A new testing method for textile reinforced concrete under impact load

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Abstract. Textile reinforced concrete, especially textile reinforced concrete with carbon fibres, was already been used for strengthening steel reinforced concrete structures under static loads up to now. The question is if the composite can also be used for strengthening structures against impact loads. The main goal of a current research project at the Technische Universität Dresden is the development and characterization of a reinforcement fabric with optimized impact resistance. But there is a challenge. There is the need to find the best combination of fibre material (glass, carbon, steel, basalt, ...) and reinforcement structure (short fibres, 2D-fabrics, 3D-fabrics, ...), but testing the large number of possible combinations is not possible with the established methods. In general, large-scale tests are necessary which are very expensive and time consuming. Therefore, a new testing method has been developed to deal with this large number of possible combinations of material and structural experiments. The following paper describes this new testing method to find the best fabric reinforcement for strengthening reinforced concrete structures against impact loads. The testing device, which is located in the drop tower facility at the Otto Mohr Laboratory, and the test set-up are illustrated and described. The measurement equipment and the methods to evaluate the experimental results are explained in detail.

1 Introduction

1.1 State of the art

The structural dynamic behaviour of reinforced concrete structures subjected to impact loads has been a research topic of many research facilities for a long time. These investigations can be separated in two main fields: the examination of the load-time behaviour of the impactor, see e.g. [1, 2], and the structural behaviour of the impacted structure, see e.g. [3, 4, 5]. In both cases, large experimental setups were used to study the effect of the impact load. The referred sources are just a small compilation of the conducted research projects; there are still many more.

Conventional reinforced concrete was not the only investigated material in the past. Many other combinations of reinforcing materials and concrete mixtures were considered to investigate the behaviour under impact loading. One possible composite is textile reinforced concrete (TRC). It was tested at the Institute of Concrete Structures (IMB) at the Technische Universität Dresden to examine the dynamic behaviour. Within those investigations, the advantageous material properties of TRC for impact loads could be shown [6].

1.2 Problem and investigation aim

In the past large-scale experiments were conducted to investigate the impact behaviour. In the case of [1, 2], the specimen size was 6.5 m × 6.0 m × 0.7 m. To deal with such large plates, a special testing environment is required. In [6], smaller plates were used with a sample size 1.0 m × 1.0 × 0.15 m. To deal with this specimen size is expensive and time consuming. Under these conditions, there is just the possibility to investigate a small range of parameters.

One of the main goals of the current project is to develop a textile reinforcement, which is optimized for the strengthening of structures against impact loads. To reach this goal the behaviour of textile reinforced concrete in the case of impact loads has to be investigated. Furthermore, there is the need to understand which reinforcing fabrics are the best to withstand impact loads, and what are the reasons for this. After understanding these aspects, it is possible to develop an impact optimized textile reinforcement fabric.

Many combinations of reinforcing fabrics and fabric materials are possible and were produced in the past for different requirements, e.g. [7, 8]. Currently there are no results which define a fibre material or fabric as a best shield against impact loads. Therefore, investigations in this field are pending. Because of the large number of

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possibilities, the test procedures used in [6] resp. [9, 10, 11] were not realisable in the planned parameter study and a new testing method was developed. With the new test setup, there is the possibility to examine the material properties of the strengthening material under impact load more time and cost efficient.

The idea behind the new testing method contains the measurement of the energy dissipation as a result of the perforation of the plate by using a rigid impactor. To do this the velocity of the impactor has to be measured during the perforating process.

The following article deals with the tasks which had to be solved to develop the new experimental setup. In detail, there were to develop a support frame, to choose a suitable specimen size and a representative load case. Furthermore, there was the need to find a way to evaluate and interpret the experimental values. To show how these were solved, the first part of the experimental investigation program is presented and evaluated in this paper.

2 Test setup

2.1 Test facility

The experiments were performed in the drop tower facility of the Otto Mohr Laboratory of the Technische Universität Dresden. With this experimental facility, it is possible to test two different load regimes. The first configuration of the drop tower facility allows the testing of low speed impact with high drop weights. This configuration is called static or free-fall drop tower facility. The second configuration allows the testing with high-speed impact but with lower drop weights. This configuration is called accelerated facility [9, 10, 11].

For the experiments, which are presented in this article, the accelerated facility was used.

2.2 Specimen's material, size, and fabrication

2.2.1 Material

The main requirement of the experiments were to test grid-like textile reinforcements (so called 'textiles') embedded into a concrete matrix. In this project, the widths of the grid openings varied between 7 mm and 14 mm. Therefore, normal concrete is not usable because of the maximum aggregate size that lies normally in cm range. Consequently, a fine grained concrete had to be used as matrix material, see e.g. [12]. The chosen fine concrete is Pagel TF10, which is well investigated for use as TRC matrix material. This concrete dry mixture are especially developed for strengthening layers made of textile reinforced concrete. The maximum grain size of this concrete is 1 mm, which solves the problem of small fabric openings.

The mean value of compressive strength after 28 d curing time was approximately 90 MPa (mean value), tested with specimen, which remains out of the Three-

point flexural test with a size of 40 mm × 40 mm × 40 mm.

2.2.2 Specimen geometry

One of the main requirements of the plate-like specimen size was the usability without lifting devices. That leads to a maximum weight of approximately 25 kg per plate.

Another requirement was the transportability and the stability to get the plate from the crafting place to the testing facility without damaging the specimen. On the other hand, there was the need that the plate should be thin enough to be perforated by an impactor by using a measurable impactor velocity. The reason for the perforation of the plates is given later in this article.

The final outer dimension of the specimen of 61 cm × 61 cm (fig. 1) was determined by fabric production because there was just the possibility to produce the special impact resistant fabrics with a width of 60 cm. The 1 cm left was considered for manufacturability of the TRC specimen.

Fig. 1. Specimen's geometry (sizes in mm); graphic:

M. Hering.

Fig. 2. Plate with spray pattern inside the support frame; photo: © IMB.

With the thickness of 3 cm, the plate is robust enough to withstand the preparation procedure which is necessary for conducting the experiments. That means the plates have to be sprayed with a pattern and the plates have to be placed and clamped into the support

frame, see fig. 2. Between these working steps, the plates are transported many times. Therefore, a robust specimen is a good choice.

Finally, the plates have a weight of approximately 24.6 kg by using the assumption of a concrete density of 2.2 kg/dm^3 for Pagel TF10. Thus, the transportability without lifting devices is guaranteed, which was a main requirement of the specimen.

Within the project, approximately 25 different reinforcing fabrics need to be tested. The fabrics are located in the neutral axis of the plates (fig. 3). By using this method, no bending stresses are expected in the fabric. The specimens are loaded to provoke perforation damage only. No bending resistance was required.

Fig. 3. Positioning of a fabric inside a plate (sizes in mm);

graphic: M. Hering.

In this article, just a small number of the complete experimental program are presented. The focus is to show how the experimental setup works. In the first tests, two different types of plates were used. On the one hand, plain concrete plates were examined as a reference. On the other hand, textile reinforced concrete plates were investigated. The parameters of the textile fabric are collected in tab. 1 and shown in fig. 4.

Fig. 4. Quadaxial fabric; picture: M. Hering.

Table 1. Parameters of the textile fabric.

Designation	Direction and fineness of reinforcing yarns		No. of specimen
Quadaxial fabric	0°	3450 tex	BP181
	+45°		BP182
	-45°	3300 tex	BP184
	90°		BP185

Considering fig. 4 the meaning of the ‘quadaxial’ gets understandable. The quadaxial fabric contains yarns in four in plane directions. For the fabrication of the reinforcing fabric, carbon yarns with fineness of 3300 tex and 3450 tex were used. Because of the multiaxiality of the quadaxial fabric, a reinforcement cross section area is hardly to specify. In this case, the basis weight of the used fabric shall be the quantification of the used reinforcement material. The basis weight of the quadaxial fabric is 411 g/m^2 . This value considers the uncoated yarn material.

2.2.3 Specimen fabrication and storage

The specimens were produced in horizontal $61 \text{ cm} \times 61 \text{ cm} \times 3 \text{ cm}$ formworks. At first, a 1.5 cm thick concrete layer was filled in. After that, the fabric was laid on the concrete surface and carefully pressed in the concrete. Afterwards the rest of the formwork was filled with concrete. The concrete surface was peeled off to get a smooth and plane surface.

As a reference, plain concrete plates were also produced. By testing these plates, reference values were created.

The ready concreted specimens (textile reinforced plates and plain concrete plates) were covered with a PE layer to prevent dry out and shrinkage of the surface. The specimens were demoulded after one day. After that, they were stored under wet towels for 6 days. Afterwards, the plates were stored in the experimental environment at approximately 20°C . The tests were carried out after approximately 56 days.

2.3 Support frame

For the support frame, H-beams (HE-B 140) were chosen. For the connection between the H-beams, M12 (property class 8.8) screws were used. With this construction a quit rigid support frame was built, according to fig. 5.

Fig. 5. Support frame; photo: M. Hering.

The plates were fixed by a construction out of screws and steel crossbars in the support frame. To compensate little bumps on the TRC specimen surface, strips out of solid rubber were used. By using this construction, a vertical displacement of the specimen plate was prevented. Furthermore, the horizontal displacement was prevented by friction between the rubber and the concrete. A rotation of the edges is possible because of the softness of the used solid rubber. These support conditions are not easy to describe for numerical investigations, but for the experimental work, it is extremely useful and efficient.

The support frame was designed in a way that the plate has a free bending length of approximately 55 cm in both main directions and is supported by a 3 cm all-round stripe of concrete.

The clamping force was applied by using the same torque for every screw in the support frame. In turn, the torque was controlled by using the same setting at the used pneumatic screwdriver.

2.4 Loading

In the case of impact loading, it is impossible to define a load case, which is representative for all imaginable scenarios. In our experimental setup, the worst-case scenario should be taken into account. In reality, the impacting object (impactor) is mostly deformable, e.g. vehicle front crashes. It is already known that an impact with a deformable impactor leads to lower forces than an impact with a rigid impactor. With this background, the choice for the experiments was to use a non-deformable impactor.

The next experimental parameter, which has to be chosen, was the shape of the impactor. The actually available impactor shapes are shown in fig. 6. It has to be considered, that the shape of the impactor is a parameter with a large influence on the failure mode, see e.g. Kühn and Curbach [11].

Fig. 6. Available shapes of the impactor; photo: M. Hering.

A sharp nose causes big damage of the impacted side but the damage inside the structure is not so large. By using a flat impactor, the damage of the impacted side is nearly invisible with exception of a nearly perfect round hole. But the rest of the structure is damaged because of the high energy input. By using a rounded impactor, the damage is located between these both cases [11].

For the experimental investigations presented here, an almost flat impactor with a radius of curvature of 2 m was chosen. The diameter of the 8.4 kg heavy impactor was 10 cm. The choice of this impactor shape was an assumption to proof the workability of the experimental setup. The use of a sharp nosed impactor is also possible for the experiment, but in the case of a flat nose the description of the loaded area is easier. The investigation of the influence of the shape of the impactor nose will be considered in further experiments.

Another important parameter is the impactor length. At first, this parameter seems to be a trivial choice because it just influences the mass of the impactor (m_{impactor}) in the case of a certain diameter. This is correct for static loads or rigid body mechanics. By considering the elastic wave propagation, another parameter is influenced by the impactor length: the so-called wavelength. It is important that the introduced wave is long enough to load the specimen in a way, which activates the full plate. A too short wave leads to localized damages, maybe just to spallation effects. However, this was not the goal in the conducted experiments. With the chosen length of 150 mm the impactor is long enough to activate the plate.

For further information about this topic, please see e.g. [13].

2.5 Measurement technique

As measurement technique, a stereo high-speed camera system was used. It was positioned diagonally above the support frame. With these camera positions, it was possible to capture the plate's surface (fig. 2) and the backside of the incoming impactor. For the conducted experiments, a sampling rate of 5000 frames per second (fps) was chosen to record the experiment. This corresponds with a measurement frequency of 5000 Hz. The used high-speed cameras are able to process a maximum recording resolution of 1024 px × 1024 px. For the conducted tests, a resolution of 1024 px × 800 px was chosen. This resulted in a maximum recording time of 1.4 s. The part of the high-speed videos that is interesting for the experimental investigations is just about 0.3 s long. To get well timed measurements, light barriers were used to determine the exact start of measurement.

An important aspect of this measurement system is the calibration of the stereo camera system setup. The calibration was performed by using a calibration artefact, which belongs to the measurement system from GOM. The dimensions of it are saved in the measurement software. The calibration artefact was placed in the measuring range and photographed. After that, the pictures were imported and processed with the measurement software system GOM ARAMIS. With this a calibration file could be created. In this file all necessary information are considered for a photogrammetric measurement. After calibration, the measurement system was ready for use.

The high-speed videos were captured during the whole experiment and saved into single pictures. These

pictures were subsequently imported into the measurement software system *GOM ARAMIS*. Next, measurement points were set on the backside of the impactor by using *GOM ARAMIS*. This was possible because a dot pattern which was also applied to the backside of the impactor. With the knowledge of the sampling rate, it was possible to get the displacement of the impactor over the recorded time. After that, the displacement-time record of the measurement points has to be differentiated to get the velocity-time record of the impactor (see section 3 and 4).

3. Preparation of the measured data

The idea behind these thin specimens and the testing setup was inspired by the investigations, which were conducted by Corbett et al., see [14]. At the experiments, which were presented in this publication, the plastic deformations of steel plates, which were perforated by projectiles, were measured. Out of these measurements, it was possible to define the perforation limit of the investigated steel plates. To estimate this perforation limit, the researchers had varied the impact velocities. Inspired by these experiments the difference velocity (Δv) and the difference mass (Δm) will also be used as a quantification value.

Fig. 7 shows a typical time-velocity measurement of the impactor during the experiment. The full measurement time shown in the diagram is 15 ms. Considering the sampling frequency of 5000 Hz, the result is approximately 75 relevant data points.

Fig. 7. Velocity-time measurement of the impactor while the experiment BP185; graphic: M. Hering.

The first step of the preparation of the experimental data contains the definition of the impact velocity (v_1) of the impactor and its residual velocity (v_2) after the impact. This velocity is defined as the impactor velocity immediately after the perforation of the plate. To determine the velocity difference (Δv) eq. 1 was used.

$$\Delta v = v_1 - v_2 \quad (1)$$

The determination of v_1 is relatively easy because v_1 is defined as the maximum velocity of the impactor. It is

reached immediately before the impact of the impactor. The definition of v_2 is more difficult. Fig. 7 shows the ready prepared measurement data. To get these results some considerations are necessary. To determine the moment when the impactor completely perforated the plate the high-speed videos were evaluated. With the knowledge of that exact time, the velocity v_2 was determinable.

Table 2. Measured velocities of the impactor and masses of the plates.

No. of specimen		v_1 in m/s	v_2 in m/s	m_1 in kg	m_2 in kg
BP181	quadaxial fabric	27.3	15.4	24.26	22.20
BP182		19.4	0.0	25.76	23.58
BP184		27.4	18.8	24.50	23.12
BP185		19.0	0.0	24.60	22.92
BP065	plain concrete	20.3	16.5	23.40	21.88
BP066		24.7	20.8	22.72	21.04
BP139		12.3	9.2	25.02	24.06
BP140		19.7	15.7	24.94	23.18
BP141		27.9	23.1	25.90	23.38
BP142		33.6	27.9	25.28	22.74
BP143		43.6	37.9	24.48	22.24
BP144		12.1	9.2	22.86	22.06

Booth velocities as well as difference velocity are marked in fig. 7. This will be enough for a simple evaluation of the experiments.

Additionally to the measurement of the velocities, the masses of the plates before (m_1) and after (m_2) testing were measured. The calculation of the difference mass (Δm) is given in eq. 2. This difference shows how well the reinforcing material can prevent the plate from being destroyed or how well the reinforcing material prevents secondary damage of people and equipment due to falling fragments. All measured values are given in tab. 2.

$$\Delta m = m_1 - m_2 \quad (2)$$

4 Evaluation of the results

The first thesis was that the difference velocity could serve as an evaluation value for the impact resistance of the fabric, which was used to reinforce the plates. To get an idea of these values the difference velocities of TRC plates and plain concrete specimens were compared. The values are shown in fig. 8.

The definition of a clear tendency out of fig. 8 is not possible. It is visible that the absorption of plain concrete

is less than that of textile reinforced concrete. However, more information cannot be gained by looking only at the difference.

Therefore, the next evaluation step considers the kinetic energy during the experiment. For this, some assumptions have to be made. At first, the used impactor has to be considered as a rigid body. Second, the impactor has a constant mass (m_{impactor}). Regarding these assumptions, the kinetic energy of the impactor is calculable. The equation for kinetic energy is given in eq. 3. Considering the impact velocity (v_1) and the residual velocity (v_2), the kinetic energy can be determined before ($E_{\text{kin},1}$) and after impact ($E_{\text{kin},2}$). The next step is to calculate the difference energy between these energies, see eq. 4. If v_1 and v_2 are inserted in eq. 3, eq. 4 can be modified. Now, ΔE_{kin} can be easily determined by equation eq. 5.

$$E_{\text{kin}} = v^2 \cdot \frac{1}{2} \cdot m_{\text{impactor}} \quad (3)$$

$$\Delta E_{\text{kin}} = E_{\text{kin},1} - E_{\text{kin},2} \quad (4)$$

$$\Delta E_{\text{kin}} = m_{\text{impactor}} \cdot \frac{1}{2} \cdot (v_1^2 - v_2^2) \quad (5)$$

Fig. 8. Comparison of the difference velocities (Δv); graphic: M. Hering.

Fig. 9. Comparison of the difference kinetic energies (ΔE_{kin}); graphic: M. Hering.

The values for ΔE_{kin} which was calculated under use of eq. 5 are shown in tab. 3. In fig. 9, the calculated values for ΔE_{kin} are plotted over the impact speed v_1 . In this figure, the relation between the difference energy and the impact velocity is better visible than in fig. 8.

In fig. 9 a clear tendency of the values for ΔE_{kin} in the case of plain concrete is visible. ΔE_{kin} increases with increasing v_1 . This effect is probably based on the effect of inertias. For the TRC plates the same tendency can be seen in fig. 9, but on a higher level. The difference between the measured values is the influence of the textile reinforcement. It is clear to see that the textile reinforcement has a greater effect on the difference energy than the plain concrete.

Table 3. Values calculated from the experimental data.

No. of specimen		Δv in m/s	Δm in kg	ΔE_{kin} in J	Ψ in %
BP181	quadaxial fabric	11.9	2.06	2138	8.5
BP182		19.4	2.18	1584	8.5
BP184		8.6	1.38	1676	5.6
BP185		19.0	1.68	1508	6.8
BP065	plain concrete	3.8	1.52	582	6.5
BP066		3.9	1.68	740	7.4
BP139		3.1	0.96	282	3.8
BP140		4.0	1.76	597	7.1
BP141		4.9	2.52	1044	9.7
BP142		5.7	2.54	1465	10.0
BP143		5.7	2.24	1944	9.2
BP144		3.0	0.80	266	3.5

In consideration of this behavior, new reinforcing fabrics or materials can be tested in an easy way. By using the direct comparison of the measured values and there tendencies, a quantification how good a new material works is possible.

In a similarly way the difference mass Δm was considered. This is simply the specimen's mass before the experiment (m_1) and after the experiment (m_2) obtained by subtraction from each other, see eq. 2 in section 3. As shown in tab. 2 there are some differences in the weights of the specimens as a result of e.g. scabbing of concrete pieces caused by the impact of the impactor or the penetration of the whole slab. To consider these in the evaluation a relation between m_1 and Δm was used. This relation is called Ψ and is shown in eq. 6. The values for Ψ , which were calculated under use of eq. 6, are also shown in tab. 3.

$$\Psi = \Delta m / m_1 \quad (6)$$

Another aspect which can be derived by the related mass loss (Ψ) is the influence of the used fabric on structural integrity of the concrete. In fig. 10 the calculated values for Ψ are plotted over the impact velocity v_1 (see fig. 10). It is easy to see that the reinforcing fabric does not affect the mass loss of the plates. To visualize what the mass loss means, fig. 11 and fig. 12 are given. The pictures show the front and the rear side of an impacted plate.

Fig. 10. Comparison of Ψ ; graphic: M. Hering.

Fig. 11. Impacted side of a plate; graphic: M. Hering.

Fig. 12. Rear side of a plate; graphic: M. Hering.

In the presented case, this tendency was to expect. Because of the large opening widths of the used textile (see fig. 4), the scabbing of the broken concrete cannot be prevented. By using smaller opening widths or more reinforcing layers, lesser material scabbing is expected.

5. Conclusions

The first step to develop a new testing method for reinforcing fabric in the case of impact loading was done. The measured data showed that in a direct comparison of the tested materials (plain concrete vs. TRC) a principle tendency is visible to evaluate. This fact will be used to compare different fabric materials and fabric shapes.

For better interpretation of the measured data, further test series with different reinforcements will be done in the future, supplemented by accompanying numerical simulations. With these calculations and the following better understanding of the observed processes, a better quantification will be possible. Under considering of all effects, there will possibly be the chance to calculate the energy, which is dissipated by the textile fabric during the experiment. Currently, in the value of ΔE_{kin} , many effects are included, e.g. the inertia forces of the accelerated mass Δm .

Furthermore, large-scale tests with steel reinforced concrete plates without and with additional strengthening layers made of TRC shall be done. With these large-scale investigations, the theses and the knowledge out of the small size tests have to be validated. If the knowledge gained from small-scale tests can be transferred to large ones, the aim to develop a new test method that saves time and money is reached.

Much more investigations have to be done in the future to understand the whole process. The presented work is just one of the first steps.

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