Small-scale plate tests with fine concrete in experiment and first simplified simulation

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Abstract
In the following article impact experiments from experimental and numerical point of view will be described. In order to keep the number of parameters to be varied manageable, the focus was firstly on similar plain concrete plates. The experiments were carried out with the aim to collect reference values and to simulate these experiments as basis for further investigations. The only parameter that has been changed was the impact velocity. The experimental part of the publication deals with manufacturing of the specimens, the experimental setup, the execution of the experiments, the measured values, and a brief evaluation of the results. The numerical part of the publication deals with the computation of experimental results using the simulation program LS-Dyna. In this context, it will be explained how the model was created and which boundary conditions and material models were used. Furthermore, the calibration of the material law is described. Subsequently, a comparison between the experimental and simulated results is carried out. The focus of the further investigations will be the consideration of concrete layers reinforced with textiles under impact load. The work presented here deals with the matrix material of the textile reinforced concrete and thus laid the foundation for these investigations.

KEYWORDS
drop tower, impact, LS-DYNA, numerical simulation, plain concrete, small-scale experiments

1 | INTRODUCTION
The investigation of plain and reinforced concrete has long been the focus of scientific research. Large-scale specimens are often used for these investigations leading to expensive experiments. Such experiments were conducted worldwide.1–6 To understand the reaction of a structure under impact load structural and material behavior has to be understood. Therefore the structural experiments are often combined with corresponding material research; see Refs. 7, 8. Such investigations have also been carried out at the Technische Universität Dresden in the past few years; see Refs. 9–14.

The overall objective of the entire research project is to investigate the strengthening effect of thin textile or carbon reinforced concrete layers applied on the side facing away from an impact load. For this purpose, the
required large-scale experiments are expensive and time consuming. To make the impact testing more efficient, small-scale experiments were developed and analyzed by different researchers; see for example, Refs. 15–17. To conduct such small-scale impact experiments at our institute, a corresponding approach in a new testing facility was implemented. This experimental setup is located in the drop tower of the Otto Mohr Laboratory (Technische Universität Dresden, see Ref. 18). Until today, a large number of small-scale experiments were realized. The focus of these investigations was on the characterization of thin textile and carbon reinforced concrete layers under impact load. In addition, a number of plain concrete plates were also used for the experimental investigations to highlight the difference between plain and reinforced concrete under impact loads. Furthermore these plain concrete plates offer a very good possibility to calibrate a material model to be used for further simulations. In the following, the plain concrete plate tests will be discussed. It is also discussed how these experiments can be computed numerically.

2 | PRELIMINARY CONSIDERATIONS AND BACKGROUND TO THE INVESTIGATIONS

The subsequent strengthening of existing reinforced concrete structures by means of thin subsequently applied strengthening layers against impact loads is the core subject of the GRK 2250 “Mineral-bonded composites for enhanced structural impact safety” project. The investigations focus primarily on cement-bound strengthening layers. In order to approach the complex topic of strengthening reinforced concrete components against an impact load, the overall problem was separated into partial problems or tasks, which are now approached individually. These partial problems are, on the one hand, the reinforced concrete plate or structure, which must be strengthened. On the other hand it is about the strengthening layer, which consists of a matrix material and ideally a fabric. A further partial problem is the contact or bond zone between the structure and the strengthening layer.

In the following article, experiments are presented in which the matrix material to be used for the strengthening layer is examined under an impact load. Based on these investigations, a simplified simulation model of the experiment was created to reproduce phenomenologically what was observed during the experiments. In further processing, the model obtained in this way is to be expanded to include layers integrated into the matrix material in order to finally represent a strengthening layer. Finally, the resulting phenomenological simulation model of the strengthening layer in combination with a reinforced concrete plate is intended to be simulated in order to observe and characterize the mechanisms at work. The numerical considerations are only a tool to better understand the experimental investigations.

3 | INTENTION OF THE PUBLICATION

In many cases, experimentally working scientists do not or only to a very limited extent deal with numerical simulations and vice versa. Consequently, a large number of simulations are carried out based on data presented in publications. However, this approach may lead to unfavorable assumptions or misinterpretations due to a lack of information. Information which seem negligible in the experiments is often extremely important for numerical simulations. However, that kind of information is often not or only partially described. In the following, we deal with a small test program with a focus on plain concrete plates. The experiments will be described from the point of view of an experimental scientist. Based on this, the experiments are simulated numerically.

4 | EXPERIMENTAL SPECIMEN AND SETUP FABRICATION

4.1 | Specimen fabrication

The small-scale specimens had the outer dimensions 610 mm × 610 mm × 30 mm, see Figure 1. The used fine concrete had a maximum grain size of 1 mm and was based on a prefabricated concrete mix PAGEL TF10 produced by the company PAGEL Spezial-Beton GmbH & Co. KG.

The fresh concrete was processed according to the manufacturer’s specifications. The amount of added water was 3.5 L per 25 kg prefabricated mixture; see Ref. 20. For

FIGURE 1 Dimensions of the small plates, dimensions in mm; source: Ref. 18
further information, see also Hering and Curbach. The reason to use this mixture for the investigations was that it is an approved concrete for strengthening of reinforced concrete structures with carbon reinforced concrete, see Refs. 21–23. The results of the plain concrete tests will be used for strengthening purposes and form an important basis for further investigations.

After the casting of the specimen, the plates were covered with a polyethylene film. After demolding on the day after fabrication, the plates were stored under moist towels for up to the seventh day. The specimens were then taken to the drop tower facility and stored there until testing. The main tests were carried out after 56 days.

In addition, prisms with edge dimensions of 160 mm × 40 mm × 40 mm were produced in order to check the uniformity of the quality of the fine concrete and to obtain its strength parameters. The prisms were stored directly next to the plates to guarantee the same curing conditions. The investigations of the prisms were carried out according to Ref. 24 after 56 days. The resulting mean value for bending tensile strength was 6.9 MPa and the mean value for cube-compressive strength was 95.7 MPa. The density of the fine concrete was 2.15 kg/dm³, also measured after 56 days. The modulus of elasticity was determined by comparative tests on cylinder samples with a diameter of 50 mm and a height of 80 mm. At an age of 56 days it was 33.1 GPa.

4.2 | Experimental setup

For the impact tests, the specimens were assembled in a support frame. This stiff frame was rigidly mounted on the foundation of the drop tower facility. The frame can be seen in Figure 2.

The support conditions of the small-scale plates are of interest for the considerations which follow later in this publication. The construction is shown in more detail in Figure 3. The specimen is fixed between two layers of a 5 mm thick and approx. and 30 mm wide rubber material. According to the manufacturer's data, the rubber has a hardness of 65 ± 5 (Shore A).

The plate was clamped by 16 M12 screws, see Figures 2 and 3. By using this frame construction a free bending length of 550 mm was obtained for the plate. In order to ensure a constant clamping force in all tests, a pneumatic torque screwdriver was used.

A cylindrical steel impactor with a diameter of 100 mm was used for the experiments. The length of this impactor was 150 mm; see Figure 3. Its nose had a slight
roundness with a curvature's radius of 2000 mm. The impacter was accelerated by compressed air. The functional principle of the accelerated drop tower system has been already described in detail in Just et al.\textsuperscript{10} and even in Refs. \textsuperscript{12, 26}. For this reason, it will not be described here in more depth.

The main parameter considered in this publication is the impactor velocity. This was measured with the help of a stereo high-speed camera system and analyzed in the frame of the following photogrammetric evaluation of this image material. The high-speed camera recordings were carried out with a recording rate of 5,000 fps (see Figure 4). A resolution of 1,024 px \(\times\) 800 px was used for the recordings. The photogrammetric evaluation was performed with the software ARAMIS of the company GOM.

### TABLE 1  Examined small-scale plates, impact and residual velocities

| Plate number | Age [d] | Impact velocity [m/s] | Residual velocity [m/s] | Difference velocity [m/s] | Difference velocity relative to impact velocity [%] |
|--------------|---------|------------------------|-------------------------|---------------------------|-----------------------------------------------|
| P01          | 59      | 12.1                   | 9.2                     | 2.9                       | 24                                            |
| P02          | 58      | 12.3                   | 9.2                     | 3.1                       | 25                                            |
| P03          | 58      | 16.5                   | 13.1                    | 3.8                       | 21                                            |
| P04          | 58      | 19.7                   | 15.7                    | 4.0                       | 20                                            |
| P05          | 54      | 20.3                   | 16.5                    | 3.8                       | 19                                            |
| P06          | 54      | 24.7                   | 20.8                    | 3.9                       | 16                                            |
| P07          | 58      | 25.2                   | 21.3                    | 3.9                       | 15                                            |
| P08          | 58      | 27.9                   | 23.1                    | 4.8                       | 17                                            |
| P09          | 59      | 33.6                   | 27.9                    | 5.7                       | 17                                            |
| P10          | 59      | 43.6                   | 37.9                    | 5.7                       | 13                                            |

5  | EXPERIMENTAL PROGRAM AND RESULTS

Ten fine concrete plates were experimentally investigated. As described above, the age of the samples should be about 56 days. Finally, the samples had an average age of 57.5 days. In order to obtain a wide range of information from the tests, the experiments were conducted with different impact velocities, see Table 1. The residual velocity describes the velocity of the impact after perforating through the small scale plate. The wide range of investigated velocity is displayed in Figure 5.

In order to examine the reproducibility of the test results, experiments were also carried out with similar impact velocities (see the gray marked tests in Table 1). However, not only the absolutely measured velocities at the beginning of an experiment and at its end are relevant. The time-dependent response of the impactor velocity is also of interest. This is presented in Figure 5 for the experiments conducted. Figure 5 displays how the impactor velocity changes as a result of impact with the plate and subsequent perforation. On the basis of the time-velocity curves shown it can be seen how the difference velocity also increases slightly with increasing impact velocity. However, when considering Table 1, it can be seen that the relative velocity difference decreases with increasing impacted velocity. Figure 5 also illustrates the

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**FIGURE 4** View from the left and the right side of the high-speed camera; Picture: M. Hering
wide velocity range that could be investigated by using this method.

The time-velocity curves shown in Figure 5 were one of the two target measurements for the numerical investigations described in the next section.

The resulting crack patterns of the plates are also an important result of the experiments and are illustrated in Figure 6. In order to receive these, the fragments of the plates had to be puzzled together after the experiments. The specimens are arranged with increasing impact velocity. In principle, the central hole catches the eye in all of them. However all samples show a circular crack in the middle part of the plate. Still common is that there are many cracks from the middle of the plate towards the edges. The crack patterns displayed in Figure 6 show a great similarity over the investigated velocity range. This indicates that the significant damage mechanism was the same in all experiments and therefore the presented plate experiments are comparable. These crack patterns form the second target parameter of the numerical investigation described in the next section.

6 | NUMERICAL SIMULATIONS

6.1 | Idealization

The numerical simulation of the experiments was carried out by using the program LS-Dyna V10.1. The set of units used is given in Table 2. A visualization of the geometric model is given in Figure 7.

Like the real specimen, the small-scale plate has an edge length of 610 mm × 610 mm × 30 mm. The discretization is done with brick elements using an element size of 2.5 mm × 2.5 mm × 2.5 mm. This resulted in a very fine meshing of the entire specimen. Due to the fine meshing and the large number of elements, significant computing times of the model were to be expected. For this reason, the option “solid element with constant stress” was selected for the calculation of the volumetric elements. This calculation option for the elements is less computationally intensive than other possible element formulations. This saves computing time to a certain amount. Although this does not allow any stress gradients within the elements. Furthermore, the fine meshing provides a good basis for crack growth through the erosion of elements.

The support of the plate was realized as in reality by an upper and lower clamping which was modeled by volume elements with a size of 2.5 mm × 2.5 mm × 2.5 mm. The experiments had shown that the support frame is very stiff in relation to the test specimen. This was checked by measuring the deformation of the support frame using photogrammetric methods. For this reason, the upper and lower clamping was simplified with rigid elements. This is done in LS-Dyna via the material law MAT020. The global movement in the z-direction was blocked. The upper and lower support frame material was given a density of 1.5 g/cm³ according to the data sheet of the rubber material.25 The modulus of elasticity and the Poisson’s ratio were estimated according to Kunz and Studer27 to 0.47 and the Young’s modulus with 6.125 MPa, respectively.

A cylinder with a diameter of 100 mm and a height of 137 mm represents the impactor. The mismatch between the height of the real impactor and the height of the impactor in the simulation reveals from a structural detail of the impactor (see Figure 8). The real impactor weighs 8.4 kg. If the real geometrical outer dimensions are used and a steel density of 7.85 g/cm³ is assumed, the weight is 9.25 kg. This discrepancy is caused by the holes in the impactor. In the experiments presented in this publication, these drill holes are of no interest. However, because the impactor nose belongs to an impactor system, the existing drill holes were taken for given. However, in order to have the same impactor weight in the
FIGURE 6  Front and bottom views of the tested plates after impact loading, the plates are ordered with rising impact velocities from top left to bottom right, 1st row: P01 and P02, 2nd row: P03 and P04, 3rd row: P05 and P06, 4th row: P07 and P08, 5th row: P09 and P10, pictures: L. S. Di Stefano and N. Oette
simulation, it was decided to shorten the impactor length. When modeling the impactor, it was deliberately decided not to reproduce the real hollow spaces, as this would have led to a much finer meshing and thus to a considerably higher computing time.

Furthermore, the impactor was described as a linear elastic material with the material law MAT001. A modulus of elasticity of 210 GPa, a density of 7.85 g/dm$^3$ and a Poisson’s ratio of 0.3 were assumed.

6.2 Material description of the fine concrete plate

For the description of concrete, *LS-Dyna* offers a variety of material laws.$^{28-30}$

| Table 2 | Used unit set |
|---------|---------------|
| **Mass** | **Length** | **Time** | **Force** | **Stress** | **Energy** |
| kg | mm | ms | kN | GPa | kNmm = J |

One of the biggest problems when using these material models is their correct parameterization. At best, a default parameterization exists. However, this rarely fits the concrete, which was used for the experimental investigations. On the one hand, a handful of parameters can be determined by quite simple experiments. On the other hand, other parameters are difficult to describe.

After a parameter study with the different material laws, the material law MAT145 was chosen. This material law is also known as Schwer-Murray-Cap-Model. Since the main focus of this publication is on application of known material models, the mathematical relationships in this material model will not be discussed further. Detailed descriptions are given in Refs. 28–33.

With the MAT145 material model, it is possible to consider a strain rate-dependent material behavior. However, it was decided to perform the numerical simulations without strain rate-dependent material behavior. Thus, the parameters ALPHAN and CALPHAN each resulted in 0.

For the material law MAT145, a known parameterization could be almost completely adopted (details can be

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**FIGURE 7** Isometric view of the model, graphic: M. Hering

**FIGURE 8** Sectional drawing, bottom view and isotropic view of the impactor, graphic: T. Kühn
The literature sources and experimental values were lacking for a meaningful assumption of the compression fracture energy. Thus the calculation of the parameter BFIT (ductile damage mechanics parameter) on the direct way is not possible. However, the value for this parameter is limited as follows: $0.0 \leq BFIT \leq DFIT/(f_{c,m,cylinder}/f_{c,m,cylinder})$ in Ref. 28. Based on this, BFIT was assumed to BFIT = $\Psi \cdot DFIT/(f_{c,m,cylinder}/f_{c,m,cylinder})$, whereby the free value $\Psi$ is undetermined and has to be chosen ($0.0 \leq \Psi \leq 1.0$). Therefore, the experiment with the test specimen P02 was examined. A systematic variation of the value for $\Psi$ was carried out. The target value to be achieved by the simulation was the residual impactor velocity of 9.2 m/s on the one hand and the crack pattern which was documented after the experiment on the other hand (compare Figure 9). The impact velocity at this experiment was 12.3 m/s.

One aspect that should not be forgotten is that Ref. 28 refers to the fact that the calibration of the material model MAT145 presented by the two authors applies to concretes with a uniaxial compressive strength between 10 and 60 MPa. However, the fine concrete used for the experimental investigations showed a higher compressive strength ($f_{c,m,cylinder} = 85$ MPa). For the considerations presented here, the calibration presented in Ref. 28 was nonetheless used. This procedure is based on the assumption that a slightly higher strength concrete is not significantly different in its material characteristics from the concretes considered by the authors.

The functionality and performance of the selected material model has already been shown and explained in detail in Refs. 31–33. Furthermore, Jiang & Zhao in Ref. 28 gave a very well working calibration possibility for the material model, for this reason a new analysis and recalibration of the material model MAT145 was not carried out. The aim of the investigations carried out was to create a quantitatively functioning simulation with simple methods and usually available material parameters in order to improve the understanding of the experimental investigations carried out.

| Parameter                      | Value | Unit      |
|-------------------------------|-------|-----------|
| Concrete parameters (mean values), available from experiments |       |           |
| Young's modulus               | $E_c$ | 33.1 GPa  |
| Compressive strength          | $f_{c,m,cube}$ | 95.7 MPa  |
| Flexural bending tensile      | $f_{ct,m,fl}$ | 6.88 MPa  |
| Density                       | $\rho_c$ | 2.15 kg/dm$^3$ |
| Derived concrete parameters   |       |           |
| Poisson's ratio               | $\nu_c$ | 0.2       |
| Compressive strength          | $f_{c,m,cylinder}$ | 85.0 MPa |
| Tensile strength              | $f_{ct,m}$ | 3.44 MPa |

a Determined on 40 mm × 40 mm × 40 mm cubes;  
b Calculated for cylindrical specimen d = 50 mm, h = 100 mm.

A similar procedure was followed to convert the bending tensile strength ($f_{ct,m,fl}$) into the centric tensile strength ($f_{ct,m}$). In Refs. 36, 37, the relationship between $f_{ct,m}$ and $f_{ct,m,fl}$ is described by the factor 2.0. This resulted in a centric tensile strength ($f_{ct,m}$) of 3.44 MPa.

Using the values summarized in Table 3, only two more material parameters had to be assumed to parameterize the material model. These are the tensile fracture energy ($G_t$) and the compression fracture energy ($G_c$). The Model Code 2010 offers an assumption for the tensile fracture energy: $G_t = 73 \cdot (f_{c,m,cylinder})^{0.18}$. This value is used for the calculation of the parameter DFIT (brittle damage mechanics parameter), see Ref. 28. For the application of this relationship, use $f_{c,m,cylinder}$ in MPa.

The ABAQUS model MAT145 are summarized. The Poisson's ratio of the fine concrete used was assumed to 0.2 which is the general assumption of a Poisson's ratio for concrete. A major problem here was that neither the cylinder compressive strength ($f_{c,m,cylinder}$) nor the centric tensile strength ($f_{ct,m}$) were available for the material. In order to determine these from the available strength values, assumptions had to be made.

For the conversion of the cube-compressive strength ($f_{c,m,cube}$) into cylindrical compressive strength ($f_{c,m,cylinder}$), the slenderness influence of the specimen on the determined compressive strength was used as a basis. In the case of a cube, the slenderness $h/d$ is 1.0. In contrast, the slenderness of a cylinder for determining the compressive strength 2.0 is significant. According to Ref. 35, the strength ratio between a sample with a slenderness of 1.0 and 2.0 is approximately 1.1 to 1.2. This means that the cube-compressive strength ($f_{c,m,cube}$) is greater by a factor of 1.1 to 1.2 than the compressive strength determined on a cylinder ($f_{c,m,cylinder}$). If this transformation is applied to the determined cube-compressive strength ($f_{c,m,cube}$), a cylindrical compressive strength ($f_{c,m,cylinder}$) of 83.2 or 87.0 MPa results. It was decided to use the mean value. This results in an uniaxial cylinder compressive strength ($f_{c,m,cylinder}$) of 85 MPa which was chosen for the simulations.

TABLE 3 Concrete parameters (mean values)
**FIGURE 9**  Simulated vs. real crack pattern (left) and relationship between $\Psi$ and residual speed (right), graphic: M. Hering

**FIGURE 10**  Velocity time relation of the impactor, simulation vs. experiment, graphic: M. Hering

**TABLE 4**  Comparison of experimental and numerical results

| Experiment | Plate number | Impact velocity [m/s] | Residual velocity [m/s] | Difference velocity [m/s] | Difference velocity [m/s] | Comparison test vs. simulation | Relative deviation $\Delta$ [%] |
|------------|--------------|------------------------|--------------------------|---------------------------|---------------------------|-------------------------------|-------------------------------|
| P01        | 12.1         | 9.2                    | 2.9                      | 9.3                       | 1.1                       | P01_num                       | P02_num                       | 1.1                           |
| P02        | 12.3         | 9.2                    | 3.1                      | 9.4                       | 2.2                       | P03_num                       | P04_num                       | 0.8                           |
| P03        | 16.9         | 13.1                   | 3.8                      | 13.2                      | 0.8                       | P05_num                       | P06_num                       | 1.9                           |
| P04        | 19.7         | 15.7                   | 4.0                      | 16.0                      | 1.9                       | P07_num                       | P08_num                       | 0.6                           |
| P05        | 20.3         | 16.5                   | 3.8                      | 16.6                      | 0.6                       | P09_num                       | P10_num                       | −2.9                          |
| P06        | 24.7         | 20.8                   | 3.9                      | 20.2                      | −2.9                      | P01         | P02         | −3.2                          |
| P07        | 25.2         | 21.3                   | 3.9                      | 20.8                      | −2.3                      | P03         | P04         | −0.4                          |
| P08        | 27.9         | 23.1                   | 4.8                      | 23.0                      | −0.4                      | P05         | P06         | 1.1                           |
| P09        | 33.6         | 27.9                   | 5.7                      | 28.2                      | 1.1                       | P07         | P08         | −3.2                          |
| P10        | 43.6         | 37.9                   | 5.7                      | 36.7                      | −3.2                      | P09         | P10         | −3.2                          |
With the basic parameterization according to Ref. 28, a very good crack pattern could already be achieved. In Figure 9 the simulated and the real crack pattern are plotted. Within the simulation, the characteristic circular crack on the plate could be reproduced very well. In order to achieve the correct residual velocity in the simulation, the free value $\Psi$ was varied until a satisfactory result was achieved. From this study, $\Psi$ resulted to 0.350. The simulation results for the residual velocity were shown in Figure 9 depending on the value of the factor $\Psi$.

After the parameterization, no more changes were made on the material model with the exception of the impactors’ speed. Now, the calculation of the experiments according to Table 1 could be done to compare the

| Plate number | Impact momentum $I_1$ [kg m/s] | Residual momentum $I_2$ [kg m/s] | Difference momentum $\Delta I$ [kg m/s] | Impact energy $E_{1,\text{kin}}$ [J] | Residual energy $E_{2,\text{kin}}$ [J] | Difference energy $\Delta E$ [J] |
|--------------|-------------------------------|---------------------------------|---------------------------------------|-----------------------------------|-----------------------------------|---------------------------------|
| P01          | 101.6                         | 77.3                            | 24.4                                  | 614.9                             | 355.5                             | 259.4                           |
|              | 101.6                         | 78.1                            | 23.5                                  | 614.9                             | 363.3                             | 251.7                           |
| P02          | 103.3                         | 77.3                            | 26.0                                  | 635.4                             | 355.5                             | 279.9                           |
|              | 103.3                         | 79.0                            | 24.4                                  | 635.4                             | 371.1                             | 264.3                           |
| P03          | 138.6                         | 110.0                           | 28.6                                  | 1,143.5                           | 720.8                             | 422.7                           |
|              | 138.6                         | 110.9                           | 27.7                                  | 1,143.5                           | 731.8                             | 411.6                           |
| P04          | 165.5                         | 131.9                           | 33.6                                  | 1,630.0                           | 1,035.3                           | 594.7                           |
|              | 165.5                         | 134.4                           | 31.1                                  | 1,630.0                           | 1,075.2                           | 554.8                           |
| P05          | 170.5                         | 138.6                           | 31.9                                  | 1,730.8                           | 1,143.5                           | 170.5                           |
|              | 170.5                         | 139.4                           | 31.1                                  | 1,730.8                           | 1,157.4                           | 170.5                           |
| P06          | 207.5                         | 174.7                           | 32.8                                  | 2,562.4                           | 1,817.1                           | 745.3                           |
|              | 207.5                         | 169.7                           | 37.8                                  | 2,562.4                           | 1,713.8                           | 848.6                           |
| P07          | 211.7                         | 178.9                           | 32.8                                  | 2,667.2                           | 1,905.5                           | 761.7                           |
|              | 211.7                         | 174.7                           | 37.0                                  | 2,667.2                           | 1,817.1                           | 850.1                           |
| P08          | 234.4                         | 194.0                           | 40.3                                  | 3,269.3                           | 2,241.2                           | 1,028.2                          |
|              | 234.4                         | 193.2                           | 41.2                                  | 3,269.3                           | 2,221.8                           | 1,047.5                          |
| P09          | 282.2                         | 234.4                           | 47.9                                  | 4,741.6                           | 3,269.3                           | 1,472.3                          |
|              | 282.2                         | 236.9                           | 45.4                                  | 4,741.6                           | 3,340.0                           | 1,401.6                          |
| P10          | 366.2                         | 318.4                           | 47.9                                  | 7,984.0                           | 6,032.9                           | 1,951.1                          |
|              | 366.2                         | 308.3                           | 58.0                                  | 7,984.0                           | 5,656.9                           | 2,327.1                          |
remaining velocities of the simulation with the experimentally recorded.

6.3 Results

The velocities obtained from the numerical simulations were shown in Figure 10 in comparison with the experimentally determined ones. Here a very good agreement between experiment and simulation can already be recognized. Table 4 displays the residual velocities from simulation and experiment. With these values the deviation between reality and experiment could be described in numbers. The maximum deviation is 3.2%. Furthermore, it can be stated that the deviation of the numerical results is both positive and negative. This indicates that the selected parameterization describes the fine concrete very well on average.

In the context of impact experiments, momentums and energies are usually also considered. The corresponding values are shown in Table 5 and presented in Figure 11. This representation also demonstrates a very good agreement between experiment and simulation.

7 Conclusions and Summary

Within the framework of the experiments described, the suitability of the newly developed test set-up could be demonstrated. The presented results from the tests with nonreinforced fine concrete plates now serve as a reference for the following investigations on fine concrete plates in which different textile reinforcements are implemented.

On the basis of these tests, a numerical description of the used fine concrete could be found. The calculation of the experimental results was well possible with the material model MAT145 implemented in LS-Dyna without consideration of strain rate-dependent material properties. With the provided simulation basis, a significant part of textile reinforced concrete—the matrix material—could be numerically reproduced. Thus, it is now possible to shift the focus of research to the simulation of textile/carbon reinforced concrete specimens.

Furthermore, the presented investigations contribute to a better understanding of the structural behavior of thin fine concrete plates. This is in turn essential to understand the effect of additional textile reinforcement in the thin concrete layers. In the frame of the planned simulations with textile reinforced concrete plates, the load bearing and failure mechanisms of these strengthening layers should be given.

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