

EXPERIMENTAL TESTING OF IMPACT LIMITERS FOR RAM PACKAGES UNDER DROP TEST CONDITIONS

André Musolff

Thomas Quercetti

Karsten Müller

Bernhard Droste

Klaus-Peter Gründer

BAM Federal Institute for Materials Research and Testing, Berlin, Germany

ABSTRACT

In context with new cask designs and their approval procedure the experimental testing of impact limiters under drop test conditions becomes more and more important in order to assess the damage mechanics behavior and safety margins for validation reasons.

In recent years various designs of impact limiters have been tested by the Federal Institute for Materials Research and Testing (BAM) within specific component testing and particularly with regard to type B package design approval procedures.

The paper focuses on the experimental realization of impact limiter tests and presents implemented measurement techniques to determine the amount of deformation and to explain the impact behavior by means of photogrammetric metrology and 3-d fringe projection method, high-speed motion analysis and adjusted deceleration measurements.

INTRODUCTION

The main objective of drop tests with RAM packages is to demonstrate that containment and radiation shielding maintain their integrity during and after the mechanical tests of normal and accident conditions of transport. Furthermore, the tests have to investigate the effectiveness of fixing of the shock absorbers at the cask. The measured deformations, deceleration and strains are the basis for the validation of Finite-Element calculations that had to be applied for transferring test results from component testing to the original package design.

Besides top and back end shock absorbers also over jackets, circumferential impact limiters and inner shock absorbing structural components were investigated experimentally. Free drop tests were performed under different orientations and heights. Furthermore, the test temperatures included lowest and maximum operational temperature during transport of the package.

The characterization of impact limiters made of different materials (wood or polyurethane composite construction or aluminum components) and geometries requires advanced test methods with increased accuracy of measurement and improved identification of image post-processing of shape and surface deformation, respectively.

The tests described here were performed mainly by BAM at the drop test facility "BAM Test Site Technical Safety".

EXPERIMENTAL REALIZATION

BAM operates three drop test facilities to evaluate package response to mechanical tests demonstrating safety under mechanical accident conditions.

The 200 tons drop test facility situated on the BAM Test Site Technical Safety in Horstwalde (50 km south of Berlin), is designed for test objects with a mass up to 200 000 kg [1]. The drop facility consists of a 36 m high drop tower, a closed test hall with an 80 tons overhead crane and an unyielding target. The maximum hook height is 30 m. The impact target is constructed of a 2 450 000 kg reinforced concrete block (14 m x 14 m x 5 m) faced with a steel plate (10 m x 4.5 m x 0.22 m) of 77 000 kg as impact pad.



Figure 1: 200 tons drop test facility, indoor drop test facility and drop test machine (from left to right)

The indoor drop test facility is located in a closed building at the grounds of BAM headquarters in Berlin [2]. The target, also a reinforced concrete block, has a mass of 280 000 kg, with dimensions of 6 m x 6 m x 3 m. The impact pad is a steel plate of 18 700 kg (4 m x 2 m x 0.3 m) embedded and fixed onto the concrete block. The maximum hook height of the crane is 12.5 m. The mass of the test object is limited to 5 000 kg.

The drop test machine allows guided drop tests [3,4]. The drop test machine consists of a 14 m high steel frame structure with a maximum load capacity of 1 000 kg, a large impact area (2 m x 2 m x 0.15 m) and a rigid foundation with a mass of 18 000 kg. A vertical sliding carriage consisting of four runner blocks is guided on rails using low friction ball bearings. The maximum drop height provided by the height adjustable frame of the test stand is 12 meters, and sled velocities at impact can be reached up to 15 m/s. The slide rails serve for the support of test objects or drop weight. The widths of the rails are 600 mm or 1600 mm, depending on the size of the test objects.

Each of these test facilities is suitable to perform drop tests with shock absorbers. Depending on the size and weight of the test specimen appropriate test facilities can be used.

REQUIREMENTS, MATERIALS AND GEOMETRY OF SHOCK ABSORBING COMPONENTS

Transport casks for radioactive materials have to withstand a most damaging 9 m drop test onto an unyielding target (cumulatively to 1 m puncture drop and 30 minutes fire test), as defined in the IAEA-Regulations [5]. In order to reduce impact energy acting onto the package and its components during a mechanical accident the casks are usually equipped with shock absorbers. The impact limiters are relatively “soft” compared to the cask. The load intensity on the cask, lid and lid screws is lowered significantly. Figure 2 shows two typical transport casks equipped with impact limiters attached to lid and bottom side.



Figure 2: 9 m drop test according to IAEA with typical transport cask configuration (full-scale SNF cask) [6]

Typical constructions of impact limiters consist of compartments of built thin steel sheets filled with different types of wood (balsa, cedar, oak, spruce) and various compositions of directions of wood fibers (Figure 3). In most cases, layered spruce wood is inserted between the thin steel sheets. But other relevant filler materials are used, for example aluminum honeycombs or polyurethane foams. Wood or other damping materials absorb the major part of the kinetic energy, while the steel sheets provide the integrity of the impact limiter during the impact process and the fixation to the cask body. Moreover, the steel sheets restrain the lateral dilation of the wood inside the impact limiter.



Figure 3: Impact limiter built of thin steel plates filled with wood of different kind and fiber direction [6]

BAM’s research also concentrates on material-related investigations on the compression behavior of the impact limiter [7].

Furthermore there are various types of shape and size but all these impact limiters have the same objective to reduce the impact energy acting on other package components. Figure 4 shows different impact limiters tested by BAM.



Figure 4: Different impact limiters designs

The main focus of drop tests with RAM packages is the experimental investigation of the mechanical behavior of lid and bottom impact limiters. Another supporting impact protection is the use of circumferential impact limiters. The investigated design consisted of three aluminum rings assembled by two half-shell segments (Figure 5). The main task of the circumferential impact limiters is to prevent the contact between trunnions and the target [8].



Figure 5: Cask with circumferential impact limiters as well as lid and bottom impact limiters

MEASUREMENT TECHNIQUES

The continuous and detailed record of measurement data is important for scientific research and analysis before and after drop test. The following issues are designed to give an idea of data acquisition at BAM focused on methods for impact limiters evaluation.

Strain and Deceleration Measurement

In drop tests the adequate instrumentation of a specimen with sensors is an important tool to evaluate its mechanical behavior during impact and to gain quantitative impact characterizing data.

Generally, the instrumentation incorporates the measurement of strains and decelerations at the package. Test results as deceleration-time and strain-time functions constitute a main basis for the validation of assumptions in the safety analysis, for the evaluation of calculations based on finite-element methods as well as are important for extrapolation of scale model testing on full-sized package within approval design assessment. Also, these test results could be an advantageous basis for the assessment of design alterations.

Strain gauges are useful to determine the time dependent magnitude of any deformation as well as associated stresses. Accelerometers are widely used for the measuring of motion i.e. speed or displacement of the rigid cask body, of vibration and shock. Appropriate electronic devices concerning range of analogue bandwidth, sample rate, etc. are utilized to acquire, record and store data.

The strain gauges were connected in a three-wire Wheatstone quarter bridge circuit. A six-wire Wheatstone full bridge circuit with sense wiring of the power supply was chosen to connect the accelerometers. Both methods are commonly used in experimental stress analysis. The data acquisition was carried out using multi-channel measuring devices from DEWETRON with wideband (analogue bandwidth up to 200 kHz -3dB) differential bridge amplifiers for direct connection of all bridge type devices. A pre-sampling filter of 100 kHz and a 500-MHz sampling frequency for each channel with a 12-bit and 16-bit vertical resolution was applied to each channel.

Figure 6 shows instrumentation examples of the test specimen by accelerometers and strain gauges and in detail the central soldering terminal from which the signals are transferred by 50 m long measuring cables to the data acquisition systems.



Figure 6: Data acquisition (left), central soldering terminal (top right), accelerometer and strain gauge on an impact limiter (bottom right)

High-Speed Motion Analysis

High-speed video technique with motion analysis of an impacting specimen represents a practical verification for the analysis of the impact event and the kinematic behavior of the cask with impact limiters in addition to acceleration measurements.

The chronological synchronization of high speed videos with corresponding acceleration time histories using adequate signal analysis software gives the opportunity for better mechanical interpretation and understanding analyzing acceleration signals, but also strain signals. Significant signal parts of the acceleration time curve during impact can be possibly related to visual mechanical events occurring at the impacting container or the target. A containers adjusted drop orientation can be validated by the high speed film e.g. in the moment just before impact and possible deviations from that orientation can be quantified. Besides other aspects, this could be one important aspect in context with the validation of numerical calculations of drop tests using the method of finite elements considering that already small deviations from the defined impact orientation can change expected results significantly.

Today, digital high-speed video technique with the possibility of a couple of thousands of frames per second by acceptable resolutions and color picture can provide an appropriate and easy to handle data basis for motion analysis. Current movement analysis software supports the automatic tracking of objects via pattern recognition. The results are displacement time histories of selected points at the surface of a specimen (e.g. high contrast markers were approved) which can be transferred by derivative with respect to time into velocity and deceleration time curves.

The following example compares test results of motion analysis with those of accelerometer measurements. The results were obtained from a 9 m corner drop test of a cask with round impact limiters onto the IAEA-target. Figure 7 shows the measured deceleration time history (blue) of the cask during impact compared to the mathematically derived deceleration curve (red) from the displacement time history determined by motion analysis of the high speed video.

The impact of the container is shown in Figure 8.

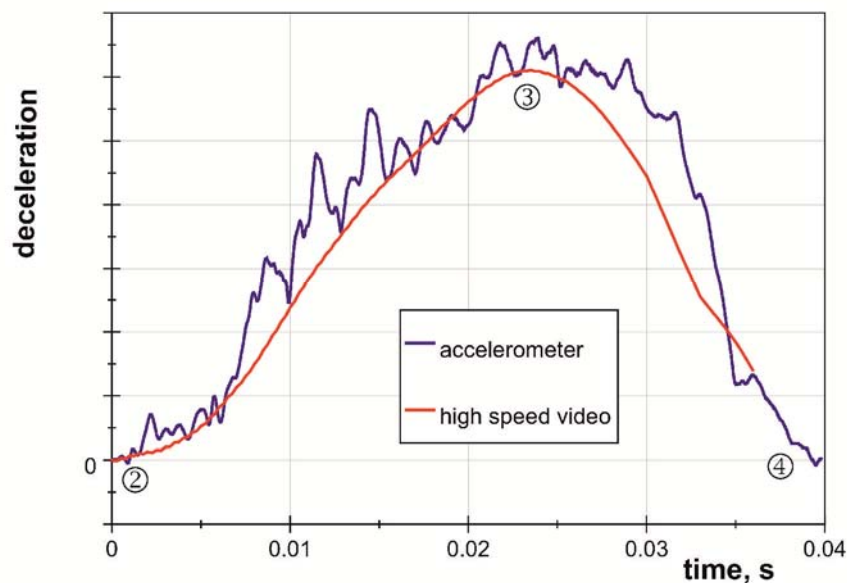


Figure 7: Comparison of deceleration time histories determined by high speed video and accelerometer. Points 2, 3, 4 see corresponding picture in Figure 8.
(No deceleration values are given because of confidentiality.)

The deceleration curves in Figure 7 show an almost useful congruence over the whole time history of the impact. Exceptions are due to higher bandwidth of the accelerometer and uncertainties of motion analysis.

Figure 8 explains in four single shots taken from high speed video (4000 frames per second, resolution of 1024x1024 pixels) showing single events of the impact: frame 1 shows the specimen just before impact; frame 2 shows the first contact between the longitudinal edge of the impact limiter and the target at time $t = 0$ s; frame 3 shows the maximum deceleration at time $t = 0.025$ s; frame 4 shows the end of the maximum limiter deformation at time $t = 0.04$ s.

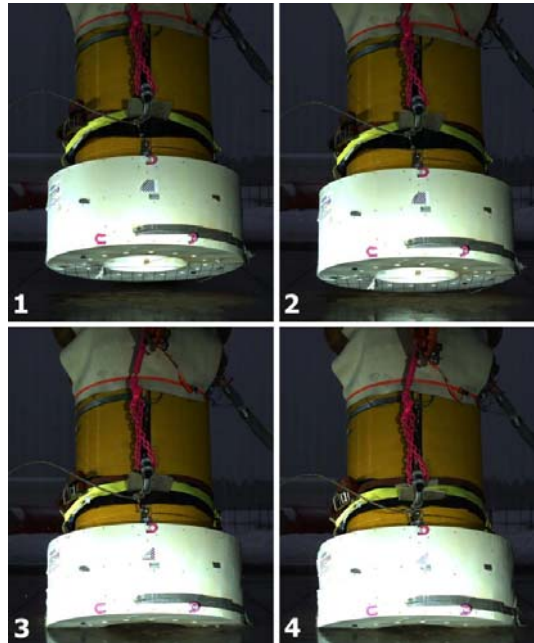


Figure 8: Impacting test specimen. Single shots taken from high-speed video (4000 fps) in chronological order.

3-d Surface Shape Measurement and Deformation Analysis

Within the experimental testing of impact limiters under drop test conditions the detailed and complete documentation of their geometric properties and behavior before and after the drop is of high importance for design approval assessment as well as in scientific research projects including Finite-Element calculation methods, respectively. The optical fringe projection method in combination with close-range photogrammetry is especially suited to investigate impact limiters implementing 3-d roundabout surface digitization. The impact limiter deformation is calculated from the difference between the surface shapes originating from the after and before drop states. This approach of digital surface shape presentation and comparison provides flexible and innovative 3-d measuring possibilities. But before that, a dense 3-d point cloud describing the limiter surface should be generated. The left picture in Figure 9 shows the sensor focused onto a subarea of the impact limiter surface. The commercially available sensor (type ATOS by GOM mbH, Germany [9]) consists of a photogrammetrically calibrated stereo camera setup observing this subarea that is illuminated by a special light projector located between the cameras. The sophisticated light projection is sequentially done by sine-like structured fringes capable to determine dense distributed 3-d points representing the subsurface shape. Depending from measuring area the typical lateral point spacing is 0.5 mm. About less than one second per fringe sequence is necessary for the image acquisition in both cameras (2M Pixel, 8 bit). In addition to the fringes brightness the images contain the position of reference dot targets fixed to the limiter surface. Their 3-d

coordinates are known from a precedent close-range photogrammetry session with an 3-d accuracy better than 0.1 mm. This way all subarea sensor views have subsequently to be transformed into a common impact limiter object 3-d coordinate system. From now on, the impact limiter surface is characterized by the overall point cloud. A final computation step is the triangulation process mathematically replacing the scattered dense point cloud by a meshed network of triangulated planes or spline functions. Both representations on the right side in Figure 9 show the photograph of a damaged impact limiter and its digitized surface, respectively.

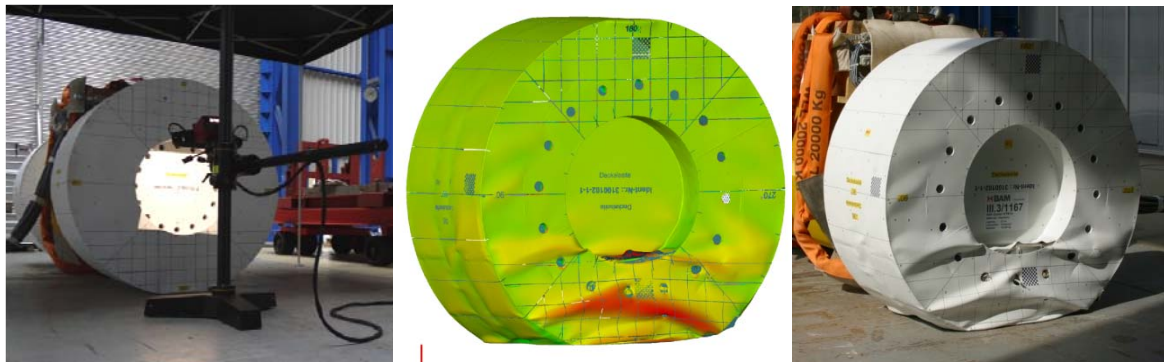


Figure 9: 3-d measurements with fringe projection method and close-range photogrammetry

This approach discussed above provides with a very flexible virtual measuring tool for 3-d shape and deformation analysis. The digital impact limiter models representing the shape before and after the drop test, respectively, can be used for a huge number of flexible documentation and analysis tasks without new or repeated measurements, such like:

- Digital documentation of complete 3-d impact limiter shape in graphical data formats
- Shape deviation from CAD model
- Shape deformation with respect to the reference state before drop test
- Surface or point based verification of Finite-Element simulation
- Data evaluation of point like or feature coordinates
- Data evaluation using the approximation of various geometric primitives

The presentation of these analyses can be performed as scaled color plot free-form surface deviations, table based compilation of coordinates, angles, distances or lengths or using freely arranged in space cross section profiles. This illustrates the fact that the fringe projection method combines with close-range photogrammetry is in a sense already applied at BAM as a standard approach in experimental impact limiter studies subjected to drop tests.

CONCLUSIONS

Radioactive materials transport packages are usually equipped with impact limiters in order to reduce impact loading onto the package and its components for containment, shielding and criticality safety. Impact limiters can have various designs, and different materials are used for that purpose. To assess impact limiters functions, and to obtain quantitative data for the verification of calculations, a set of appropriate measurement techniques has to be applied during drop tests.

BAM recommends strain and acceleration measurements, high-speed video for kinematic analysis and comparison with acceleration measurements and photogrammetry for evaluation

of lid movement and projected fringe methods for quantitative impact limiter deformation analysis. The combined application of these methods provides a good knowledge on impact limiter behavior, and a useful basis for a state-of-the-art transport package safety case.

REFERENCES

- [1] Droste, B., Müller, K., Minack, M.: The new BAM 200 tons drop test facility – construction and operation experiences, *Packaging, Transport, Storage and Security of Radioactive Material*, Volume 17, Number 3, S. 131-135, 2006.
- [2] Droste, B., Quercetti, T., Gogolin, B.: Test facilities for radioactive materials transport packagings, *RAMTRANS*, Volume 12, Number 2/3, S. 105-113, 2001.
- [3] Müller, K., Quercetti, T., Musolff, A.: Characterization of shock-absorbing components under impact loading, *Proc. 9th International Conference on the Mechanical and Physical Behaviour of Materials under Dynamic Loading, DYMAT 2009*, pp. 569-574, DOI: 10.1051/dymat/2009081, EDP Sciences, 2009.
- [4] http://www.bam.de/de/kompetenzen/fachabteilungen/abteilung_3/fg33/fg33_medien/fg33_characterisation_of_shock_absorbing_componrnts_d.pdf
- [5] International Atomic Energy Agency (IAEA): *Regulations for the Safe Transport of Radioactive Material*, 2012 Edition. Safety Standard Series No. TS-R-1, Vienna, 2012.
- [6] http://www.tes.bam.de/de/umschliessungen/behaelter_radioaktive_stoffe/dokumente_veranstaltungen/pdf/BAM_Foerderkennzeichen_02S8274.pdf
- [7] Eisenacher, G., Scheidemann, R., Neumann, M., Droste, B., Völzke, H.: Dynamic crushing characteristics of spruce wood under large deformations. *Springer, Wood Science and Technology*, 47(2), 369-380. doi: 10.1007/s00226-012-0508-5, 2013.
- [8] Musolff, A., Quercetti, T., Müller, K., Droste, B., Komann, .: Drop test program with half scale model CASTOR HAW/TB2, *Packaging, Transport, Storage and Security of Radioactive Material*, Volume 22, Number 3, S. 154-160, 2011.
- [9] <http://www.gom.com>