Experimental Study of Reinforced Concrete Slabs Strengthened by CFRP Subjected to Impact Loads

AbdulMuttalib I. Said\textsuperscript{1, a} and Enas M. Mouwainea \textsuperscript{2, b, *}

\textsuperscript{1}Civil Engineering Department, University of Baghdad, Baghdad, Iraq.
\textsuperscript{2}Civil Engineering Department, Al-Esraa University College, Baghdad, Iraq.
\textsuperscript{a, b}Dr.AbdulMuttalib.I.Said@coeng.uobaghdad.edu.iq, \textsuperscript{b}enas_mabroom @esraa.edu.iq

Abstract: This paper shows a progression of experimental studies to investigate the response of reinforced concrete slabs when subjected to high-mass low-velocity impact loads. The researcher has confirmed that FRP composites are effective for strengthening a wide variety of concrete structural members. To date, very little published research has been performed on the behavior of strengthened two-way slabs under impact loads. The purpose of this study is to investigate experimentally on behavior slabs strengthening with CFRP. A total of seven reinforced concrete slabs were tested under the effect of impact load by a drop-weight facility. Measurements involved a load cell, accelerometer, strain gauges in the reinforcement steel and concrete, and using (a laser sensor, LVDT) to measure deflection in the center and quarter of the slabs. These experimental variables included in this study were focused mainly on the formation and dimension of carbon fiber under impact loads. The test results showed that the adding carbon fibers were active in increasing slab capacity and mitigating local damage under the impact, as the strengthening of slabs by CFRP, the increased in an impact force of the slabs about (11.9–19.5%) and the maximum deflection at the central slabs decreased by (6.5–22%). It can be observed that the increase in the area of the CFRP layer under the impact region led to more decrease of the deflection. With regard to acceleration, it is evident that the distribution of forces acting on the plate also varies over the course of the event and that the evolution of the inertial forces resulted in load distributions that are significantly different from those developed in static test conditions. The evolution of inertial forces in impact loading conditions resulted in observed responses then failure patterns governed by shear.

Keywords: Reinforced concrete, slabs, drop mass, impact test, CFRP

1. Introduction

In the civil engineering field, reinforced concrete (RC) structures are frequently exposed to various extreme dynamic loads due to accidental impacts of rigid bodies that may happen during their service life with a very little probability of occurrence. The failure resulting consequences of structures subjected to such extreme loads might be extremely high, which makes the analysis and design very difficult especially when working with nonelastic materials. Impact loads are considered by a force of significant amount applied within a short duration, they might be caused by vehicles collision with buildings or bridges, falling rock impact on protection galleries, flying objects due to natural forces such as volcanos and tornados, fragments generated due to accidental explosions on civil structures [1]. Carbon fiber reinforced polymer (CFRP) has been commonly used in the civil engineering field for several decades [2]. The material can be utilized to improve the impact resistance of structures. It has been utilized in strengthening or modifying current structures or building new structures ranging from beams, slabs, and columns to walls. Among these types of structures, the RC slabs can be strengthened by CFRP in relation to shear failure or bending failure to withstand shock load. The behavior of...
Structural member reinforced concrete strengthened or without strengthened with FRP against impact loading is limited to a little qualitative study [3,4]. Pham and Hao conducted tests a series of CFRP strengthened reinforced concrete beams tested under impact loads. The width and height of these tested beams were 150 mm and 250 mm respectively. The compressive strength of the concrete was 46 MPa at 28-day age. It was reported in the experimental results that the beams strengthened with CFRP being laid longitudinally failed with CFRP debonding. Locally strengthening RC beams in shear at the probable impacting region is crucial to avoid the shear failure. Impact load may cause premature debonding of FRP thus anchorage method should be used to strengthening RC beams against impact loads. This failure type can easily be avoided by proper surface preparation for concrete and FRP. Xiao et al. [4] tested fifteen 1200 × 1200 × 150 mm (RC) slabs in low-velocity impact loads. The slabs were fixed on all four edges and vertically impacted using a drop-weight system. The effects of impact energy, the diameter of the impacted area, and impactor nose shape on the damage of the RC sample were studied. The damage of the slabs in low-velocity impact increases through increasing impact energy. Moreover, punching shear failure-mode was observed for all specimens that failed during the test.

In the review of literature cited above, no inclusive experimental studies investigating the impact load behavior of reinforced concrete two-way slabs strengthened by CFRP sheet were identified using different methods. So, an experimental study was planned and a total of seven test slabs samples with 1800×1800×100 mm dimensions were tested under impact loads. This paper presents the methodology, details regarding the constructed slab specimens, the drop-weight test frame, materials, specimens’ preparation, a detailed account of the provided instrumentation, and data measurement techniques are provided. Through the experiments, the acceleration-time history, displacement-time history, strain measured of steel reinforcement, concrete and CFRP-time history, impact load-time history was measured, and the effect of strengthening techniques on impact behaviors of RC slabs was studied.

2. Details of Specimens

Seven square reinforced concrete slabs with dimensions of 1800×1800×100 mm are manufactured and tested under sequential impacts, with constant impact velocities and mass of striking. The drop-weight was 50 kg and the drop height of the impacting mass was 1.5 m above the top surface of the slab, resultant in a nominal impact velocity of 5.4 m/s. Testing termination of each slab was governed by the occurrence of any one of the following conditions: 1) the maximum impact forces decreased significantly from those measured through prior impacts, or 2) the case severely damaged state of the slab significantly increased the likelihood of damaging instrumentation under additional impacts. Dimensions and reinforcement details of the test samples are presented in Table 1 shows the properties of test samples; the concrete compressive strength for the samples was 30 MPa. The concrete compressive strength of the samples was measured by performing an unconfined compressive test on standard cylindrical samples.

| Slab No. | Slab Dimension (m) | Drop weight (kg) | Reinforcement ratio, ρ (%) | Area of CFRP (m) | Drop Height (m) | f’c MPa |
|----------|-------------------|-----------------|---------------------------|-----------------|-----------------|---------|
| S12      | 1.8×1.8×0.1      | 50              |                           |                 | 1.5             | 29.2    |
| S15      | 1.8×1.8×0.1      | 50              |                           | 0.9×0.9         | 1.5             | 30      |
| S52      | 1.8×1.8×0.1      | 50              | 0.58                      | 1.2×1.2         | 1.5             | 28.9    |
| S53      | 1.8×1.8×0.1      | 50              | Ø8@82 mm                  | 1.8×1.8         | 1.5             | 30.5    |
| S54      | 1.8×1.8×0.1      | 50              | 2 layers T and B          | 0.3×1.8         | 1.5             | 30.7    |
| S55      | 1.8×1.8×0.1      | 50              |                           | 0.6×1.8         | 1.5             | 29.2    |
| S56      | 1.8×1.8×0.1      | 50              |                           | 0.9×1.8         | 1.5             | 31.11   |

Five cylindrical samples are taken from each specimen to calculate the average concrete compressive strength. These slabs are doubly reinforced with the same amounts of the steel in the top and bottom mats of reinforcement, one type of reinforcing bars was used with cross-sectional areas of 50.24 mm².
and nominal diameters of 8 mm. Steel links made of bent bars were utilized in the end region of slabs to connect the reinforcement together at the top and bottom mats. All the tested slabs were designed according to Building Code Requirements for Structural Concrete [5]. Figure 1 shows the geometric and steel reinforcement layout of the tested slabs. These experimental variables included in this study were focused mainly on the formation and dimension of carbon fiber. One slab will be the reference sample S12 which represents the unstrengthened slab. Six different CFRP sheet layouts which were used with 0.3 m width CFRP sheet were used for strengthening of RC slab covering an area of (0.9×0.9 m, 1.2×1.2 m, 1.8×1.8 m, 0.3×1.8m, 0.6×1.8 m and 0.9×1.8 m in two orthogonal directions) of the bottom slabs, the layouts of CFRP sheet are given in Figure 2. Two-component epoxies (Sikadur 330) are used to connecting unidirectional fibers CFRP sheets (Sikawrap-330C) to RC slabs. In order to avoid adhesion failure, special attention was given for surface preparation, Surface preparation (cleaning) to remove a weak layer and rough surface for good adhesion was then performed see Figure 3. The mechanical properties of the epoxy and CFRP provided by the manufacturer are shown in Table 2.

![Figure 1. Geometric, steel reinforcement layout, and casting of the tested slabs.](image1)

![Figure 2. The layouts of the CFRP sheet.](image2)
Figure 3. Application of CFRP.

Table 2. Mechanical properties of CFRP and epoxy

| Properties of CFRP          | Remarks of CFRP |
|-----------------------------|-----------------|
| Thickness (mm)              | 0.167           |
| Tensile Strength (MPa)      | 4000            |
| Elastic Modulus (MPa)       | 230000          |
| Ultimate Tensile Strain (%) | 1.7%            |

| Properties of Resin         | Remarks of Resin |
|-----------------------------|------------------|
| Tensile Strength (MPa)      | 30               |
| Elastic Modulus (MPa)       | 3800             |

3. Testing of Reinforced Concrete Slabs - Impact Loading

All slabs are tested by adopting the same procedure, the set-up was individually designed to be able to test two-way slabs under impact loads as shown in Figures 4 and 5. In fact, the frame must be stiff enough to support the loads without significant deformation. The specimen slab rests at the testing rig with supports under the specimen, all the experiments on slabs considered the samples being simply supported. The dropped mass is free by gravity without any external force. The specimens were placed in their position in the test frame with the finished surface up. Then the falling mass was dropped and deflection was recorded. The test-rig consists of main parts as follows:

- Strong steel frame and heavy with simple supports to hold rigidly through impact loading by connected all structural elements to build the frame.
- A steel section: was used as a vertical guide for the falling mass.
- The drop hammer was used to apply an impact load to the slabs. The load cell was connected with the steel mass to measure impact force and an impactor made from stainless steel with a blunt nose was connected to the load cell.
• The slabs were subjected to a common loading protocol consist of sequential impact events with a mass of 50 kg up to failure.

![Manufactured physical model used for impact tests.](image)

**Figure 4.** Manufactured physical model used for impact tests.

![Steel frame for impact test.](image)

**Figure 5.** Steel frame for impact test.

### 4. Test Instrumentation

Several factors must be considered when selecting the sensors and instrumentation for dynamic testing. One of the major requirements is to measure dynamic parameters, which requires high-speed data acquisition systems. These dynamic parameters, as shown in Table 3, include impact load, acceleration, steel and concrete strain, and deflection at the center and quarters of the slabs. Typical placements for all sensors are shown in Figures 6a to 3d and Figure 7.

| Parameter                          | Sensor                                      |
|------------------------------------|---------------------------------------------|
| Applied load                       | Load cell                                   |
| Acceleration                       | Accelerometer                               |
| Reinforcing steel and Concrete strain | Embedded strain gauges and Concrete strain gauges |
| Specimen deflection                | Laser sensor and LVDT                      |

**Table 3.** Utilized Instrument.
5. Results and Discussion

Through the test of the slab sample, five types of data were recorded and offered hereafter:
1) Crack pattern;
2) Impact force-time history;
3) Displacement-time history in the vertical direction;
4) Acceleration-time history in the mid-point between the center and the end span of the slab;
5) Strain-time history.

5.1 Crack patterns and damage

Under the first impact test; limited mass penetration and no concrete scabbing were observed. Subsequent impacts led to increased Penetration of mass was observed at the top surface for all slabs and significant scabbing was noticed in the tension side of the slab around the location of circular crack for slab S12 [6]. For other slabs that strengthening by CFRP, the number of drops increased, and an
exceptional case was observed on the S51 slab during the tests, Bond failure in the interface between the concrete and the adhesive layer where there was little concrete attached to the CFRP after failure, but for the rest of the specimens within this group, it is observed interlaminar failure of CFRP and concrete shearing beneath the adhesive layer. The final cracking pattern for all RC slabs is shown in Figure 8.

Figure 8. The response of all slabs.

5.2 Impact force-time history

Figure 9 (a) to (g) show the peak impact forces, noted as $F_{max}$, and calculated response impulse values, noted as I, have been included on each time history plot. The effect of formation and dimension of carbon fiber on the behavior of tested slabs (S51, S52, S53, S54, S55 & S56) as compared with the slab (S12), the values of the peak impact force for the slabs were usually higher for the strengthened samples. The increase in the magnitude of impact force for first event is (11.9%, 14.6%, 19%, 5.7%, 19.5%, and 16%) respectively. It can be observed from Figure 9 that the increase in the area of the CFRP layer under the impact region led to an increase in the peak impact value.

5.3 Midpoint displacement-time history

Figures 9 (h) and (i) show the effect of formation and dimension of carbon fiber on the behavior of tested slabs (S51, S52, S53, S54, S55 & S56) as compared with the slab (S12), the decrease in the deflection for the first event is (14.2%, 20%, 22%, 6.5%, 14.2%, 14%), respectively. It can be observed that the increase in the area of the CFRP layer under the impact region led to more decrease of the
deflection. A summary of midpoint displacements (event peaks and residuals) and the peak impact forces are reported in Table 4.

![Force-time history and Displacement-time history](image)

Figure 9. (a-g) Impact force-time history and (h-i) Displacement-time history, for the first event.

5.4 Strain–time history

Figure 10 (a) to (b) show the effect of formation and dimension of carbon fiber on the behavior of tested slabs (S51, S52, S53, S54, S55 & S56) as compared with the slab (S12). We did not notice a clear difference in the strain of the top rebar mat as well as the strain of the upper concrete surface, but there was a decrease of the rebar strain in the impact zone of the SG5 about 32% and the decrease of the concrete strain of SG14 in the tension zone about 37%.

5.5 Acceleration-time history

The acceleration versus time data from the accelerometer channel, which was attached to the midpoint between the center of the slab and the edge of the supports, was used to determine the response of acceleration. Figures 10 (c) to 10 (i), present the acceleration-time histories for all slabs. It was observed that the computed acceleration distributions are very non-uniform and change significantly over the course of the impact event. As such, it is obvious that the distribution of the forces acting on the slab
also varies over the course of the event and that the evolution of the inertial force resulted in load distributions that are significantly different from those developed in static testing conditions [8]. To reduce noise, the results from accelerometers were filtered by a Butterworth filter with a cut-off frequency of 1200 Hz [9].

| Impact event | Total Disp* (mm) | Peak impact force* (kN) | Impact event | Total Disp* (mm) | Peak impact force* (kN) |
|--------------|------------------|-------------------------|--------------|------------------|-------------------------|
| S12-1        | 4.41             | 2.8                     | 145.6        | S53-11           | -                       |
| S12-2        | 8.3              | 5.1                     | 148          | S54-1            | 4.12                    |
| S12-3        | 11.5             | 10                      | 128          | S54-2            | 6.8                     |
| S12-4        | 16               | 13                      | 117          | S54-3            | 9.6                     |
| S12-5        | 18.6             | 16.3                    | 106          | S54-4            | 12.1                    |
| S12-6        | -                | -                       | 65           | S54-5            | 14.5                    |
| S12-7        | -                | -                       | -            | S54-6            | 17.4                    |
| S51-1        | 3.78             | 2.3                     | 162.1        | S54-7            | 20.3                    |
| S51-2        | 7.1              | 5.6                     | 160          | S54-8            | -                       |
| S51-3        | 8.5              | 7                       | 159          | S55-1            | 3.78                    |
| S51-4        | 10               | 8.6                     | 152          | S55-2            | 6                       |
| S51-5        | 12.7             | 11.4                    | 150          | S55-3            | 7.6                     |
| S51-6        | -                | -                       | 145          | S55-4            | 10                      |
| S52-1        | 3.53             | 2.3                     | 172.6        | S55-5            | 12                      |
| S52-2        | 6.5              | 5.4                     | 180.3        | S55-6            | 13                      |
| S52-3        | 8.3              | 7.3                     | 169          | S55-7            | 13.5                    |
| S52-4        | 10.2             | 9.5                     | 162          | S55-8            | 14.7                    |
| S52-5        | 12.6             | 11                      | 143          | S55-9            | 16                      |
| S52-6        | 15               | 13.5                    | 145.4        | S55-10           | -                       |
| S52-7        | 18.5             | 15.2                    | -            | S56-1            | 3.79                    |
| S52-8        | 20.4             | 17.8                    | -            | S56-2            | 5.3                     |
| S53-1        | 3.4              | 2.1                     | 173.6        | S56-3            | 7.3                     |
| S53-2        | 5                | 4.1                     | 182          | S56-4            | 8                       |
| S53-3        | 7.2              | 5.6                     | 179.2        | S56-5            | 9.7                     |
| S53-4        | 8                | 6                       | 165          | S56-6            | 11                      |
| S53-5        | 9                | 7.6                     | 169          | S56-7            | 12.5                    |
| S53-6        | 11.7             | 9.3                     | 172.3        | S56-8            | 13.5                    |
| S53-7        | 13.1             | 11.9                    | 165.8        | S56-9            | 15                      |
| S53-8        | 14.3             | 13.1                    | 159          | S56-10           | -                       |
| S53-9        | 16.7             | 15                      | -            | S56-11           | -                       |
| S53-10       | -                | -                       | -            | -                | -                       |

*There are some cases that the reading not recorded

6. Conclusion

An experimental study of the behavior of reinforced concrete slabs under high-mass low-velocity impact loads is described. The results obtained from the current experimental study are listed below.

- The strengthening by CFRP sheets increased the toughness and stiffness of RC slabs and correspondingly the maximum displacement values measured from test slabs decreased. The decrease in displacement values indicates an increase in the resistance of test specimens against impact load and an increase in the energy absorbed capacities under the impact load effect.
- The strengthening methods applied in the experimental study greatly improved the impact behavior of the RC slabs, the increase in the area of the CFRP layer under the impact region led to an increase in the peak impact value.
- Locally strengthening RC slabs in the expected impact region is crucial to prevent shear failure.
- Impact loads may cause premature debonding of CFRP so an anchorage system must be used to strengthening RC slabs against impact loads.

Figure 10. (a-b) Strain-time history and (c-i) Acceleration-time history, for the first event.

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