Impact experiments with reinforced concrete plates of different thicknesses

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Abstract
A test series of 15 reinforced concrete (RC) plates was carried out in the drop tower of the Otto Mohr Laboratory of Technische Universität Dresden. In these tests, the structural behavior of RC plates of different thicknesses was investigated under impact load. Within this report, the investigated specimen and the used drop tower facility are introduced. Furthermore, the experimental program and the experimental results will be shown. Following, the influence of different thicknesses and impact velocities are presented and discussed. The different damage levels of the RC plates influenced by the specific variation of the impact speed form a very good basis for further investigations in this scientific field. Especially the view into the plates, which was made possible by saw cuts, extends the understanding of the impact behavior considerably.

KEYWORDS
damage description, drop tower, impact loading, reinforced concrete

1 | INTRODUCTION

The investigation of the impact behavior of concrete and reinforced concrete (RC) has long been a focus of research. In order to understand, describe, and simulate plain concrete under high load rates, numerous investigations have been carried out worldwide, see, for example, Abrams1, Bischoff and Perry2, or Zielinski et al.3, and also at our institute, see, for example, Curbach4, Quast and Curbach5, Mosig and Curbach6, and Häußler-Combe et al.7 Investigations concerning the bond behavior of the reinforcement steel are also known, for example, References8,9. However, the understanding of the material behavior is just the first step to better understand the effects which occur on the structural level of RC.

For this reason, a large number of impact experiments have been carried out on structural level in the past, for instance, Jonas et al.10, Eibl and Keuser11, and Tuomala et al.12. In addition, not only the behavior of the affected structure is of interest but also the behavior of the acting structure (e.g., an aircraft), see Eibl and Keuser11 or Sugano et al.13–16. During the last years, a large number of impact experiments were even conducted at the Otto Mohr Laboratory of Technische Universität Dresden. Most of these experiments were published in two research reports, see Just et al.17, and Hering et al.18. Small experimental series have also been published elsewhere, for example, Kühn and Curbach19, Hering et al.20, and Kühn et al.21.

In a current research project, the scalability of impact experiments with RC plates is being investigated. The first step of these investigations consisted of a series of impact experiments in which the plate thickness was varied.
2 | AIM OF INVESTIGATION

The aim of the study was to systematically conduct and evaluate large-scale RC plate impact experiments in order to obtain a well-documented database for experimental investigations and numerical simulations. For the experiments, a proven and well analyzed experimental setup was used, see Just et al.\textsuperscript{1}, and Hering et al.\textsuperscript{18}. In the experiments, different failure and damage levels were to be shown and the influence of the plate thickness of the damage achieved was to be characterized and analyzed. The different levels of damage should be achieved by systematic variation of the impactor velocity.

3 | SPECIMEN AND TEST SETUP

3.1 | Used materials, specimen geometry, and their fabrication

The specimens were fabricated in formworks made of plywood panels. The inner dimensions of these formworks were $1.50 \times 1.50 \times 0.30 \text{ m}$. The different plate thicknesses ($t_{\text{plate}}$) of 10, 20, and 30 cm were fixed by the filling height of the formwork. The concrete grade was C35/45. For the reinforcement, steel bars made of BSt500S(B) with a diameter ($d_{\text{RC}}$) of 8 mm were used. The reinforcement steel was specified in accordance with DIN 488-1\textsuperscript{22}. An additional examination of the steel properties was not carried out. According to DIN 488-1\textsuperscript{22}, a yield strength of 500 MPa can be expected. The distance between the reinforcement bars was chosen as 100 mm. The concrete cover was 2.5 cm. The plate geometry and the reinforcement grid are shown in Figure 1. The picture also shows the positions of the measuring equipment (see Section 3.2). Furthermore, the additionally used transport brackets (Figure 1, shown in green) are displayed. These have no constructive function and serve as attachment points for crane hooks.

The fabrication of the plates started with the production of the reinforcement cages outside the formwork. The reinforcement bars were spot-welded to fix their positions. Following, the reinforcement cages were lifted into the formworks. Then, the concrete was brought in and compacted. After completion, the surfaces of the plates were smoothed and covered with a PE foil to prevent them from drying out. The plates were stored up to the seventh day inside the formworks. After this curing time, the plates were demolded and stored at the backyard of the Otto Mohr Laboratory. Cylindrical standard samples with a diameter of 150 mm and a high of 300 mm were also produced to check the quality and uniformity of the concrete used. The specimens were stored next to the large-scale plates on the backyard to provide the same curing conditions like the plates. The cylindrical standard specimens were tested after 28 days according to DIN EN 12390-3\textsuperscript{23} as well as at the beginning of testing the large-scale plates. Due to the time-consuming test procedure of the large-scale plates, the tests were conducted after more than 6 months in order to neglect the time-dependent strength development of concrete.

The average cylinder compressive strength after 28 days was 39.2 MPa. According to Reference\textsuperscript{24}, an average compressive strength of approximately 43.0 MPa was expected for the planned concrete class C35/45. However, because the tested cylinders were stored under nonstandard curing conditions, this strength is acceptable. After 6 months, the average compressive strength of the standard cylinders increased to 67.7 MPa. This increase in strength was documented based on compression tests carried out over a period of 6 months so that it can be taken into account in the subsequent evaluation.

3.2 | Experimental setup

The experiments were conducted at the drop tower facility of the Otto Mohr Laboratory. This facility allows
experimental investigations in two loading modes. The different available modifications are the gravity drop tower mode and the accelerated drop tower mode. Both are described in detail in Just et al.\textsuperscript{1,25} For the experiments presented in this publication, the accelerated drop tower mode was used.

At the beginning of the design of the experimental setup, there were two requirements for the support conditions of the tested plates. The first was that it had to be possible to measure the support reaction. The second was that the bending deformation of the plate should be as free as possible in order to be able to measure deflections that occur as well as possible. To fulfill both requirements, a four-point support of the plate was chosen. So, the span of the plate is maximized which leads to a maximum free bending deformation capacity. The support forces can be measured with load cells (LCs) under each support point. Figure 2 shows the LCs without plate (left picture) and on the right side, the complete test setup with built-in sample ready for testing.

Self-developed LCs with a maximum load capacity of 10 MN were used to measure the support reactions of the plate, see Figure 1. Full bridges made of semiconductor strain gauges were installed into the LCs to compensate potential moments entered directly into the LCs. For more information, see Reference \textsuperscript{1}.

Two high-speed cameras (HSC) recorded everything that happened during the experiments. One of these cameras was installed diagonally above the specimen and the other perpendicular to the front of the plate (Figure 3). The HSC sampling rate was 10,000 frames per second at a resolution of

\begin{figure}[h]
\centering
\includegraphics[width=\linewidth]{figure2.png}
\caption{Support points on the foundation of the drop tower facility (a) without (picture by Bracklow) and (b) with (picture by Hering) an applied specimen.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\linewidth]{figure3.png}
\caption{High-speed cameras view, (a) HSC diagonal above the plate (picture by Hering) and (b) HSC perpendicular to the front of the plate (picture by Bracklow).}
\end{figure}
1,024 × 640 pixels. A large amount of light was required to record at this high sampling rate. It was supplied by four 2,600 W headlight batteries.

The deflection of the plate was measured at three different points, compare Figure 1—points L1, L2, and Vibrometer. Two of the points were located on the bottom side of the plate (L1 and L2) and the third on the top (Vibrometer, here, a Laser Doppler Vibrometer was used). The exact locations of these measurement positions are given in Figure 1. Laser displacement sensors were used to measure the displacements at the “L1” and “L2” measuring points. In addition to the measurements described above, the accelerations of four points on the surface of the plates were recorded. Three measurement points were located on the plate's top surface and one at the bottom side. Acceleration sensors with a maximum range of ± 5,000 g were used. The exact locations of these sensors ACC1–ACC4 are shown in Figure 1.

The measurement rate for all devices described above was 200 kHz. The data were collected without prefiltering.

The plates were placed on the LCs with a leveling mortar. This was necessary to provide good contact between the LCs and the sample. Furthermore, the use of a leveling mortar guarantees a perfect fit of the plate. Additionally, the plates were fixed with threaded rods in each corner which, for the sake of security, prevent uncontrolled horizontal displacement of the plate. A special sliding/rotation was not used to apply the plate on top of the support cells. When loading the plate, it must be assumed that the plate rotates on the support points and thus on the LCs. This was taken into account in designing the LCs. For this purpose, 16 semiconductor strain gauges were integrated per LC, which provide a measured signal corrected for torque, see Hering et al. The threaded rods were screwed into the LCs, and the plates were clamped with nuts to prevent the plate from lifting off in the case of rebound after the impact event. Furthermore, with this procedure, the position stability of the specimens was guaranteed. The applied clamping force for each LC was 25 kN. These forces were controlled during the clamping process to guarantee the equality. The forces are low enough to allow a small horizontal movement of the plate to prevent extra membrane effects.

A uniform impactor was used in all experimental investigations. The length of the impactor was 380 mm. The diameter of the impactor was determined by the pipe diameter of the drop tower facility in accelerated configuration, and it was 100 mm. This resulted in an impactor mass of 21.66 kg.

4 | EXPERIMENTAL PROGRAM

All samples had a base area of 1.50 × 1.50 m, resulting in spans of 1.25 × 1.25 m. As described before, three plate thicknesses were examined. Five different velocities were selected for each plate thickness. The speed of the impactor was controlled by the charge-pressure of the facility which was adjusted for each test. The objective of the velocity variation was to achieve different damage grades of the RC plates due to the impact. It was planned to start with the tests at medium speed. The speed was then varied according to the desired damage grade that should be achieved.

The used charging-pressures are summarized together with the resulting impactor velocities $v_{\text{impactor}}$ in Table 1. The gray values marked indicate the start configurations of each series. Per configuration, one plate was tested. The fact that the choice of the first speed can be wrong despite the experience got in many experiments before can be seen in the experiments with the 10 cm thick plates. With the first selected charge-pressure of 2.0 bar, the impactor perforated the plate completely, see Figure 4. Thus, the experiments were started with the highest speed against the original intention.

In the case of boost pressure = 0.0 bar, we have considered two possibilities. As for the faster version, the air supply was simply opened, so that the impactor could accelerate in free fall. For the slower one of the two experiments, the air supply was kept closed. Now, the air had to flow from the front around the impactor. The resulting “negative” pressure in the tube behind the impactor provided a braking effect which led to a lower impactor velocity.

After the experiments, the plates were cut into two parts using a concrete saw. This made it possible to look into the damaged RC plates. More information will be given in the next section.

| Plate number | Plate thickness, $t_{\text{plate}}$ (cm) | Vessel pressure, $p$ (bar) | Impactor speed, $v_{\text{impactor}}$ (m/s) |
|--------------|---------------------------------------|---------------------------|------------------------------------------|
| PL124        | 20                                    | 1.0                       | 25.2                                     |
| PL121        | 2.0                                   | 2.0                       | 32.7                                     |
| PL120        | 4.0                                   | 4.0                       | 44.6                                     |
| PL122        | 6.0                                   | 6.0                       | 53.9                                     |
| PL123        | 8.0                                   | 8.0                       | 61.4                                     |
| PL133        | 10                                    | 0.0                       | 9.2                                      |
| PL132        | 0.0                                   | 0.0                       | 12.7                                     |
| PL134        | 0.5                                   | 0.5                       | 21.6                                     |
| PL131        | 1.0                                   | 1.0                       | 26.1                                     |
| PL130        | 2.0                                   | 2.0                       | 33.4                                     |
| PL143        | 30                                    | 4.0                       | 44.6                                     |
| PL140        | 6.0                                   | 6.0                       | 54.5                                     |
| PL142        | 8.0                                   | 8.0                       | 61.3                                     |
| PL141        | 10.0                                  | 10.0                      | 68.4                                     |
| PL144        | 12.0                                  | 12.0                      | 73.9                                     |
5 | RESULTS

5.1 | Evaluation of the occurred damage

The damage observed in the experiments was a combination of bending and punching cone failure. In the tests presented here, the punching cone failure was the dominant failure pattern. Furthermore, spalling and scabbing could be observed. An increasing damage of the upper side of the 30 cm thick plates could also be detected.

Figures 5–7 display the saw cuts of all tested plates arranged according to the impactor speeds. The place where the saw cut was carried out is shown in Figure 1 as a red dashed line. The compilation of the saw cuts starts with the lowest impactor velocity. The further saw cuts follow with increasing impactor velocity. In Figures 5,6 the expected behavior or damage is visible: as the speed of the impactor increases, the damage increases too until the plate is fully perforated. However, also the plates that appear undamaged from the outside (PL124 and PL133) are interesting. It is visible that the damage or crack formation which will lead to a full punching cone failure of the plate already exists.

In these two figures, it is also easy to see how the destruction of the fracture cone increases with increasing the speed of the impactor. At low speeds, there is almost no segmentation of the cone, while at high speeds, it is fragmented into ever smaller pieces. In the beginning, the fragments are still so large that they get caught in the bending reinforcement. At the end, they become so small that they can fall through the bending reinforcement.

In contrast to Figures 5,6, the plates displayed in Figure 7 show a partly deviating behaviour. The upper three specimens PL143, PL140, and PL142 follow the behavior described before. At the beginning, only a hardly recognizable fracture cone can be observed. This cone becomes more and more pronounced as the velocity of the impactor increases. At speeds of 68.4 m/s and higher, the damage behavior observed before changes. Although
the speed of the PL141 and PL144 specimens has been further increased, the punching cone damage did not increase. Now, however, a kind of damage could be observed that did not occur during the tests on the thinner plates. The damage on the top sides of the plates increased. While the thin plates (e.g., PL122 and PL123) showed a clearly defined round hole in the size of the impactor, the plates PL141 and PL144 now show a significant crater on the top of plates.

It is assumed that the kinetic energy existing due to the higher velocity of the impactor can no longer be completely converted into the generation or destruction of the fracture cone. Much of the kinetic energy seems to flow into the surface damage of the plate. By increasing the speed, the surface damage has increased from plate PL141 (68.4 m/s) to plate PL144 (73.9 m/s). In parallel, the internal damage of the plates remained almost the same.

### 5.2 Evaluation of the reaction forces

The first focus of the test evaluation is on the measured support forces. In order to obtain the total support force, the measured forces of the LCs LC1 to LC4 were summed up. Before doing that, the measured signal of each LC was smoothed. A moving average with a 10-point value window was selected for smoothing the data. This moving average filter is comparable with a 20 kHz deep-pass filter. The use of different filter methods and the subsequent comparison of the results showed that this method could smooth the measurement data as far as possible without significantly modifying them. The difference between a smoothed and a not smoothed measurement signal is shown in Figure 8. The unfiltered signal is shown in gray and is hardly visible behind the filtered signal, which is proof of the good approximation. Furthermore, all measured signals were adjusted in
time so that the moment of impact corresponds to the time 0.0 ms on the x-axis.

The support reactions of the 15 plates are shown in Figure 9. The time is plotted on the horizontal axis of the diagrams and the summed up support forces on the vertical axis. In the case of the 20 cm plates, the support reaction increases with increasing impactor speed. However, this behavior only occurs until the impactor is so fast that it perforates the plate. The experiments show that the so-called “perforation limit” of the 20 cm thick plate is located something between 54.9 and 61.4 m/s. The perforation limit is the velocity at which a projectile or impactor begins to penetrate the target body or plate.
Figure 9 displays this due to the fact that the measured support force of PL123 plate decreases compared to plate PL122. The 10 cm thick plates show a similar behavior. Up to a velocity of 12.7 m/s, the measured reaction forces increased. By using higher impactor speeds, the plates were perforated and the measured reaction forces decreased.

In the series with the 30 cm plates, this behavior could not be observed. The reason for this is probably the observed change of the damage mechanism by increasing impactor velocities. This change was already recognizable in the saw cuts. However, a change in the measured values is already noticeable under consideration of plate PL142. With this plate, the measured support force decreased in comparison to plate PL140 although the speed of the impactor was increased. As already described, no perforation of the plate occurred, which was the reason for such a behavior of the support forces in the case of thinner plates. The further increase of the speed at plates PL141 and PL144 resulted in a further increase of the measured support forces. This suggests that only part of the impactor's energy is used to destroy the surface of the plate. The rest seems to continue to affect the whole plate. Although this was not to be assumed in the saw cuts necessarily, the damage did not continue to grow noticeably.

**FIGURE 10** Measured plates displacements, graphic by Hering
FIGURE 11  Measured plates accelerations, graphic by Hering
5.3 Evaluation of the plate displacement

Figure 10 shows the displacement-time diagrams of the plates. The exact measuring points are shown in Figure 1. The measurement marked with “Displacement Vibrometer” corresponds best to the displacement of the plate's midpoint on the upper side of the plate, because the vibrometer was placed only a few centimeter away from the centre. A more exact determination of this plate displacement is not possible because the impactor hits directly the centre of the plate. As before, it has been observed that the measured maximum displacement increases until the perforation limit of the plate is reached. These observations correspond to the description of the perforation limit in Reference 26. This behavior could be recognized very well at the 20 and 10 cm plates. However, it could not be observed with the 30 cm plates. On the one hand, these plates could not be perforated during the experiments, and on the other hand, the surface damage led to the fact that the measured signals were not completely analyzable.

When considering the displacement of L1 which is situated in the plate's centre on the underside, the speed at which the impactor penetrates the plate can only be recognized to a certain degree. Above a certain impactor speed, spalling occurs on the underside of the plate. From this speed on, the displacement of the rear side of the plate can no longer be measured exactly. The spalling can be very well noticed in these signals by overloading the laser displacement sensor. This could be observed very well especially with the plates with a thickness of 20 and 10 cm. The overdrive of the laser displacement sensor can be recognized by the fact that a constant value of about 10 cm can be seen in the measurement. This measurement could only be carried out for the 30 cm thick plates for all investigated impactor velocities because these specimens were neither perforated nor spalled significantly.

A measurement, which unfortunately did not bring the desired results, was the displacement measurement at the measuring point L2. Considering the 20 cm plates, the measurement seems to be a little bit noisy but still evaluable. However, with the 10 cm thick plates, it became clear that there was something wrong. This can be seen in Figure 10, PL130. A smooth signal as measured at L1 was to be expected. However, a very noisy signal for the laser displacement sensor L2 has been observed. Ultimately, it had to be determined that the laser displacement sensor L2 had failed. Although now a comparison at point L2 is not possible for all experiments, it should be made for the plates where the sensor was still functioning.

5.4 Evaluation of the plate accelerations

The acceleration values measured at the points ACC1–ACC4 are summarized in Figure 11. The arrangement of the measuring points has already been shown in Figure 1. In this measurement, it was expected that higher impact energies would also cause higher accelerations on the plate. A significant difference in the maximum and minimum amplitudes of the acceleration values could not be determined. Surprisingly, the acceleration sensors ACC1 and ACC2 did not show the same values. Due to the positioning of these sensors in the same distance to the location of impact, this could have been expected at least theoretically. But, of course, this is only being a purely theoretical consideration. Under realistic conditions, a large range of variation can be expected. However, the decay of the measured acceleration which results from the damping can be seen very clearly.

At the end, one aspect should be mentioned when considering the acceleration sensor ACC4. It was determined that this sensor overdriven at all experiments (consistent signal at approximately 50,000 m/s²). For further experiments, it is recommended to use an acceleration sensor with higher measurement range (e.g., 100,000 m/m²). Even better would be the recording of deformations directly on the underside of the plate.

6 CONCLUSIONS AND OUTLOOK

A large number of interesting effects could be recognized in this series of experiments. Thus, the continuous increase of the damage with increasing impact speed could be shown very well. The direct comparison of the measured values created a relationship between the measured quantities and the structural behavior of the components. The great benefit of the conducted investigations can be seen not only in the experimental analyses and qualitative descriptions of the structural behavior but also in the generated data basis for numerical simulations.

However, after these experiments, many further questions arose. Some of them should be named:

1. The influence of the impactor length and thus of the impactor mass remained unanswered by the experiments conducted.
2. The influence of the shape of the impactor nose was not investigated.
3. Neither the reinforcement nor the concrete class was varied.

In order to answer the still open questions, numerical simulations will be used, which will be calibrated with the help of the collected measurement data. Further investigations will focus on the relationships between surface damage and the impactor velocity. The interaction of reinforcing steel and concrete in the event of an impact load must also be investigated further. Here, reinforcement shape (e.g., stirrups), diameter, ratio, and arrangement in the plate's
cross section have to be taken into account. In addition to this, the dynamic bond behavior between reinforcement steel and concrete and the dynamic material properties of the concrete have to be further investigated.

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