Behaviours of reinforced concrete slabs under static loads and high-mass low velocity impact loads

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Abstract: This paper examines a progression of experimental studies designed to investigate the response of reinforced concrete slabs subjected to static and high-mass low-velocity impact loads. A total of ten reinforced concrete slabs were tested: three specimens were tested under static load by loading the specimens at their mid-point, and seven specimens were tested under impact load to research the high-mass, low-velocity impact behaviours of reinforced concrete slabs using a drop-weight facility. Measurements methods included a load cell, acceleration, strain in the reinforcement steel and a laser sensor to measure deflection in the centre and various quarters of the slabs (LVDT). The experimental variables included in this study focused mainly on the thickness of slab under static and impact loads, the mass of the striking object, and the height of the striking object for impact loads.

The results showed that under static loads, the mean of the thickness of the slab increased by 33 to 100%, the maximum deflection at the central point decreased by 45 to 63 %, and the load capacity of the slabs increased by 77 to 265%. With respect to high-mass low-velocity impact loads, as the slab thickness increase by 33 to 100%, the maximum deflection at the centre of the slabs decreased by 47.7 to 84 % and the impact force increased by 37.5 to 102%. When the height of the striking object was increased by 33 to 66%, the maximum central deflection of the slabs also increased by 24 to 72.3%, and the impact loads increased by 11 to 23.3%. Increases in the mass of the striking object by 50 to 100% led to the maximum central deflection of the slabs increasing by about 54 to 122% and to the impact loads increasing by 13 to 18.6%.

Keywords: reinforced concrete slabs; drop-weight impact; impact test; static test; drop heights.

Introduction:
Structural design applications undergo continuous improvement in accordance with the changing demands and requests of humanity. With the development of reinforced concrete (RC) technology, reinforced concrete structures have become a majority among new structures, yet despite the huge number of such slabs that have been designed and built, the details of their behaviours under the effect of impact loads are not generally valued or properly taken into account. Local phenomena of impact loading can be difficult to evaluate analytically as the dynamic contact between two bodies and their corresponding material behaviours under high bearing stresses are not easy to model. Experiments are thus required to support the development of understanding of the behaviours of reinforced concrete slabs under impact loads. Impact loads are any forces of considerable magnitude applied over a short duration, such as might be caused by falling rock impact, missile impact, vehicle collisions, ice or other crash impacts, flying objects in tornados and volcanic eruptions, fragments created due to accidental explosions, military action, or dropped objects. Analysis and design of RC structures subjected to impact...
loads have attracted a great deal of research interest; for example, Chen and May (2009) [1] gathered data from experimental tests on structural elements such as RC slabs and beams under impact loading with the aim of building a numerical model. They adopted 14 beam specimens with 2.7 m spans and four with 1.5 m spans that were then tested under impact loads from a freely dropped mass. The four slabs with dimensions of 800 mm square had 76 mm thickness and the two slabs of 2,300 mm square had 150 mm thickness. The main parameters measured in their tests were acceleration, velocity, and displacement and they focused on local failure. The test results showed that the beams and slab supports were less affected by impact force than the span.

Batar-lar (2013) [2] presented the results of an experimental programme designed to investigate the behavior of RC slabs under low-velocity impact loads. The programme involved making comparisons between the static and dynamic behaviours of three pairs of simply supported slabs. The results obtained from these tests showed that the impact behavior of slabs differed significantly from their static behaviours. Ali and Al-Khafaji 2014 [3] offered an experimental study of reinforced concrete slabs subjected to impact loads that included examining the effects of dimensions of slabs as well as reinforcement ratio and support conditions. They found that the central deflections of slabs under impact were reduced as the tensile reinforcing steel ratio increased, but that the ratio of the decreases in the deflection was lower in high steel reinforcement ratios. Those deflections were also found to be oscillatory in nature, being out-of-phase with the applied load. However, clamping the edges of the slabs caused larger oscillation frequencies as compared to the case of simple supports.

The current study researched the behaviour of RC slabs tested under various impact loads and compared the results with the behaviours of identical specimens tested under static loads to facilitate a comparison of static and impact tests. For the impact loads, the dropped objects had low impact velocities, and damage arising at the impact zone was expected to be dependent on the relative masses of the colliding bodies and the resulting impact energy.

**Specimens.** Ten intermediate-scale specimen square slabs were cast in dimensions of 1,800 x 1,800 mm at different heights of 75, 100, and 150 mm. These slabs were doubly reinforced with the same amounts of the steel in top and bottom mats of reinforcement, with reinforcing bars with cross-sectional areas of 50.24 mm² and nominal diameters of 8 mm used in each case. Steel links made from bent bars were utilised in the end region of slabs to connect the reinforcement together at the top and bottom mats. All tested slabs were designed according to Building Code Requirements for Structural Concrete (ACI 318-19) [4]. Figure 1 and photo 1 show the geometric layout and steel reinforcement layout of the tested slabs. The experimental scheme, which included testing simply supported two-way slab sections, was divided into four groups as shown in table 1, in which the information about the test programmes, including the specimen properties, test setup, instrumentation, and test processes, is presented. All concrete mixtures were adapted from 30 MPa nominal cylinder-strength designs, as shown in table 2. The test results in terms of major observations are also offered.

The experimental variables included in this study were mainly

- Slab thickness.
- Mass of the striking object.
- Height of the striking object.
Figure 1: Details of slab geometry and reinforcement.

Photo 1: Steel reinforcement layout and casting of specimens
| Group no. | Slab No. | Type of Test | Slab Dimension (mm) | Drop Weight (Kg) | Reinforcement ratio ρ % | Drop Height (H) (m) | $f'c$ Mpa |
|----------|---------|--------------|---------------------|-----------------|-----------------------|---------------------|---------|
| G1       | S61     | Static       | 1800*1800 *75       | -               | 0.58 Ø8@110 2 layer top and bottom | -                   | 30      |
|          | S62     | Static       | 1800*1800 *100      | -               | 0.58 Ø8@82 2 layer top and bottom | -                   | 29.5    |
|          | S63     | Static       | 1800*1800 *150      | -               | 0.58 Ø8@55 2 layer top and bottom | -                   | 30.66   |
| G2       | S11     | Dynamic      | 1800*1800 *75       | 50              | 0.58 Ø8@110 2 layer top and bottom | 1.5                 | 31.11   |
|          | S12     | Dynamic      | 1800*1800 *100      | 50              | 0.58 Ø8@82 2 layer top and bottom | 1.5                 | 29.2    |
|          | S13     | Dynamic      | 1800*1800 *150      | 50              | 0.58 Ø8@55 2 layer top and bottom | 1.5                 | 30.05   |
| G3       | S12     | Dynamic      | 1800*1800 *100      | 50              | 0.58 Ø8@82 2 layer top and bottom | 1.5                 | 29.2    |
|          | S31     | Dynamic      | 1800*1800 *100      | 50              | 0.58 Ø8@82 2 layer top and bottom | 2                   | 28.3    |
|          | S32     | Dynamic      | 1800*1800 *100      | 50              | 0.58 Ø8@82 2 layer top and bottom | 2.5                 | 29.6    |
| G4       | S13     | Dynamic      | 1800*1800 *150      | 50              | 0.58 Ø8@55 2 layer top and bottom | 1.5                 | 30.05   |
|          | S41     | Dynamic      | 1800*1800 *150      | 75              | 0.58 Ø8@55 2 layer top and bottom | 1.5                 | 30.5    |
|          | S42     | Dynamic      | 1800*1800 *150      | 100             | 0.58 Ø8@55 Two layers, top and bottom | 1.5                 | 29      |

Table 1: Details of the test program.

* High Range Water Reducing Admixture (NanoCast 500W), 1/100 kg of cement (max limit 2.4)
Table 2: Details of the trial mixes.

| Mix Ratio (by volume) | w/c | Mix Proportion (kg/m3) | S.P.* | Comp. strength MPa $f'_c$ |
|-----------------------|-----|------------------------|-------|--------------------------|
|                       |     | Water | Cement | Sand | Gravel |       |
| 1: 1.7: 2.1           | 0.34| 131   | 385    | 800  | 1000    | 1     | 30    |

Test Program:

1. **Testing of reinforced concrete slabs under static loading.** The frame used in the tests, located in the Structural Engineering Laboratory of the College of Engineering, University of Baghdad, had a 2,000 kN capacity. Before testing the specimen, the positions of the supports, central applied load, and dial gauges were marked. The strain gauges were then tightened within the data logging machine. Photo 2 shows the testing setup.

2. **Testing of reinforced concrete slabs under impact loading.** Previous investigational studies have shown that elements under impact loading conditions often display reversals leading to specimen uplift [5]. The testing frames were thus tied up at the corners and impacted in the centre. All slabs were tested using the same procedure, with the set-up designed to allow testing of two-way slabs under impact loading. The frame had to be sufficiently stiff to support the load without any significant deformation, and the specimen slab rested in the testing rig in a simply supported state. The weight was constructed from steel, with a circular gross section with a radius of 200 mm, and two HSS vertical steel angle legs were used to lead the striker, which was raised up to 4 m high to allow the drop mass to be moved by gravity without any additional external force. High-strength HSS sections were used to support the columns, which were fixed to a concrete ground at each corner of the slab, and specimens were sited in the testing frame with the finished face up. The falling mass was then released, and the resulting deflection recorded. Photo 3 shows some details of the frame.
Test Instrumentation: A number of 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 strain and deflection in the centre and quarters of the slabs. Typical placements for all sensors are shown in Figures 2a to 2c and photo 4.

Table 3: Measurement Instruments

| Parameter          | Sensor                        |
|--------------------|-------------------------------|
| Applied load       | Load cell                     |
| Acceleration       | Accelerometer                 |
| Reinforcing steel strain | Embedded strain gauges       |
| Specimen deflection| Laser sensor and LVDT         |
Figure 2. a) Typical locations of strain, b) Typical locations of accelerometers and LVDTs, c) Dimensions of impactor and load cell

Photo 4. Test Instrumentation

**Impact test results:** During testing of the slab sample, three types of data were recorded in five areas:

1. Crack patterns
2. Impact force-time history.
3. Transient deflection-time history in the vertical direction.
4. Acceleration-time history at the mid-point between the centre and the end of the surface slab.
5. Strain-time history.

Table 4 shows the area under the curves of load-time history (Impulse) for all slabs, along with the momentum, velocity, and kinetic energy developed due to the impact force where

\[ \text{Impulse} = \int F \, dt \]  
(1)

The area is calculated numerically using the trapezoidal rule.

\[ \text{Momentum} = m v \]  
(2)

\[ m = \text{mass of the striker} \]

\[ v = \text{striker velocity} = \sqrt{2gh} \]  
(3)

\[ h = \text{drop height}, \ g = 9.81 \text{ m/s}^2 \]

\[ KE = \frac{1}{2} mv^2 \]  
(4)
| Group | Slab No. | Striker Mass (kg) | Calculated Impact Velocity of striker (m/s) (per equation 3) | Impulse (kg.m/s) | Momentum (kg.m/s) | Kinetic Energy (Joules) |
|-------|----------|------------------|---------------------------------------------------------------|------------------|------------------|------------------------|
| G2    | S11      | 50               | 5.4                                                           | 316              | 270              | 729                    |
|       | S12      |                  |                                                               | 308              | 270              |                        |
|       | S13      |                  |                                                               | 300              | 270              |                        |
| G3    | S12      | 50               | 5.4                                                           | 308              | 270              | 729                    |
|       | S11      |                  |                                                               | 356.3            | 313              | 979.69                 |
|       | S12      |                  |                                                               | 391              | 350              | 1225                   |
| G4    | S13      | 50               | 5.4                                                           | 300              | 270              | 729                    |
|       | S41      | 75               |                                                               | 452              | 405              | 1093.5                 |
|       | S42      | 100              |                                                               | 613              | 540              | 1458                   |

**Crack patterns and damage.** The observable damage and crack development were discovered to be typical among all RC slabs. Under the first impact test; limited mass penetration and no concrete scabbing were observed; then, as the number of blows increased some new cracks were seen and these cracks continued widening along the tension side of the slab. Subsequent impacts led to significant scabbing around the location of the circular cracks, eventually exposing the reinforcing bars, which was accompanied by a yielding of the reinforcement. Mass penetration occurred locally on the top surface. The final cracking pattern for all RC slabs is offered in photo 5.

**Impact force-time history.** Figures 3-a to 3-g show the impact load versus time. For slab S13, with slab thickness=150, and S12, with slab thickness=100, the increases in the magnitude of impact force were 102% and 37.5%, respectively as compared with slab S11 with slab thickness=75. This may be attributed to slab stiffness, and period elongation due to decreasing slab stiffness can also be noted [6]. However, for slabs S31, H=2 m, and S32, H=2.5 m, the increases in the magnitude of impact force were 11%, and 23.3%, respectively, as compared with slab S12, H=1.5 m. For slabs S41, dropped mass=75 kg, and S42, dropped mass=100 kg, the increases in the magnitude of impact force were 13% and 18.6%, respectively as compared with slab S13, dropped mass = 50 kg.

**Deflection-time history.** Figures 3-h to 3-j show that the increase of slab thickness had a significant influence on the midpoint displacement responses of the slabs, with increases in slab thickness of 33 to 100% leading to reductions in peak displacement of about 47.7 to 84%. It was also observed that the maximum deflection was 8.2 mm for slab S11, explained by the overall stiffness of S11 being smaller than that of slabs S12 or S13, thus making the natural frequency highly sensitive to the change of mass [7]. The time required to cause maximum deflection is not the same as that for the maximum impact force, however, as some time is required to translate the stress wave between top and bottom face; energy dissipation through the slab depth also has a delaying effect [8]. For slabs S31 and S32, as compared with slab S12, the increases in deflection were 24% and 72.3%, respectively. For slabs S41 and S42, as compared with the slab S13, the increases in the deflection were 54.4% and 122%, respectively.
Photo 5: Slabs after impact, bottom face

(a): Impact force - time history of S_{11}

(b): Impact force - time history of S_{12}
(c): Impact force -time history of $S_{13}$.

(d): Impact force -time history of $S_{31}$.

(e): Impact force -time history of $S_{32}$.

(f): Impact force -time history of $S_{41}$.

(g): Impact force -time history of $S_{42}$

(h): Displacement-time history of G2
Figure 3: (a-g) Impact force-time history and (h-i) Displacement-time history

(i): Displacement-time history of G3
(j): Displacement-time history of G4

Acceleration-time history: Based on the acceleration versus time data from the accelerometer channel, attached to the mid-point between the centre of slab and the edge of the supports, the acceleration from reaction was derived. Figures 4-a to 4-c, present the acceleration-time histories for slabs S_{11}, S_{12}, and S_{13}, showing that the computed acceleration distributions are very non-uniform and change significantly over the course of the impact event. This clarifies 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 results in load distributions significantly different from those developed under static testing conditions. To reduce noise, the results from the accelerometers were filtered with a Butterworth filter with a cut-off frequency of 1,200 Hz.

Strain-time history: The strains in the reinforcement in slabs S_{11}, S_{12}, and S_{13} were also measured; the results are presented in Figure 4-d for the first hit of the impact loads.
**Static Test Results.** The static test procedure involved measuring the crack load and ultimate load, with results as shown in Table 5. The test results were then classified into three categories to allow development of a better understanding of the behaviours of reinforced concrete slabs:

- Crack pattern and load capacity.
- Load- deflection relationships.
- Load – strain relationships.

**Crack Pattern and Load Capacity.** The general behaviour was almost the same across specimens, though their intensities differed. As the load increased, the first crack appeared around the sides of the area of loading on the tension face of the slab in each case. On increasing the load, other cracks formed at the central region of the slab and extended towards the edges of each slab specimen. However, while these cracks increased in number, they did not widen. Finally, the modes of failure for specimens were defined by excessive yielding of the tension steel reinforcement, leading to cracking concrete in the tensile zone, while in the compression zone, only the cracks from the plate loading penetration inside the slab at failure were observed.

For the S61 specimen, the number of these cracks was higher than in the other slabs; this occurred because crack numbers decreased as the thickness of slab increased, as this in turn increased the stiffness of the slab. Photos 6-a to 6-c show the crack patterns of the tested specimens.

| Specimens | Crack load (kN) | Ultimate load (kN) | P_cr/P_u % |
|-----------|----------------|-------------------|------------|
| S61       | 30             | 79                | 38         |
| S62       | 50             | 138.1             | 36         |
| S63       | 110            | 288.5             | 38         |
Load-Deflection Relations. Vertical deflection was recorded below the applied load at each loading step of the static test programme. The load-deflection response of each slab in the first group is shown in Figure 5-a. For all slabs, the first crack appeared at a different load level based on the stiffness of the slab [9]. After the formation of the first crack, the deflection increased to failure, which was associated with an increase in the number of cracks. The greater the slab thickness, the higher the stiffness of the slab, and the increase in slab thickness by 33 to 100% caused the maximum central deflection of the slabs to decrease by 45 to 63%; in addition, the load capacity of the slabs increased by 77 to 265% in the cases of S62 and case of S6, respectively, and less displacement occurred for S63 due to increased slab thickness, suggesting that the S63 slab was stiffer than the others, with the slope of the curve being larger than the other three specimens. Specimen S61, which had a lower thickness of slab, carried a lower level of load, but was nevertheless able to withstand a load with increasing displacement, making the resulting failure more ductile.

Load-Strain Relationships. The load-strain relationships of steel reinforcement were measured at a specific location (SG5) at the centre of slab in the bottom reinforcement steel mesh; the results are shown in Figure 5-b. The strains indicate that some of the reinforcement yielded during the static load tests.

Conclusion. An experimental study of the behaviours of reinforced concrete slabs under high-mass low-velocity impact loads and static loads was undertaken. Transient measurements of impact force, load capacity-deflection of static loads, accelerations of the slabs, and the reinforcement strain were thus presented.
1. Slab tests have confirmed that slab thickness has more influence on the impact force than the height or mass of the dropped load.
2. Acceleration increases as the slab thickness decreases due to related decreases in slab stiffness.
3. Increasing slab thickness influences static load capacity and decreases ductility.
4. The impact tests revealed the importance of inertia forces. According to the force-time histories produced by these tests, the resistance to impact forces in the initial phases is generated by the inertial forces of the slabs.

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