Experimental investigation on reinforced concrete slabs strengthened with carbon textiles under repeated impact loads

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Abstract

This study presents the performance of carbon textile reinforcement used as strengthening layers for reinforced concrete (RC) slabs under repeated impact loads. In order to reveal the contribution of carbon textile reinforcement to the behavior of RC slabs under impacts, five identical RC slabs with the dimensions of $1.5\, \text{m} \times 1.5\, \text{m} \times 0.20\, \text{m}$ were manufactured and tested at the Technische Universität Dresden. To understand failure mechanisms of RC slabs under impact loadings, two specimens were kept unstrengthened and tested under different impact velocities. The rest of the specimens was strengthened with three different carbon textile reinforcements embedded in an additional $2\, \text{cm}$ fine-grained concrete layer and subjected to impact loads with the same striker velocity. The results observed from the tests revealed that the carbon textile reinforcement is very effective at increasing the impact capacities of the specimens. Additionally, displacement–time histories and crack profiles are highly affected due to the carbon textile reinforcement types and ratios during the impact loadings.

KEYWORDS

reinforced concrete slabs, impact load, repeated impact, TRC strengthening, drop tower

1 | INTRODUCTION

The behavior of reinforced concrete (RC) structures under dynamic loading conditions is essential for structures to resist impact loading scenarios. This can be relevant for structures such as bridges in the event of vehicle collisions, offshore facilities, or rockfall protection galleries. Therefore, an investigation of the behavior of RC members under various dynamic loads is presented in this work. With the aim of revealing failure mechanisms of RC structures under impacts, experimental studies have been carried out by researchers.$^{1-6}$ All these studies showed that shear failure mechanisms were observed in tests even for statically flexural-critical members. With the developments in concrete technology, new methods and techniques were employed to improve the behavior of RC structures under different loading conditions. For example, Hrynyk and Vecchio$^7$ carried

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out experimental investigations on steel fiber RC slabs subjected to high-mass, low-velocity impacts. It is reported that the RC slab specimens with steel fibers exhibited better performances compared to nonfibrous RC slab specimens. Similarly, Máca et al.\textsuperscript{8} and Othman and Marzouk\textsuperscript{9} reported that structures of reinforced high-performance concrete showed better performance and lower damage under impact loading than structures of reinforced normal concrete.

Reinforcing the concrete members with fabric materials is a relatively new method which is attractive due to its advantages in increasing flexural and shear capacities. The studies on concrete specimens reinforced with different types of textile showed that textile reinforcements were quite effective in terms of load-carrying and energy absorption capacities, depending on their mechanical properties.\textsuperscript{10,11} By combining the advantageous mechanical properties of carbon compounds (e.g., tensile strength capacities) with textile reinforcement technology, carbon textile reinforced concrete (TRC) provides a highly effective strengthening method for reinforced concrete structures. The experimental studies showed that carbon textile reinforcements are very useful to increase the bending\textsuperscript{12-15} and shear\textsuperscript{16,17} capacities of reinforced concrete members. Also, an experimental study on impact behavior of reinforced concrete slabs strengthened with carbon textile reinforcements showed that textile reinforcement had an enormous effect on impact resistance.\textsuperscript{18}

In this paper, experimental findings on the impact behavior of reinforced concrete slabs with and without strengthening layers of carbon textile reinforcement are documented and discussed. Considering combined failure mechanisms of bending and shear under impact loadings, the contribution of carbon textile reinforcements as a strengthening layer for reinforced concrete structures was investigated by using an advanced testing setup and instrumentation. While other studies present single impact load, in this work the investigation of repeated, consecutive impact load is presented. Crack patterns, concrete scabbing mass, and penetration depth are measured after each impact to particularly describe impact behavior and impact resistance of the RC slabs with and without textile strengthening. The experimental data provided by this study of RC slabs with and without a TRC layer under repeated impact load can be used for validating future numerical studies.

2 | EXPERIMENTAL PROCEDURE

2.1 | Test specimens

Five reinforced concrete slab specimens, two unstrengthened and three strengthened, with identical dimensions and conventional steel reinforcement ratios, were manufactured and tested in the Otto-Mohr-Laboratory of Technische Universität Dresden (TU Dresden). All specimens had a size of 1.5 m × 1.5 m × 0.20 m and 25 mm concrete cover was provided for the steel reinforcement. Steel reinforcement bars of 8 mm in diameter (Ø8) and spacing of 100 mm were placed in the longitudinal and transversal direction (Figure 1). The specimens with additional textile reinforcement were subsequently strengthened with carbon textiles embedded in a 2 cm thick fine-grained concrete layer. With the aim of revealing the effectiveness of textile reinforcements on the impact resistance of the strengthened RC slab, three different types of carbon textile reinforcements were used for the strengthening layers of the slab specimens. The geometrical properties of the carbon textile reinforcements are presented in Figure 2.

In order to apply strengthening layers to TRC, the surface of the concrete slab needs to have sufficient roughness. To achieve this, exposed aggregate concrete was used on the bottom of the slab instead of sandblasting the surface of the concrete slab. The bottom surface of three formworks was therefore covered with a retarder paper before casting the concrete of the RC slab in order to decrease the setting time of the concrete on the bottom of the slab. All five specimens were casted at the same time using the same concrete batch ordered from a local company. After 24 hr from concrete casting, three specimens were lifted up and the retarder papers were peeled off from their bottom surfaces, and the unset concrete on the bottom surface of the specimens was washed off using a pressurized water nozzle. After 7 days from concrete casting, the strengthening layer was applied to three RC slabs. The strengthening layer of 20 mm in total thickness was provided for all strengthened
slabs using fine-grained concrete with a maximum aggregate size of 1 mm. The textile of Type 1, which has approximately the same material properties in the longitudinal and transversal direction, was embedded as a single textile reinforcement layer between two equal layers of fine-grained concrete. For the textiles of Types 2 and 3, two layers of the textile were embedded in between three equal layers of fine-grained concrete. Due to the different geometrical properties in longitudinal and transversal direction of textile Types 2 and 3, the two textile layers were placed at an angle of 90° to provide the same reinforcement area in both directions. The application of the strengthening layer was done in the following way. The bottom surface of the specimen was moisturized for 24 hr. The fine-grained concrete was plastered on the bottom surface of the specimen, and carbon textile reinforcement mesh was placed on the fresh fine-grained concrete matrix. Then, the next layer of fine-grained concrete was plastered until the final number of textile and concrete layers was reached and the entire strengthening layer was obtained. To specify material properties used in the experiments, concrete samples were taken and tested on the 28th day. Furthermore, specific material test specimens with textile reinforcements embedded in fine-grained concrete matrix were manufactured to obtain uniaxial tensile strength and strain capacities by following the testing procedures explained in Schütze et al.19 For each textile reinforcement type, 10 specimens were tested and the tensile properties of each TRC composite were obtained. It should be noted that the TRC specimens showed linear behavior after crack formation was complete. The mechanical properties of steel reinforcement were provided by the local company in accordance with DIN 488-I.20 Table 1 summarizes the material properties.

In the following chapters, the slab specimens are denoted with “S,” followed by the specimen number, ranging from 1 to 5. Additionally, carbon textile reinforcements are denoted with “T,” and followed by the number which indicates the type of carbon textile reinforcement. The specimens used in the experimental program are summarized in Table 2.

### 2.2 Test setup

The impact tests were carried out by using the drop tower facility of the Institute of Concrete Structures of TU Dresden (Figure 3). This test setup can be used in testing specimens by means of the free fall of either weights21 or accelerated weights.22,23 In this experimental study, accelerated weights were used. All specimens were subjected to hard impacts by using the same accelerated cylindrical steel striker with 21.6 kg of mass, 100 mm in diameter of flat contact surface, and 380 mm in length. The striker is held by magnets and released by air pressure from the top of the testing setup with the help of controllable air pressure stored in the tanks of the testing facility (Figure 3a). The support conditions were designed as a fixed support at four corners by means of a steel rod passing through the specimen connected to the steel frame. At each support location, reaction forces are recorded by the load cells with the capacity of 10 MN (Figure 3b). The displacement measurement is recorded by using a contactless laser sensor which is located at the midpoint on the bottom surface of the specimen.

### 3 EXPERIMENTAL RESULTS AND DISCUSSION

#### 3.1 General

The main objective of the experimental investigation is to reveal the overall behavior of reinforced concrete slabs strengthened with carbon textile reinforcement under consecutive hard impact loads without total perforation at the first impact. For this purpose, two unstrengthened specimens were tested under two subsequent impacts with different contact velocities to observe damage levels, starting from the bottom limit of the testing facility. Then, in the light of experiences of these tests, the impactor velocity of slab S1T0 was chosen as the reference velocity for all further tests, and the three strengthened specimens were tested with the same striker velocity as slab S1T0. The striker...
velocity was selected for the strengthened specimens in order to reveal the effectiveness of different TRC layers and to catch the total impact resistance capacities for each slab before perforation occurs. The impact load application was repeated as many times as necessary until total perforation occurred. The number of impacts resisted by a particular slab was recorded for each slab. Table 3 summarizes the number of impacts, velocities of striker, and final damage levels of each specimen.

### 3.2 Damage levels and crack profiles

To identify the damage levels and crack patterns of slab specimens, cracks that developed on the bottom surface of specimens were marked and penetration depths of the striker were measured after each impact. According to crack profiles developed during tests, visible cracks on the middle and diagonal axes were observed for all specimens. Additionally, substantial circular crack profiles were developed around the impact region as a sign of punching failure. It can also be said that, for all specimens, crack profiles developed after first impacts dominate the following crack profiles generated by consecutive impacts. Generally, the cracks developed in the first impacts were widened in the following impacts and resulted in significant scabbing around the punching zone. The crack patterns after first impact and the final state of the specimens are presented in Figure 4 for all specimens.

In the first impact test of specimen S1T0, no concrete scabbing was observed, and the maximum penetration of the striker was measured as 5 mm. As a sign of the punching failure cone, the widest cracks were observed around the punching cone area (Figure 4a, left). The subsequent impact led the inherited cracks to widen, and 4 kg mass of concrete scabbing was measured. Due to the excessive damage, steel reinforcements were visible on the bottom surface (Figure 4a, right). The penetration depth of the striker was measured as 20 mm. The second unstrengthened specimen, S2T0, was subjected to impacts with higher contact velocity. Therefore, after the first impact, wider cracks developed compared to the S1T0 specimen and slight concrete scabbing was observed on the punching cone boundary. At the first impact, the penetration depth of the striker was measured as 7 mm, whereas the penetration depth increased significantly to 63 mm in the following impact. The concrete scabbing area was also larger than the previous specimen, which resulted in more visible steel reinforcements on the bottom surface compared to specimen S1T0 (Figure 4b, right). 14.5 kg mass of concrete scabbing was measured after the final impact.

The specimens strengthened with a TRC layer, S3T1, S4T2, and S5T3, were tested with the same impactor velocity as slab S1T0. The specimen strengthened with the lowest carbon textile reinforcement ratio, S3T1, had more homogenously distributed crack developments after the first impact compared to other specimens, considering both circumferential cracks around the punching cone area and diagonals (Figure 4c, left). The depth of

| Slab | Long. reinforcement/spacing (mm) | Textile reinforcement/number of layers |
|------|---------------------------------|---------------------------------------|
| S1T0 | φ8/100                          | None/none                             |
| S2T0 | φ8/100                          | None/none                             |
| S3T1 | φ8/100                          | Type 1/1                              |
| S4T2 | φ8/100                          | Type 2/2 orthogonal                    |
| S5T3 | φ8/100                          | Type 3/2 orthogonal                    |

| Textile reinforcement number in warp/weft directions | Area of a strand in warp/weft directions (mm²) | Tensile strength and strain in warp direction (MPa/mm/m) | Elasticity modulus in warp direction (MPa) |
|------------------------------------------------------|-----------------------------------------------|----------------------------------------------------------|------------------------------------------|
| Type 1                                               | 48 K/48 K                                    | 1.83/1.83                                                | 2,660/14.28                              | 187,000                                  |
| Type 2                                               | 48 K/12 K                                    | 1.83/0.92                                                | 3,052/15.40                              | 198,000                                  |
| Type 3                                               | 48 K/12 K                                    | 1.83/0.92                                                | 2,035/9.57                               | 213,000                                  |
penetration was the same, 5 mm, as in the first impact test of the S1T0 specimen, whereas the penetration depth at the second impact was measured as 10 mm, which is half of the amount of the second impact of S1T0. Additionally, no scabbing at the first impact and very slight scabbing on the punching cone boundaries at the second impact were observed. This shows the protective effect of the TRC layer. On the third impact, the specimen was heavily damaged and significant scabbing of the fine-grained concrete layer around the punching cone was observed, which resulted in the textile reinforcement becoming clearly visible. Also, excessive damage in the plain concrete section was observed but remained in place due to the textile reinforcement net. A penetration depth of 29 mm and 3.4 kg of fine-grained concrete mass were measured at the third impact. At the final impact, the textile reinforcements around the contact surface of the striker ruptured and the specimen was totally perforated (Figure 4c, right).

The crack development of specimen S4T2 was denser and more distributed than all other specimens. In addition to circumferential cracks around the punching cone and cracks on the middle and diagonal axes, numerous hairline cracks were formed and distributed over the bottom surface after the first impact (Figure 4d, left). However, the widths of the cracks that developed at the first impact were very small and barely visible. In the proceeding impact test, the hairline cracks became apparent around the punching cone. No scabbing of fine concrete was observed in the first impact test. The depths of penetrations in the first and second impact tests were similar to S3T1, namely 6 and 10 mm, respectively. However, at the third test of S4T2, the penetration depth was measured as 18 mm, which is significantly lower than the depth measured at the third impact.
The test of specimen S3T1. Scabbing of the fine concrete layer was observed at the fourth impact test and measured as 1.2 kg of mass. The amount of scabbing of fine concrete slightly increased at the fifth impact test and was approximately 1.5 kg. However, the penetration measured after the fourth impact increased from 34 to 110 mm at the fifth impact. After the fifth impact, the strengthening layer still maintained its integrity and an apparent bulge formed on the bottom surface of the specimen. At the sixth impact test, the specimen was totally perforated (Figure 4d, right). The mass amount of scabbing increased to 7 kg and the numerous filaments of textile reinforcement were ruptured in the scabbing area.

The last specimen, S5T3, was the most resistant and was perforated at the seventh impact test (Figure 4e, right). Similar to the S4T2 specimen, numerous hairline cracks were formed around the punching cone after the first impact (Figure 4e, left). Penetration depths were measured closely to previous specimens—5, 9, and 20 mm for the first three impacts, respectively. Similarly, a slight scabbing of the fine concrete layer was observed at the fourth impact on the punching cone boundaries which was measured as 0.3 kg. On the other hand, the penetration depth of 65 mm at the fourth impact was significantly higher than the penetration depth at the fourth impact test of specimen S4T2. However, in the following test, a penetration depth of 104 mm was measured, which was lower than the penetration depth of the previous specimen at the fifth impact. Bulging of the punching cone area started to be apparent after the fifth impact. At the sixth impact test, the bulging became very apparent, coupled with the highest penetration depth of 165 mm. At the seventh impact test, the specimen was totally perforated by the striker and many yarns of textile reinforcement in the scabbing area ruptured.

Although the S1T0 and S2T0 specimens were subjected to impacts with different striker velocities, the punching cone geometries were similar, which can also be estimated by means of circumferential cracks after the first impacts (Figure 4). However, for the strengthened specimens, smaller circumferential crack formation in diameter was observed after the first impact. After the tests, all tested slab specimens were cut into two equal pieces to observe the actual punching cone geometry (Figure 5). Regardless of the striker velocity and TRC layer type, all specimens S1T0-S5T3 had similar punching cone geometries.

### 3.3 Measured reaction forces

The total reaction forces measured from load cells located at the four corner supports are depicted for the first and second impacts of specimens S1T0 and S2T0 in Figure 6. Despite the different contact velocities of the striker at the first impact tests of the S1T0 and S2T0 specimens, measured total reaction responses are similar. Considering differences in crack patterns and damage levels of these specimens after first impacts, such as wider cracks and deeper penetration depths, the kinetic energy difference generated by the striker velocities between these tests dissipated in specimen S2T0 and this increased the degree of damage. Due to this increase in damage level, a
reduction in the peak tension force at the second impact
test of specimen S2T0 was observed (Figure 6b). How-
ever, at the second impact test of S1T0, the reaction force
magnitudes and progression until 50 ms were observed
similar to the previous impact test, and beyond this point
reaction forces decay more quickly.

The total reaction forces at sequential impact tests for
the strengthened specimens are presented in Figures 7
and 8. As clearly seen from measured reaction forces for
the first impact tests, the peak tension forces are rela-
tively higher compared to the unstrengthened specimens
at the first impact tests. One of the reasons is the increase
in the thicknesses and the reinforcement ratio of the slab
specimens with the carbon textile reinforcement layers,
obviously resulting in a higher stiffness and bearing
capacity. Even though the strengthened specimens were
subjected to the same impact loading parameters as speci-
men S1T0, the observed crack profiles were limited in
terms of width of the developed cracks. Also, at the post-
impact phases, the numbers of cycles observed at the first
impact tests of strengthened specimens were higher. This
can again be explained as a result of an increase in the
bending stiffness of specimens which can be seen in dis-
placement–time histories. The measured reaction forces
for strengthened specimens showed similar progressions
up to the fourth impact. Besides an increase of the thick-
ness and reinforcement ratio, a reason for the enhanced
impact resistance is that the strengthening layers
provided efficient load distribution and body integrity
after the first impact where the punching cone occurred.
At the fourth impact test, the lowest reactions were mea-
sured during the test of specimen S3T1, which had the
lowest carbon textile reinforcement ratio (Figure 8a). It
should be noted here that this specimen was totally per-
forated at the fourth impact. Additionally, the highest
reaction forces were observed at the fourth impact of
specimen S4T2. Beginning from the fourth impact of
S5T3 and the fifth impact of S4T2, large reductions in
support reactions were observed (Figure 8b) with an
increase in the damage levels of slabs such as striker pen-
etration and concrete scabbing.

3.4 | Measured midpoint displacements

The midpoint displacement profiles provide a quite indic-
ative measure to reveal the contribution of carbon textile
reinforcements during impact events. To make a compar-
ison between displacements of specimens, selected
impact events of specimens are displayed in Figures 9–11.
At each impact, the midpoints of specimens oscillated
and the specimens suffered from permanent displace-
ments. It should be noted here that the displacement pro-
files of specimens represent displacement–time histories
for individual impact tests, independent from residual
displacement. As mentioned previously, midpoint dis-
placement measurements were recorded by contactless
laser sensor. With the crack developments at the mid-
point during impact events, recorded data was affected,
which created unreasonable peaks in the displacement–
time histories. This deficit in measuring can clearly be
seen in the first impact tests of S1T0 and S3T1 in Figure 9,
and the second impact test of S3T1 in Figure 10, where
the discrepancy is presented as a dotted line.

The displacement responses of unstrengthened speci-
mens for the first impact tests were presented in Figure 9.
As clearly seen from their displacement–time histories,
an increase in velocity of the same striker from 25.9 to
30.2 m/s is very influential on peak and residual displace-
ments of the specimens. The peak displacement of speci-
men S2T0 is approximately one and a half times greater
than specimen S1T0. Additionally, the residual displace-
ment of S1T0 is slightly higher than half of the residual
displacement of specimen S2T0. Due to excessive damage
and scabbing of concrete on the bottom surfaces in the
second impact tests, reasonable data can only be recorded
for the first cycle in the displacement–time histories.
According to peak values at the second impacts, the effect
of striker velocity on the peak displacements is increasing
with the increasing damage level. The displacement–time
histories of the strengthened specimens of S3T1, S4T2,
and S5T3 are displayed for the first impact tests (Figure 9b). The positive and negative peak values of the S3T1 and S4T2 specimens at the first cycles are close to the peak values of the unstrengthened specimen S1T0 at the same cycle. However, the vibrations of strengthened specimens decay more quickly. One of the reasons is the contribution of strengthening layers to stiffness by means of increasing thickness of slab specimens; another reason is the load distributing effect of the textile reinforcement. It should be remembered here that the strengthened specimens and specimen S1T0 were subjected to impacts by using the striker with the same contact velocities. Starting from the second impact tests, the contribution of carbon textile reinforcements to displacement–time histories differs (Figure 10a). Specimen S3T1 with the lowest carbon textile reinforcement ratio exhibits the highest peak and residual displacement values at the second impact compared to specimens S4T2 and S5T3. Furthermore, specimen S5T3 has a lower peak and residual displacements compared to the S4T2 specimen despite having the same textile reinforcement ratio in the strengthening layers. To figure out the reasons for these different reactions in spite of equal textile reinforcement ratios, further studies are required to investigate the influence of the other properties of the reinforcement textiles such as bonding properties, coating properties, configuration of the rovings' in warp and weft direction, and type of knitting yarn. The peak displacement values for S5T3 were also lower than the S4T2 specimen for the third and fourth impact tests, whereas residual displacements for both specimens were equilibrated (Figures 10b and 11a). It should be noted here that due to the
excessive scabbing and perforation at the third and fourth tests of specimen S3T1, the displacement–time histories are not presented. In contrast to the third and fourth impact tests, the peak displacement of S5T3 was higher than specimen S4T2 at the fifth impact test. Nevertheless, recovery from the peak value was remarkable compared to the S4T2 specimen and the residual displacement was substantially lower than specimen S4T2 (Figure 11b).
**FIGURE 11** Displacement–time histories of strengthened specimens for the fourth and fifth impact tests; (a) fourth impact tests, (b) fifth impact tests (graphics: Baturay Batarlar)

**TABLE 4** Measurement results of the tests

| Slab-impact # | Velocity (m/s) | Penetration depth a (mm) | Peak reactions a (kN) | Midpoint displacements a (mm) |
|---------------|----------------|--------------------------|-----------------------|-----------------------------|
|               |                |                          | Compression     | Tension     | Peak | Residual |
| S1T0-1        | 25.9           | 5.0                      | 117.8           | 450.1       | 11.2 | 3.3      |
| S1T0-2        | 25.3           | 15.0                     | 86.7            | 417.5       | 31.2 | N/A      |
| S2T0-1        | 30.2           | 7.0                      | 115.0           | 431.5       | 17.1 | 4.9      |
| S2T0-2        | 29.7           | 56.0                     | 64.9            | 280.2       | 41.4 | N/A      |
| S3T1-1        | 26.0           | 5.0                      | 128.5           | 520.7       | 9.0  | 2.1      |
| S3T1-2        | 26.0           | 5.0                      | 79.9            | 650.6       | 27.0 | 10.1     |
| S3T1-3        | 26.2           | 19.0                     | 64.9            | 456.6       | N/A  | N/A      |
| S3T1-4        | 25.4           | Perforation               | 46.2            | 182.3       | N/A  | N/A      |
| S4T2-1        | 26.0           | 6.0                      | 131.2           | 555.5       | 7.7  | 2.0      |
| S4T2-2        | 25.9           | 4.0                      | 87.9            | 592.2       | 18.6 | 4.0      |
| S4T2-3        | 25.9           | 8.0                      | 73.0            | 892.7       | 20.4 | 6.0      |
| S4T2-4        | 25.4           | 16.0                     | 69.2            | 444.7       | 22.2 | 9.0      |
| S4T2-5        | 26.0           | 76.0                     | 43.5            | 215.2       | 16.7 | 11.8     |
| S4T2-6        | 25.9           | Perforation               | 34.8            | 46.7        | N/A  | N/A      |
| S5T3-1        | 25.9           | 5.0                      | 135.7           | 536.3       | 3.0  | 1.95     |
| S5T3-2        | 25.9           | 4.0                      | 72.0            | 509.0       | 13.4 | 2.8      |
| S5T3-3        | 25.2           | 11.0                     | 69.0            | 465.0       | 16.6 | 6.0      |
| S5T3-4        | 25.5           | 45.0                     | 46.4            | 276.7       | 17.8 | 9.2      |
| S5T3-5        | 25.7           | 39.0                     | 48.4            | 198.4       | 22.7 | 8.0      |
| S5T3-6        | 25.9           | 61.0                     | 35.8            | 152.6       | 43.2 | 28.5     |
| S5T3-7        | 25.2           | Perforation               | 23.0            | 67.3        | N/A  | N/A      |

*aDisplayed for individual impact events, not accumulated from previous tests.

### 3.5 Summary of test measurements

The measured responses of each impact test are presented in Table 4. One of the purposes of this experimental investigation is to improve future numerical investigations of reinforced concrete slabs strengthened with carbon textile reinforcements under impact loading. Therefore, measured response characteristics are summarized with the aim of providing measured data in detail which can be used for validating future numerical investigations.

### 4 CONCLUDING REMARKS

The main purpose of this experimental investigation is to reveal the contribution of carbon textile reinforcements...
applied as a strengthening layer to reinforced concrete slabs subjected to repeated impact loads. In contrast to other studies, the focus of this study lies explicitly on repeated and consecutive impact load. As a reference, two un-strengthened slab specimens were subjected to impacts loads with the same mass but varied velocities of a striker in order to show the influence of the velocity parameter on failure mechanisms. Based on the test results and observations, the following conclusions can be made:

1 All specimens developed circumferential cracks as a sign of punching cone failure after the first impact. However, visible shear plug formation was only observed in the unstrengthened specimens. An increase in striker velocity created a significant difference between damage levels of specimens, whereas the observed punching cone diameter was not greatly affected. Strengthening layers had a considerable effect not only on reducing the crack widths but also on distributing the cracks on the bottom surface of the specimens. With an increase in the carbon textile reinforcement ratio, more minor cracks developed and they were distributed throughout the bottom surfaces of the strengthened slab specimens.

2 Although the unstrengthened specimens were tested under different striker velocities, the reaction force time histories for the first impacts are quite similar. When dynamic equilibrium is considered during impact events, accelerations on the specimen generated by the striker with higher velocity caused higher inertial forces that resulted in more damage to the specimen. Furthermore, the degree of damage level has an influential effect on transmitting the impact forces to the supports for consecutive impacts. Strengthening layers provide better force transfer to supports and body integrity after the first impacts where a punching cone occurs. The effect of strengthening layers on load distribution is significant even though they are applied as a thin layer compared to the overall thickness of the specimen.

3 Strengthening the specimens with carbon textile reinforcements is found to be very effective in enhancing impact capacity when the number of impacts until failure occurs is considered. The contribution of carbon textile reinforcements is increasing with the increase in carbon textile reinforcement ratios, particularly for the further impact test stages.

4 The formation of bulging became apparent for all strengthened specimens up to the final tests where total perforation occurred. All strengthened specimens failed due to the rupture of carbon textile reinforcements. Hence, it can be concluded that the bonding between strengthening layers and reinforced concrete slab specimens was sufficient to resist impact loads, and the material characteristics of carbon textile reinforcements are the determining factors for perforation resistance along with the textile reinforcing ratios.

5 The bonding between textile reinforcement and concrete as well as textile engineering properties such as roving arrangement and knitting or weaving technique have to be further investigated to understand the influences on the structural behavior in terms of displacement, support reaction, and impact capacities of the specimens.

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