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LARGE-SCALE IMPACT TESTS WITH REINFORCED CONCRETE PLATES FOR IMPACT SAFETY

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ABSTRACT

This study investigates the impact resistance of reinforced concrete structures under extreme loading conditions, with a particular focus on scenarios relevant to the safety of nuclear power plants. Since airplane crashes have been a critical design consideration since 1977, understanding the structural response of reinforced concrete under high-velocity impact is essential for ensuring safety and resilience. Large-scale impact tests are limited in availability and have been conducted infrequently, but they provide valuable insights that complement small-scale laboratory experiments, allowing researchers to validate scaling laws and improve predictive models. This research, conducted as part of a collaboration between Technische Universität Dresden (TUD/IMB) and the Bundesanstalt für Materialforschung und -prüfung (BAM), aims to bridge the gap between laboratory-scale experiments and real-world structural performance.

The experimental setup involved reinforced concrete plates (3.0 m × 3.0 m × 0.4 m) tested in a four-point supported configuration under hard impact conditions using a gravity-driven drop tower system. A cylindrical steel impactor (404 kg) was released from a height of 9.5 m, achieving an impact velocity of 13.6 m/s. The study employed high-precision measurement techniques, including load cells, accelerometers, triangulation lasers, and high-speed cameras, to capture force, deformation, and failure characteristics.

The results indicate a distinct progression of force transmission and deformation, with localized damage characterized by global deformation, a breakout cone and rear scabbing. 3D laser scanning is used to document the outer damage pattern and create a digital image of the specimen after impact event. The experimental data confirmed a significant transfer of impact energy, leading to plastic deformations and possible reinforcement yielding. The findings contribute to a growing database for validating numerical models and refining impact-resistant design strategies for critical infrastructure, such as nuclear power plants. The test results will be further consolidated with additional tests in subsequent publications.

INTRODUCTION

Since 1977, airplane crash has been an essential load scenario in the design of nuclear power plants. To investigate this scenario, comprehensive studies have been carried out to analyse the reaction of reinforced concrete structures under impact loading. As large-scale tests are costly and time-consuming, small-scale laboratory tests have been carried out in the past to allow for larger variations. In order to show that scaling is possible, large-scale tests are also necessary. As part of a research project at Technische Universität Dresden, Institute of Concrete Structures (TUD/IMB) and the Bundesanstalt für Materialforschung und -prüfung (BAM), the basic principles of scaled impact tests on a large scale were investigated to allow transferability from laboratory to real scale. This contribution will present the test setup, the test preparation, the first large-scale drop test and first experimental results.

The aim of the investigations is to examine the scalability of impact tests both experimentally and numerically. Preliminary work has already been carried out in [1-3]. The scaling law according to SUGANO ET AL. [4; 5] was used here. The results of these investigations proved to be promising, which is why a further investigation phase was started. In NERGER ET AL. [3], BRACKLOW ET AL. [1] and HERING ET AL. [2], the scaling of the experiments was still 1.00, 1.25 and 1.50. In the current investigations, the experiments are based on a scaling factor of 2.0. The experimental investigations are divided between the two research partners TUD/IMB and BAM. The test specimens made of reinforced concrete have dimensions of 3.0 m × 3.0 m × 0.4 m and are tested as a four-point supported plate. The large-scale experiments were carried out at the Testgelände Technische Sicherheit (TTS) at BAM.

In the following article, the topic of scalability of experiments is not discussed in detail, as the focus is on the design and realisation of large-scale tests. The focus is on the preparation, execution, and initial evaluation of the experimental data. A completed experiment will be used as an example. Such large tests offer the opportunity to reproduce the response and damage behaviour on more realistic components.

EXPERIMENTAL PARAMETERS AND TEST SETUP

RC Specimen

Four reinforced concrete plates with external dimensions of 3.0 m × 3.0 m × 0.4 m were used as test specimens (Figure 1). Here, the results of only one plate are presented. Conventional B500B reinforcing steel was utilised for the reinforcement, with a bar diameter of 16 mm. The reinforcement spacing was determined to be 200 mm, and the reinforcement of the test specimen was uniform in both directions. The upper and lower reinforcement layers were also produced identically. The concrete cover is specified at 50 mm.

A C35/45 concrete with a maximum aggregate size of 16 mm was used. According to the manufacturer, with the mix design used for the C35/45. The concrete was mixed by the manufacturer in such a way that it reaches its standard strength after 56 days and not after 28 days as usual. To ensure the desired concrete quality, cube samples with an edge length of 150 mm and cylinders with a geometry of d = 100 mm and h = 300 mm were produced. The cubes were tested after 56 days and after 280 d. In addition, the cubes will be tested after 360 days. The cylinders were tested after 280 d. The results of the tests are presented in Table 1.

The test age of 280 d results from the time of testing the large-scale plates. A noticeable increase in strength to 56 d can be observed. Two plates were always produced during one casting. The routine test day was set between the large-scale experiments. In view of the substantial degree of preparation that is necessary for the large-scale tests, a test age >>90 d was determined. The test day of the presented plate is 197 d. This is intended to minimise the influence of the sample age, which affects the concrete strength and the results of the large-scale tests, respectively.

Table 1: Results of the compressive strength and modulus of elasticity tested on cubes and cylinders.

age [d]	$f_{c,cube,mean}$ [N/mm²]	$f_{c,cyl,mean}$ [N/mm²]	$E_{c,mean}$ [N/mm²]
56	58.5	/	/
280	65.3	50.5	31300

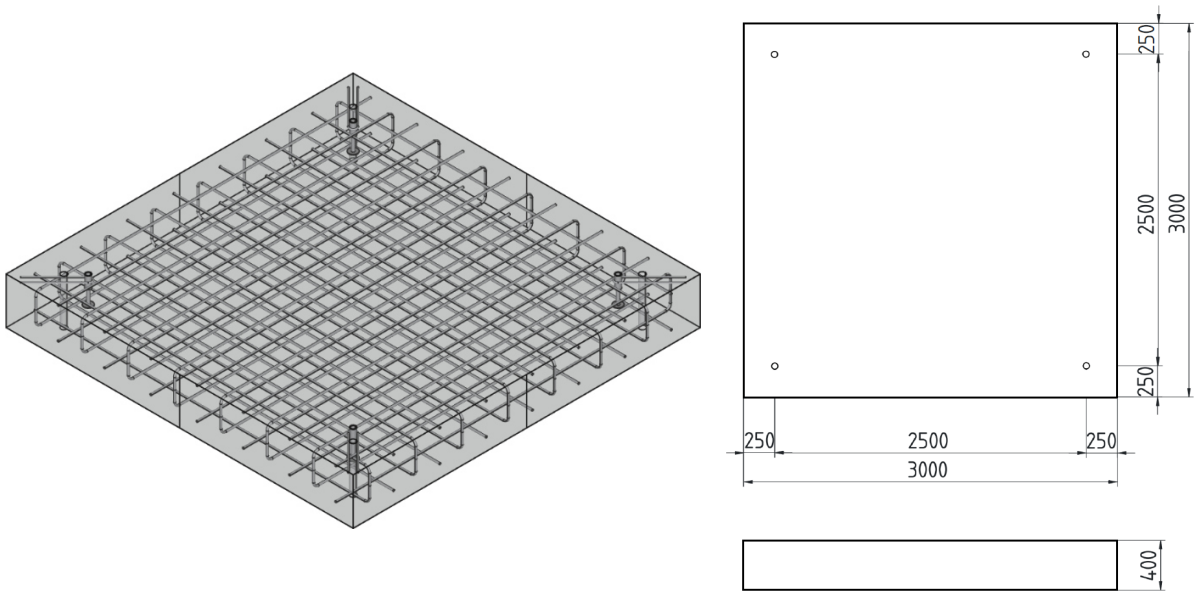

Figure 1. Overview of the reinforcement and specimen geometry with support points.

Experimental setup

The tests were carried out in a gravity-acceleration-controlled drop tower as seen in Figure 2. Here using a winch, the impactor (drop mass) together with an ejection device is lifted to the required height and then decoupled torque free onto the supported plate. The drop tower consists of an enclosed 55 t winch. The foundation of the test rig weighs approx. 600 tons and has an impact area consisting of a 21 cm thick steel slab measuring 7 × 4 m. The maximum drop height is 18 m, which corresponds to a maximum achievable speed of 16.6 m/s.

To achieve global deflection of the plate, it was raised on four supports at the corners. To facilitate this setup, a steel framework constructed from HEM100 profiles was developed which is firmly connected to the steel slab.

Four load cells (LC) were installed beneath the corners of the slab to quantify the support forces resulting from the impact. The four-point support configuration was selected to maximise the plate's deformation, while ensuring the availability of the four corner points for direct measurement of the support forces. This configuration has previously proven effective, as evidenced by prior experimental observations, see [1; 2; 6-8].

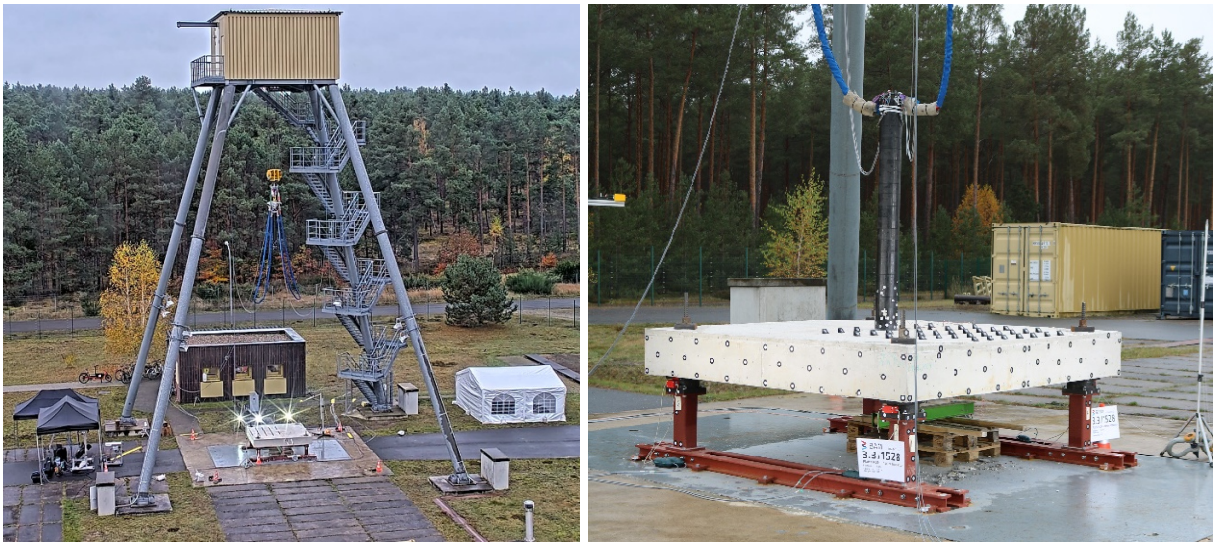

Figure 2. left: 18 m drop tower shortly before impact test, right: prepared plate on steel framework with erected impactor.

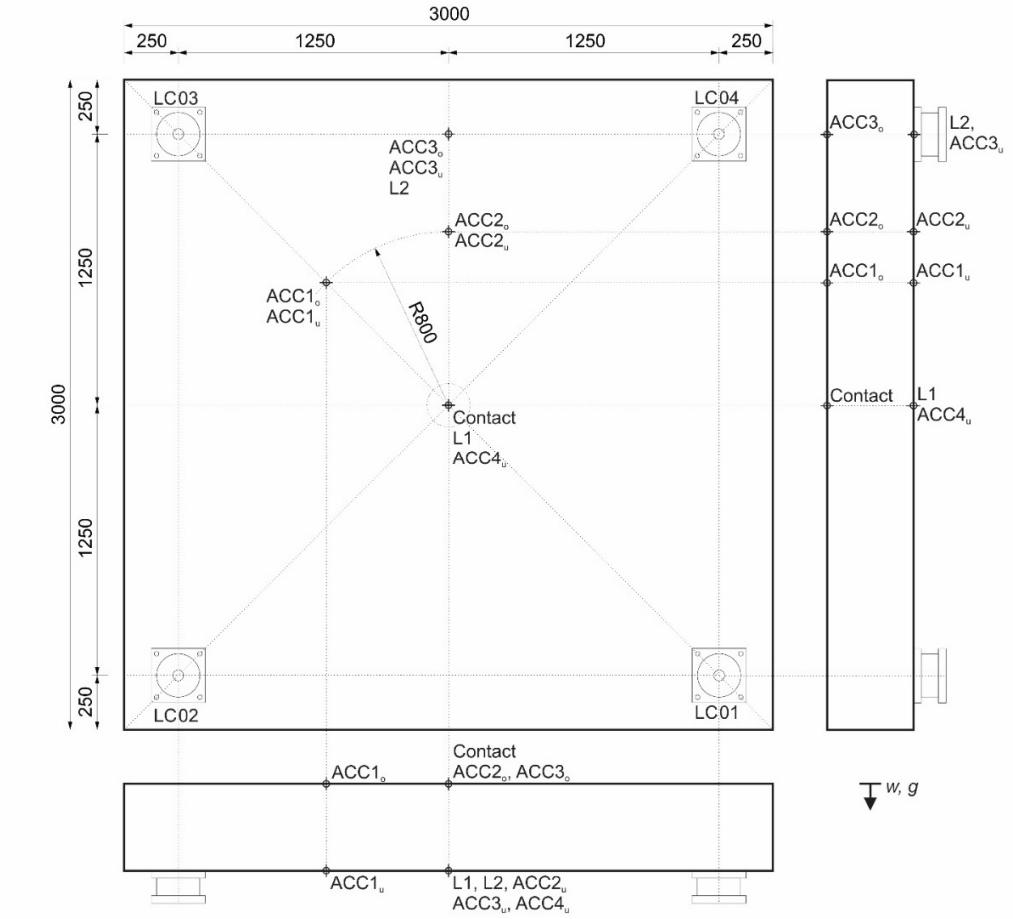

Figure 3. Geometry and measurement points of the tested plates.

The LCs represent an in-house development that was adapted and further developed as part of the current experimental investigations (see [8]). Each LC has a maximum load capacity of 10 MN, with the force measured via a strain gauge arrangement utilising two measuring arrays. Conventional constantan strain gauges were used for one measuring array, while semiconductor strain gauges were used for the second. Prior to the application of the load cells, the linearity factors necessary for the calculation of strain to force were determined at BAM. Further information on the LC can be found in HERING ET AL. [9].

In addition to the LC, accelerometers (ACC) and triangulation lasers (L1 and L2) for deformation measurement on the bottom side were applied. The two lasers are used for the estimation of the plate's global deformation resulting from the impact, as well as the possible displacement of a resulting breakout cone (local damage). The locations of measuring devices are summarised in Figure 3. Furthermore, an electrical resistor was applied to the plate in the impactor's striking area to determine the exact impact time (see Figure 3, contact). The moment the impactor hits the plate, it is destroyed, which makes it possible to measure the moment of impact.

To ensure a standardised support of the reinforced concrete plates on the LC, a quick-hardening mortar bed was applied on top of the LC. While the mortar was still workable, the reinforced concrete plate was placed on it, and then a prestress of 50 kN per LC was applied with the aid of prestressing steel and a nut and locknut system, to fix the reinforced concrete plate to the LC in a defined manner.

Used impact conditions

A cylindrical impactor, composed of hardened steel, was used to apply the hard impact. The impactor has an outer diameter of 200 mm, a length of 2034 mm and a flat striking tip. The impactor is assembled from individual discs, with two distinct types of discs in use: full discs and weight-reduced discs (circular disc). This facilitates the adjustment of the impactor's weight incrementally. Additionally, the centre of gravity of the impactor can be adjusted towards the impact surface, thereby promoting a linear free fall. At the tip of the impactor, a measuring ring was installed to quantify the impact force. This ring is a circular disc equipped with strain gauges on its inner surface, enabling the interpretation of the measured strain to determine the existing stress or force. The impactor's selected assembly configuration resulted in a weight of 404 kg (m_{impactor}).

The drop height that was selected for the experiment was 9.5 m. This resulted in an impact velocity (v_{impactor}) of approximately 13.6 m/s.

Measurement devices

A *DEWETRON* measuring system (DEWE3-RM16), in combination with four high-speed cameras, was utilised to facilitate the digital documentation of the experiments. The measuring system was configured to record at a rate of 500 kHz. The high-speed cameras were set to record at a rate of 5,000 fps.

The high-speed cameras were configured to form a stereo camera system. Two cameras were combined, enabling a three-dimensional photogrammetric evaluation of the impactor, upper half of the plate and the steel framework. The positioning of the other two high-speed cameras at a planar level relative to the test specimen ensured that the experiment can be adequately documented. Conversely, a two-dimensional (planar) photogrammetric evaluation of the experiment is possible with these images. The planar photogrammetry serves as a redundant method of evaluation regarding the three-dimensional photogrammetric evaluation of the experiment. The photogrammetric evaluation of the experiments is not discussed in this article.

EXPERIMENTAL RESULTS

Measured forces and acceleration

As displayed in Figure 4, the recorded forces and deformations are plotted over time, thus providing a visual representation of the dynamic processes under investigation. The figure illustrates the support force (∑LC-SG and ∑LC-SCSG), which is the sum of the four LCs, and the impact force, which is measured in the impactor. The acronym ∑LC-SG is an indication of measurement using constantan strain gauges, whereas ∑LC-SCSG signifies measurement using semiconductor strain gauges. The designation IMP-SCSG refers to the impact force recorded in the impactor tip, which was determined on the basis of a strain measurement using semiconductor strain gauges. The left axis of the diagram was used to represent the force. Furthermore, the plate deformation, measured using lasers, is plotted on the right-hand axis of the diagram. The time of contact of the impactor is set as the origin.

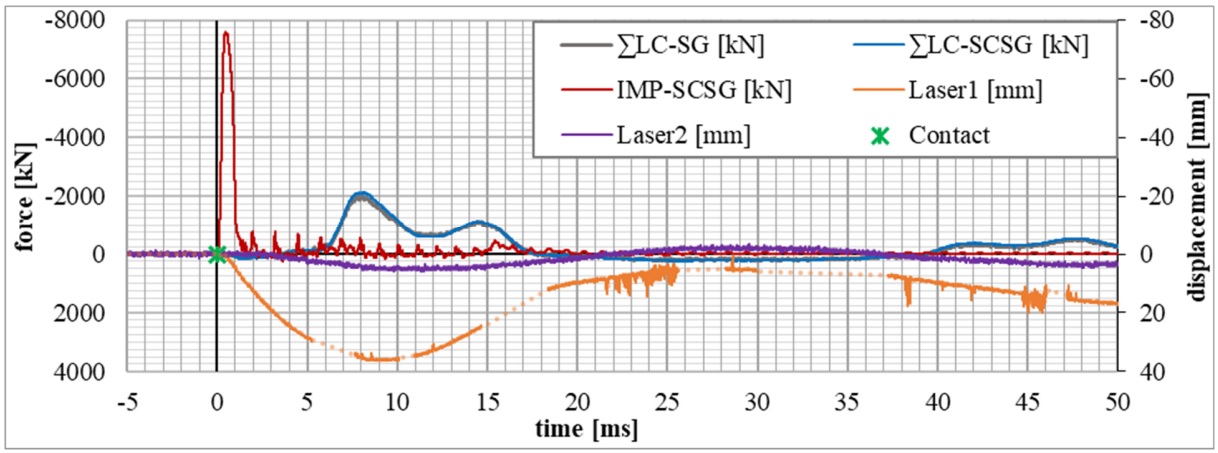

Figure 4. Measured forces and deformations over time.

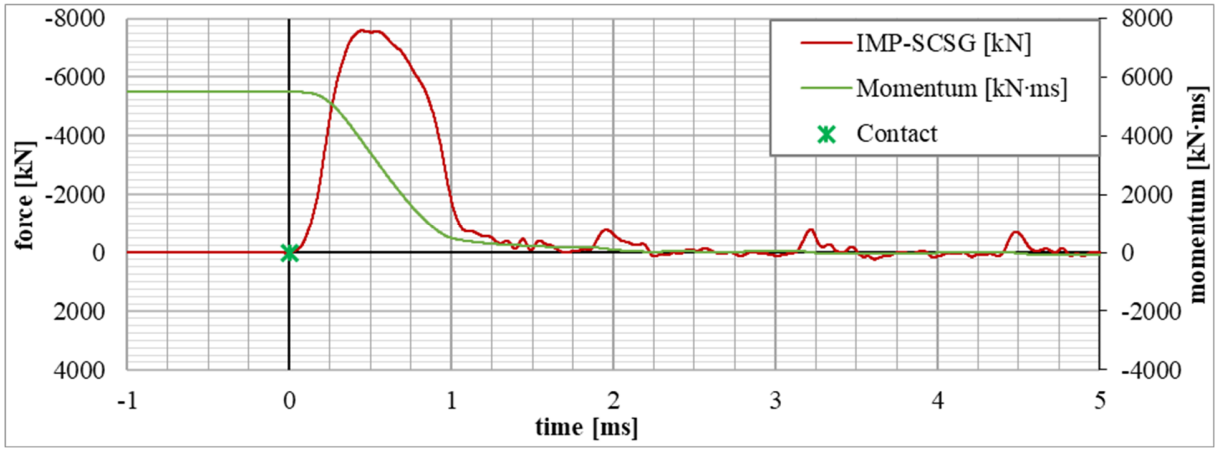

Figure 5. Measured impactor force and momentum of the impactor over time.

As demonstrated in Figure 4, the time offset of the measured forces is clearly evident. The impactor force initially rises rapidly before reaching a peak and subsequently falling again with equal rapidity. The support force measured in the LC and total global deformation measured with Laser2 only begin to increase significantly later. The deflection of Laser1, which measures the local deformation of the reinforced concrete plate beneath the impacted area, starts with a very short delay after the impactor strikes. The recording of the laser signals indicates a substantial difference in deformation between the edge and centre surfaces of the plate. The measurement data show evidence of localised damage to the plate as a result of the impact.

In the experiment presented, attention is paid to the impactor force. For this reason, it is shown in Figure 5 at a higher temporal resolution.

The initial momentum of the impactor before impact is calculated using equation (1) at 5494.4 kg·m/s, based on an impact velocity of v_{impactor} = 13.6 m/s and an impactor mass of m_{impactor} = 404 kg. Utilising equation (2) and the measured impactor force (IMP-SCSG), the momentum of the impactor can now be calculated over time. Measured force and calculated momentum are shown in Figure 5 using a two vertical axes. The left axis shows the force and the right axis the momentum.

It was observed that at the end of the impact test, the impactor remained motionless on the reinforced concrete plate. This is congruent with the resulting impulse after the impact process. (I_{impact} = 0 kg·m/s).

$$I_{\text{impactor}} = m_{\text{impactor}} \cdot v_{\text{impactor}} \quad (1)$$

$$I_{impact} = \int F_{impactor}(t)\, dt \quad (2)$$

Characterization of the damage pattern of the reinforced concrete plate

The global damage to the test specimen is noticeable through plastic deformation, which can be recognised by the bending cracks in the concrete on the bottom side of the plate.

As it is not yet possible to look inside the specimen, localised damage is shown schematically as a section in Figure 6. This is characterised by a break-out cone, following a shear failure, as well as front spalling and rear scabbing.

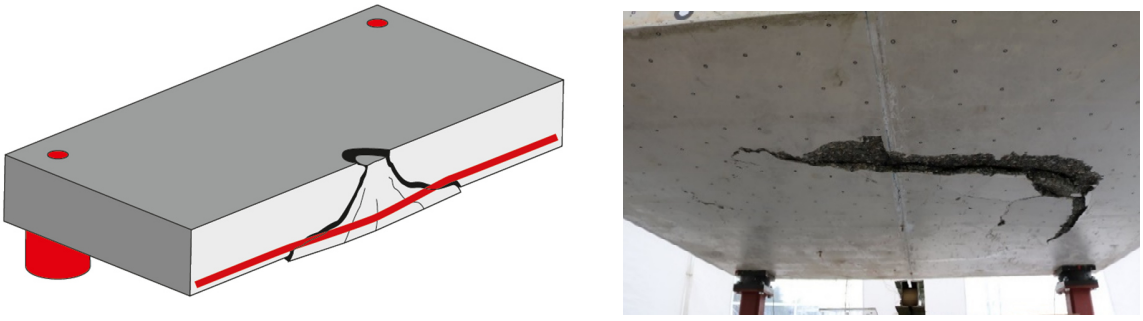

Figure 6. left: Schematic section through the reinforced concrete plate, with fracture body, right: View of the spalling under the plate after the test (point of view between load cells 2 and 1).

The damage on the upper surface of the plate is characterised by a circular impact area with a diameter of 200 mm. After the experiment, no spalling was detected on the upper surface of the plate.

The damage is more extensive at the back of the plate, as illustrated in Figure 6, which shows a substantial fracture body breaking out of the reinforced concrete plate. As described in the previous section, clearly localised damage to the slab in the form of a fracture body can be seen. After the experiment,

42.51 kg of concrete fragments that had broken out of the plate as a consequence of the impact were collected from beneath the reinforced concrete plate.

The geometry of the samples was digitised using a portable 3D laser scanner 'T-SCAN hawk' from Carl Zeiss GOM Metrology GmbH. This is carried out with the undamaged geometry before and the damaged geometry after the test. According to the manufacturer, the scanner has a local measurement accuracy of 0.02 mm ± 0.015 mm/m. To measure the plate geometry, the scanner is first used to perform photogrammetry of scales and the reference points. With these reference points, the scanner is guided over the surface using a cross line laser to capture a point cloud. This was subsequently meshed with the ZEISS Inspect software. By scanning the undamaged samples, a difference in the meshes can be determined. Tolerances in the production of the plate can thus be equalised. In Figure 7 the global plastic deformation on the upper side of the plate is shown after the test. Negative values correspond to a deformation 'downwards'. The support points of the load cells are shown in grey in the corners.

After the test, the upper surface was deformed with a maximum plastic deformation of about 3 mm. The impactor penetrates the plate by an average of about 4 mm (accounting for global deformation). The impactor penetrated evenly, which indicates a complete vertical transfer of the impact energy, which is congruent with the assumptions made in the previous Section.

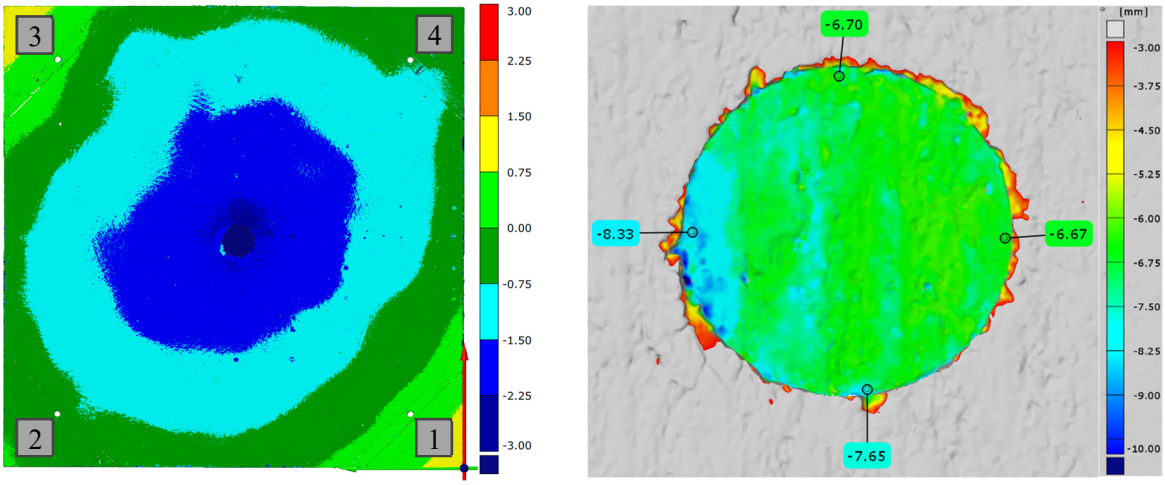

Figure 7. left: Deformation of the upper side of the plate in the Z direction, right: close-up of the impact area with different scales in mm.

The bottom side of the plate showed clear spalling after the impact (see Figure 8). In order to be able to work safely under the plate, loose parts of the break-out cone were removed before the scan. In contrast Figure 6 shows the condition directly after the experiment.

Due to the limited space under the plate, no photogrammetry was carried out at this side. As only a cross-line scanner was used, the same global accuracies were not achieved as at the upper side. The area between LC1 and LC4 is the furthest away from the calibration and shows deformations of up to 7 mm (green area in Figure 8 left). However, this is due to measurement inaccuracy. In reality, the surface does not have a 7 mm deformation, but is relatively flat.

The scan in Figure 8 shows that the break-out cone is not symmetrical due to the heterogeneity of the material and load transfer to the supports. On the bottom side it has a diameter of about 1.8 m. Spalling occurred in areas with greater deformation. The maximum vertical plastic deformation of the break-out cone is therefore approx. 20 mm. This significantly greater deformation than at the upper side shows that the break-out cone has not deformed downwards as a whole but has become segmented. Some of the shear failure has taken place in the plane of the reinforcement layer as seen in Figure 8 on the right. The vertical displacement of the reinforcement compared to the surrounding concrete was measured in the three areas

highlighted in white in Figure 8. The difference here is a maximum of 10 mm vertically from the original position.

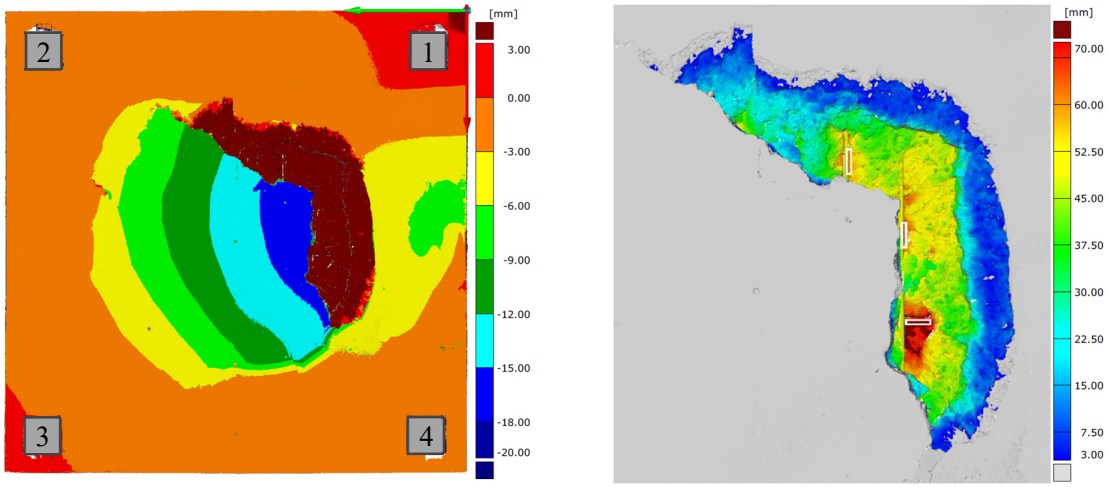

Figure 8. left: Deformation of the bottom side of the plate in the Z direction, right: close-up of the spalling area (with areas of reinforcement highlighted in white) with different scales in mm.

SUMMARY AND OUTLOOK

The article presents the test setup of an impact experiment in which a reinforced concrete plate was loaded and damaged by a hard impact. The metrological methods used to document the test and the damage that occurred is discussed. Phenomenologically, the damage caused by the impact event can be well presented using the recorded result data. However, a single test does not allow a systematic analysis in its entirety, and further test are needed to supplement the database and to obtain a holistic view of the topic. For this reason, further large-scale tests are being carried out to improve the database. The experiment presented here was chosen exemplarily.

The impact test carried out serves to supplement the database started in [1; 7; 8]. With the help of the collected data, it is possible to validate and to improve the existing simulation methods used in design and assessment.

Further experiments are being carried out with the impact-damaged reinforced concrete plates to investigate their fluid penetration. This is used to determine whether the impact event has compromised the leak-resistance of the reinforced concrete structure.

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