applications.

Investigations on scaled container wall segment with optical strain field determination

In the context of in-licensing investigations of transport containers for radioactive materials, several scaled container wall segments were subjected to dynamic load tests in the test bench for guided drop tests to validate FEM model calculations.

Nearly the entire range of examination methods considering the state-of-the-art technology was applied. In addition to an elaborate instrumentation of the test samples with numerous single and series strain gauges, a force-measuring device, developed by BAM, can register up to 2 MN dynamic loads.

For central deflection measurement the electro-optic Sensor 100R and a 2D high-speed camera are used. The falling mass was instrumented with accelerometers and the striker as impact tool was instrumented with strain gages. The load line of the dropped mass was additionally recorded by a laser vibrometer. The secondary impact of the falling mass onto the test specimen was prevented by an electro-pneumatic interceptor unit (App. No. DE201110056350). In addition to strain measurement by strain gauges, the optical strain field measurement was also realized within two experiments, which will be explained more in detail.

Camera-based measurement techniques are used to analyze 3D deformation and displacement of materials and components under drop conditions. In Fig. 1, the two outer cameras form after calibration a suitable stereo arrangement. It shows a part of drop test in which a 500 kg mass falling from a height of 3 meters reached a final velocity of approx. 7.6 m/s.

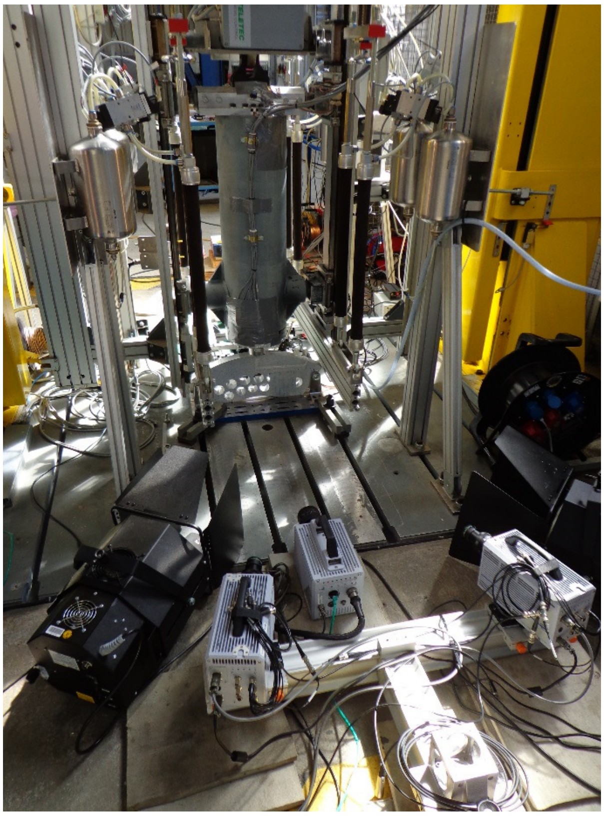


Figure 2.
Stereo camera arrangement for the 3D coordinate measurement of a component subjected to a drop load

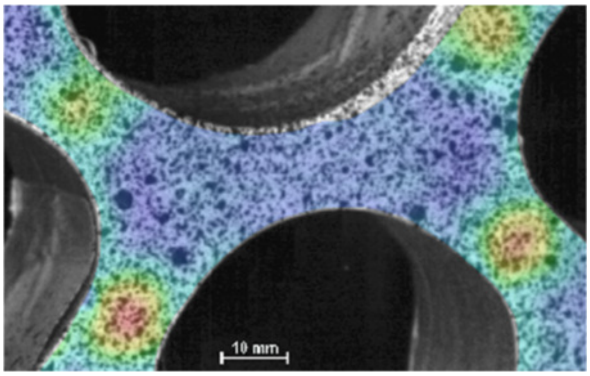


Figure 3.
Principal strain field of a component area of approx. 80 mm x 60 mm in the highest deformation stage [1]

Photogrammetric methods are used for measurements, which can be based both on point and pattern tracking. The latter method called 3D Digital Image Correlation (DIC) is given as an example in Fig. 3. Here, the speckle pattern on the component surface is shown. Its deformation is evaluated by means of small 14x14 pixel areas, so-called facets. For the strain evaluation, not only the 3D coordinates of the facets themselves, but also their surrounding ones have been used for calculation and set in relation to the reference state. The result for the principal strain eps1 at the highest deformation level is as a scaled pseudo color overlay displayed in Figure 4. The evaluation is carried out in a 3x3 environment, which corresponds to a spatial resolution of approx. 4.3 mm. Quantitatively, the highest strains are concentrated in the vertically oriented narrow walls, while in horizontal direction there is very low deformation. The experimental results are in good agreement with the Finite-Element simulation. [1]

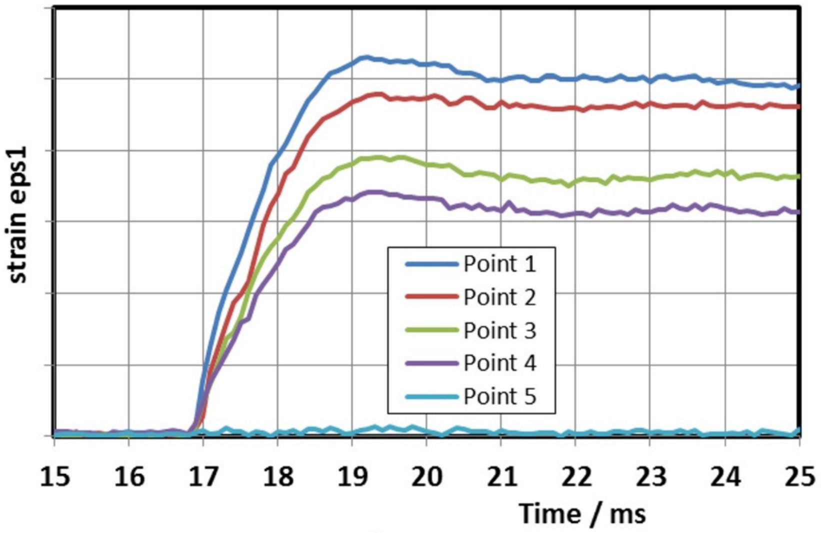


Figure 4. Schematic strain time curve of selected measuring points [1]

Figure 4 shows the strain-time functions belonging to the selected measuring points. The stereo cameras had a 10,000 Hz frame rate at an image size of 512 x 512 pixels. The individual curves show that the deformation process lasted roughly 2.4 ms up to the maximum principal strain value, only. After a similarly short time, the elastic strain component was no longer present and the residual strain component converged to a certain value [1].

Three-Point Bending Tests on DCI Specimens with Deriving a New Method for Determining Dynamic Crack Fracture Toughness J_{di}

The aim of the test campaign supporting safety evaluation of packages was to clarify the influence of the specimen thickness on the absolute values of the dynamic crack resistance values of ductile cast iron component commonly used for packages in Germany.

In the BAM laboratory a large number of samples of SE(B) geometry have been tested in the test bench for guided drop tests using a dynamic Three-Point Bending Test (dTPBT). On this basis and taken into account the concept of elastic plastic fracture mechanics (EPFM) the dynamic fracture toughness value, J_d-integral, has been determined for the bulk of non-circumferentially notched rectangular SE(B) specimens made od DCI. The maximum permissible crack propagation for evaluation according to EPFM was on average around 3.2 mm.

Furthermore, the dynamic fracture toughness, J_{di}, at onset of crack initiation is determined on some single SE(B) specimens by means of one-off technique, when the total among of stable crack propagation more than 3.2 mm is permissible.

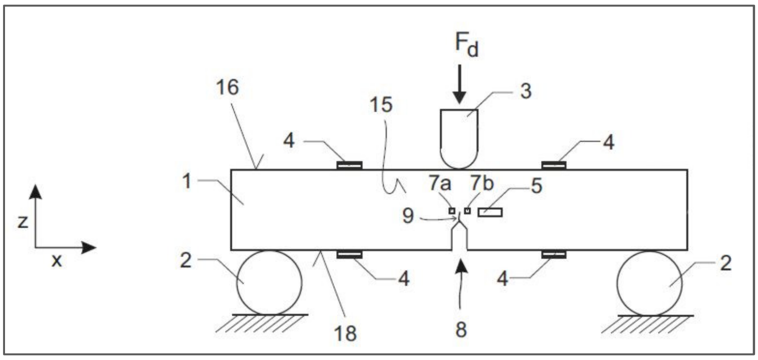
In order to determine the onset of crack initiation so called Crack Propagation Strain Gauges (CPS-Method) are used as the default method and applied to the long side surface of the rectangular specimen above the steady-state crack front.

The force measurement was carried out by means of a calibrated full bridge circuit on the steady bending test according to ASTM E 1820, Annex 14. The measurement of the dynamic deflection of the rectangular sample was carried out by means of a contactless, electro-optical sensor 100R from H.-D. Rudolph GmbH realized.

The electronic data were recorded with a DEWETRON 5000 transient recorder at a sampling rate of 2 MHz. The test temperature was -40 °C, the rectangular specimens were pre-cooled in a tempering chamber to -55 °C prior to installation in the test bench. Furthermore, the rectangular specimen for the determination of the dynamic crack tip opening according to the CTOD concept was uniformly provided with pyramidal δ5 markings at the level of the stabilized crack tip.

The dTPBT-setup is shown in Figure 5 and 6.

Figure 5.
dTPBT–setup front view

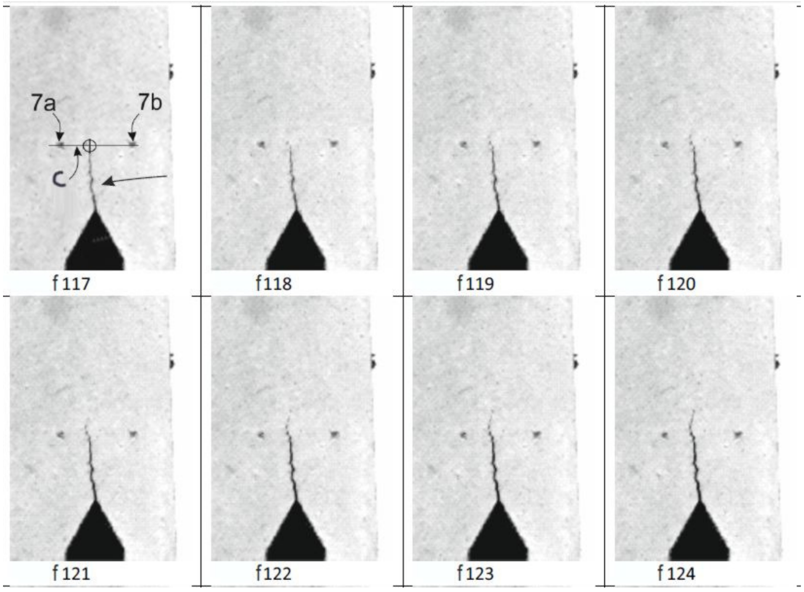


1	bending specimen	7b	δ5 mark on the right
2	cylindrical bearing	8	mechanical notch
3	semi-cylindrical tool	9	fatigue crack
4	full bridge strain gauge	15	first side surface
5	near field strain gauge	16	top side
7a	δ5 mark on the left	18	bottom side

Figure 6.
Schematic view of dTPBT–setup [2]

Supplementary, an acceleration sensor signal on the 180 kg falling mass and the signals of a fin instrumented with two single-strain gauges were recorded to ensure deflection and force measurements, as well as a 2D high-speed video recording with a frame rate of initially 40 kfps and in the last section of the test series made of 54 kfps.

The observation field of the 2D high-speed video recordings was located in the center of the long side surface of the rectangular specimen, into which the pyramidal δ5 markers were also introduced. This constellation allowed the observation of the crack tip opening and the laterally visible crack growth course in a time-sufficient resolution to register a dynamic crack tip opening near real-time resolution.



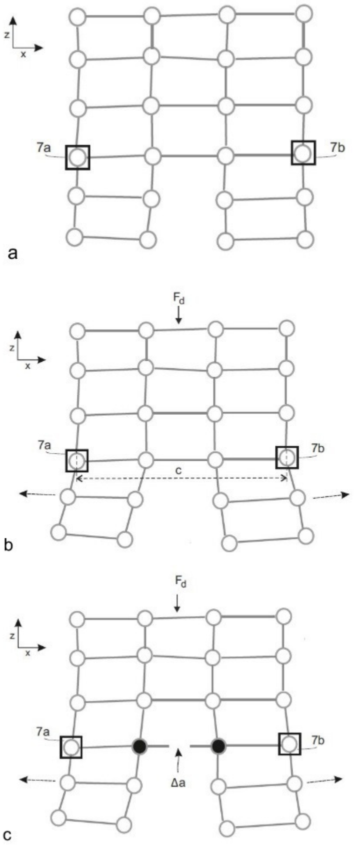


Figure 7. Single frames of 2D high-speed video recording at onset of crack initiation [2]

Figure 8. Postulated node model [2]

Based on the present supplementary high-speed video sequences, an attempt was made to develop a reference method to determine the onset of crack initiation for the CPS-Method more precisely.

In postulating the effect of the new method for determining the point of crack initiation, it was assumed that during the elastic deflection of the SE(B) specimen, the model assumed fibers at the crack tip (as seen in Fig. 8a and 8b) and the immediate in the direction of the ligament, at first stretch steadily. When microcracking starts as a result of the assumption that the fibers are modeled, the crack will break and grow in the direction of the ligament, depending on the acting load and dynamic materials fracture toughness. At the onset of crack initiation, a discontinuity in the expansion behavior of the model assumed fibers at the tip of the crack (see Figure 8c) and at the fibers directly above it in the direction of the ligament should therefore be expected.

By means of a pattern-matching software it is possible to calculate a 2D-tracking of the pyramid-shaped δ5 marks. Then the distance c of the δ5 marks in the z-x plane could be determined versus the measurement time (s. Figure 9).

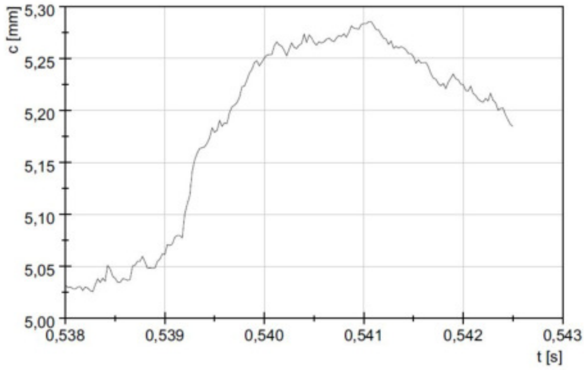


Figure 9.
Distance c of the δ5 marks in the z-x plane over the measurement time [2]

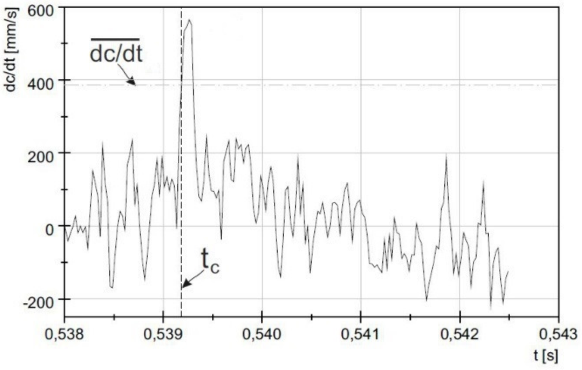


Figure 10.
δ5 mark distance velocity dc/dt [2]

Calculating the modification rate, dc/dt, of the distance between the δ5 marks in the z-x plane confirms the discontinuity in the expansion behavior postulated in the model node (see Figure 10. 03-06) in the region of the crack tip at the beginning of the crack growth t_c.

The time t_c could be determined with sufficient accuracy (+ [1 / framerate]) on the basis of the individual images by gray scale correlation. A possible advance of the crack inside the sample could not be considered. The effect of discontinuity in the crack tip elongation behavior at the onset of crack growth t_c could be confirmed for all samples with crack growth more than 4 mm. In these cases, a referenced determination of the dynamic fracture toughness J_{di} is possible. The temporal resolution for detecting the effect should be at least 40 kHz, but better is 54 kHz.

The exact detection of the onset of crack growth would in particular enable a more accurate determination of the stress intensity factor according to the K concept (LEFM).

In situ He-leackage testing of flange sealing systems under impact loading

In the context of container design tests, scaled flange pairs were tested under dynamic load in the guided drop test machine. The aim of the analysis is the correlation of the among of flange displacement caused by an external shock event on the leaktightness of metal seals installed in the flange system. In hypothetical accidents during transportation such loads can occur e.g. in the case of a horizontal or pin drop onto the cover lid system of a cask.

The He-leakage is measured as initial measurement and after cycling tests followed by recording of the leakage signal continuously during the dynamic load test. Thereby, the analog output signal of the He-leakage mass spectrometer PHOENIXL 300 (Oerlikon Leybold Vacuum GmbH) is recorded during the abrupt lateral displacement of the flange pairs.

In order to avoid influence to the classical XY plotter, the measurement signal conducted to the transient recorder is previously decoupled galvanically from the primary measuring circuit by means of an isolating amplifier. The output signal of the He-leakage mass spectrometer is updated 10 times per second and the time constant is given as > 1 s. Thus, the mantissa and exponent signals were recorded each at a sampling rate of 1 kHz.

The required test temperature for the test campaign is -40 °C. The cooling is realized by an specially manufactured circulating air temperature control system (VÖTSCH) with an insulated outdoor unit and additional LN_2 cooling (Figure 11 and 12).

Figure 11.
LLD - Setup during the tempering phase (outdoor unit)

The temperature measurement has been carried out after extensive preliminary tests to determine the temperature distribution of the flange pairs in the installed state by means of calibrated Ni-Cr-Ni elements. The lateral dynamic displacement of the test flanges is detected by the sensor 100R.

The dynamic load tests of the scaled test flange pairs are performed with an energy of 5.8 kJ at the impact velocity of 7.3 m/s.

In particular, the nozzle of the He suction line has been modified during the preliminary test phase in order to counteract a gaping of the connection by the load impulse. Recorded He-leakage timings first confirmed the occurrence and then prevention of this effect.

According to the measurements, the shock-like lateral shifts (on stop block) lead to a short-term increase in the He-leakage rate and then recover to a remaining slightly higher leakage rate. Differences between aluminum and silver-coated seals became apparent (Fig. 12).

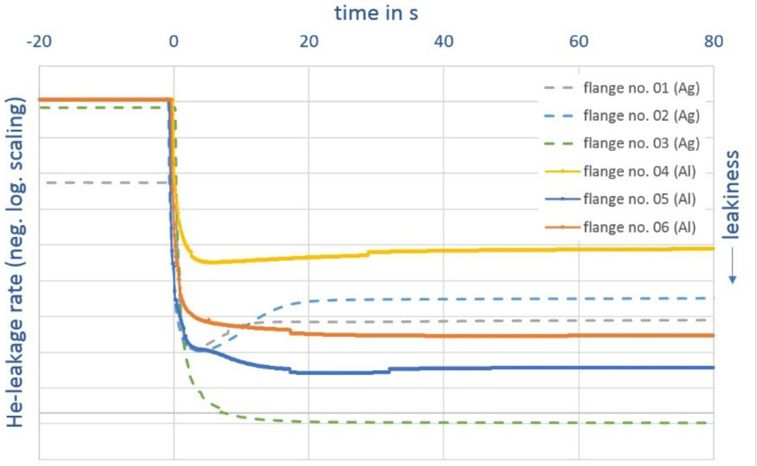


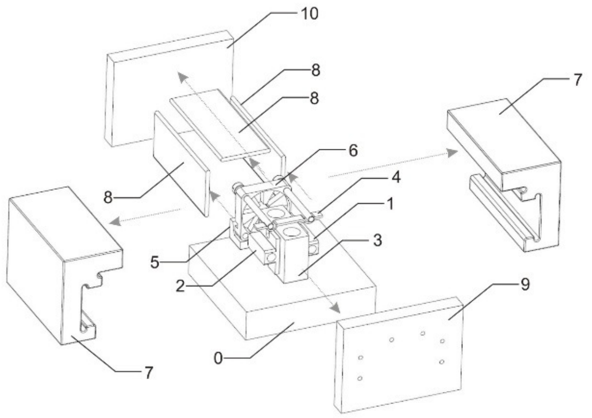
Figure 12. He-leakage rate response of Al and Ag – sealings

The investigations have shown the possibility of a reproducible dynamic in-situ measurement of the He-leakage rate.

A new method of acceleration sensor-temperature control under low temperature test conditions

For a test campaign of component tests of package shock absorbers, miniature accelerometers of the type EGCS-D0-5000 for low temperature impact conditions should be used. The range of operating temperatures is specified by the manufacturer ALTHEN between -40 °C to +100 °C, and the test temperature should not fall below -40 °C. For technical reasons, the test sample must be cooled down to less than -40 °C, so that the specified operating temperature is needed to undercut. In particular, oil or gel-damped accelerometers exhibit undesirable hysteresis effects during 'thawing'.

To prevent this, a self-regulating sensor tempering unit (Fan Convector Box FCB) was developed, patented (Appl. No. DE102014100652A) and has been successfully used. The structure is shown in Figure 13.



Legend:

0	Test specimen surface
1	Accelerometer
2	Accelerometer - Dummy
3	Prism
4	Strap
5	Fan-Socket
6	Fan
7	Insulator side panel
8	PTC- Heating element
9	Insulator gable part with Cable glands
10	Insulator gable part closed

Figure 13. Structure of FCB [3]

Basically for the correct function of the FCB is the minimization of the thermal bridge effect from the specimen to the sensor, the use of PTC heating elements (Positive Temperature Coefficient), as well as the guarantee of convection within the FCB.
Furthermore, a sensor temperature equivalent inside an accelerometer dummy is registered by means of a Ni-Cr-Ni element in order to take into account the temperature-dependent sensitivity of the accelerometer post-experimentally.

CONCLUSIONS

The paper describes the technical equipment, features and possibilities of BAM’s test bench for guided drop tests on the basis of three applied examples of component and material tests under dynamic load conditions.

In addition to dynamic, non-contact displacement measurements like high-speed 3-D surface deformation a recently patented 2-D tracking method is presented. By means of in-situ determination of fracture parameters with relevance to the materials stress intensity factor, the method has been successfully applied for a typical fracture mechanics specimen geometry. Furthermore, the possibility of detecting in-situ He-leakage rates on laterally impact loaded flange sealing systems as well as a method of acceleration sensor-temperature control under test conditions in the low temperature range are reported.

REFERENCES

1. Gründer, K.-P. and Kadoke D.: Optical strain field determination, not published, Berlin, Germany, 2019

2. European Patent EP 3 473 997 A1: Optisches Trackingverfahren zur Bestimmung des Zeitpunktes der Rissinitiierung bei der dynamischen Belastungsprüfung von SE(B)-Proben (OTRi), Den Haag, Netherlands, 2019

3. German Patent DE 102 014 100 652 A: Temperiervorrichtung für einen an einem Pruefkoerper starr befestigten Sensor, Berlin, Germany, 2014