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Experimental Study of Reinforced Concrete Slabs under Different Loading Rates

by Yao Xiao, Bing Li, and Kazunori Fujikake

Eighteen reinforced concrete (RC) slabs were manufactured and tested under static (0.0004 m/s [0.0013 ft/s]), medium (0.4 m/s [0.13 ft/s]), and high (2 m/s [6.6 ft/s]) rates of concentrated loading at slab center using a displacement-controlled rapid-loading machine. The data from the experiment were used to study the effects of loading rates and other parameters (such as slab depth and longitudinal and shear reinforcement ratios) on the performance of RC slabs. From test results, the load-carrying and energy absorption capacities of specimens, inertial force, and strain rate were found to increase with higher loading rates. Shear reinforcement was found to be more effective than longitudinal reinforcement in enhancing slab's performance under a high loading rate. The failure modes of specimens were governed by punching shear irrespective of loading rate. Additionally, another six slabs were made and tested under low-velocity (5.425 m/s [17.8 ft/s]) impact using a drop-weight machine. A comparison between the results from high loading rate and impact tests indicates similar damage process, failure mode, strain rate, and energy absorption capacity. This comparison well correlates a high-loading-rate test with impact testing, which suggests the possibility of using high load rate test to help understand slab's performance under low-velocity impact.

Keywords: dynamic behavior; impact; loading rate; reinforced concrete slab.

INTRODUCTION

Reinforced concrete (RC) structures may experience various kinds of dynamic loadings such as earthquake, impact, or blast. These types of dynamic loadings can lead to different loading rates on structure and result in dynamic structural response which is different from static. For example, the maximum strength, cracking patterns and failure modes of structures may change under different loading rates.^{1,2} Strain rate effects on concrete and steel and participation of inertial forces are the two main reasons for the mentioned differences. Both concrete and steel reinforcement are strain rate-sensitive materials whose properties are influenced by their strain rates.³⁻⁶ RC structures may also gain acceleration and inertial force under dynamic loads. As a result, it is very important to understand the effect of loading rate on the behavior of reinforced concrete structures and its relation with strain rate and inertial effect.

Early experimental investigations mainly focused on the influence of loading rate on the behavior of RC beams. For example, Mutsuyoshi and Machida,¹ Kulkarni and Shah,⁷ Fujikake et al.,⁸ and Adhikary et al.⁹⁻¹¹ carried out a series of tests on RC beams with the loading rate ranging from 0.0000071 to 2 m/s (0.000023 to 6.6 ft/s). For RC slabs, the available experimental data is considerably less. One well documented experiment was conducted by Saito et al.,¹² who tested seven types of RC slabs with static (0.00003 m/s [0.000098 ft/s]), low (0.03 m/s [0.098 ft/s]), and high (3 m/s

[9.8 ft/s]) loading rates. From the experiment, Saito et al.¹² found the load-carrying capacity of slabs increases together with loading rate, and attributed the enhanced strength to the strain rate effect on concrete and steel. However, Saito et al.'s¹² experiment did not provide information on strain rate and inertial force during test. For the purposes of gaining more understanding in this field, an experimental program was carried out to investigate slab behavior under different loading rates. Emphasis was placed on the influence of loading rate on slab response, and in contrast with Saito et al.'s¹² work, on investigating the induced strain rate and inertial effect.

It is well-known that by carefully choosing the loading rate, tested specimen can reach a similar strain rate as that induced under impact load, which implies the possibility of using the displacement-controlled high-loading-rate test to help study impact problems. Compared with the impact test,¹³⁻¹⁷ the displacement-controlled high-loading-rate test has a distinct advantage in obtaining the load-displacement curve of tested specimens, which is essential for assessing the specimen's load and energy capacities. Therefore, a low-velocity impact experiment was also conducted and compared with the high-loading-rate experiment to investigate their correlations.

RESEARCH SIGNIFICANCE

The performance of RC slabs under a wide range of loading rates was evaluated in the present study. The load-carrying and energy absorption capacities and failure mechanism of slabs obtained from this research will be useful for engineers to understand the dynamic behavior of RC slabs. The evaluated inertial effect and strain rate can also facilitate the development and verification of analytical or numerical models. Moreover, a comparison study between high loading rate and impact tests was conducted and the observed similarities suggested the possibility of using high-loading-rate test to help study low-velocity impact problems.

EXPERIMENTAL INVESTIGATION

Specimens

Six types of 1200 mm (47.2 in.) square reinforced concrete slabs with different longitudinal reinforcement ratios (from 0.25 to 0.66%), shear reinforcement ratios (from 0 to 0.56%), and slab depths (100 and 150 mm [3.9 and 5.9 in.]) were designed for the experimental program. For each type of

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Table 1—Summary of slab specimens

Specimen	Slab thickness, mm (in.)	Compressive strength of concrete, MPa (ksi)	Longitudinal reinforcement	Shear reinforcement	Flexure capacity, kN (kip)	Shear capacity, kN (kip)	Expected failure mode	Observed failure mode
I-10-0.59	100 (3.9)	42.9 (6.2)	T10	—	161 (36)	140 (32)	Shear	Shear
I-15-0.25	150 (5.9)	42.9 (6.2)	T8	—	134 (30)	266 (60)	Flexure	Shear
I-15-0.39	150 (5.9)	45.0 (6.5)	T10	—	268 (60)	266 (60)	Shear	Shear
I-15-0.66	150 (5.9)	42.9 (6.2)	T13	—	462 (104)	266 (60)	Shear	Shear
I-15-0.39-0.14	150 (5.9)	42.3 (6.1)	T10	R6	268 (60)	326 (73)	Flexure	Shear
I-15-0.39-0.28	150 (5.9)	42.3 (6.1)	T10	R6	268 (60)	416 (94)	Flexure	Shear

Fig. 1—Details of slab specimens: (a) reinforcement layout of slab specimens; and (b) geometrical details of typical shear reinforcement.

design, four slabs were made for static-loading-rate, medium-loading-rate, high-loading-rate, and low-velocity impact tests. The specimen details are summarized in Table 1 and their reinforcement layouts are shown in Fig. 1. Twenty-four 20 mm (0.79 in.) diameter holes were made with PVC pipes on four sides of each slab, which were used for fixing the slab into the test support with bolts. Each type of slab was named by its thickness (cm) and longitudinal and shear reinforcement ratios. For example, 10-0.59 means the slab is 10 cm (3.9 in.) thick with a longitudinal reinforcement ratio of 0.59%, but no shear reinforcement; 15-0.39-0.28 means the slab is 15 cm (5.9 in.) thick and its longitudinal reinforcement ratio and shear reinforcement ratio are 0.39 and 0.28, respectively. When calculating the shear reinforcement

ratio, the marginal slab area without shear reinforcement was excluded and the slab area was taken as 780 x 780 mm (30.7 x 30.7 in.). Due to the large quantity, the 24 specimens were cast in three batches. For each time of slab casting, three 150 mm (5.9 in.) diameter and 300 mm (11.8 in.) height concrete cylinders were casted with the same concrete. These cylinders were then tested at 28 days and average compressive strengths were 45.0, 42.9, and 42.3 MPa (6.5, 6.2, and 6.1 ksi) for the three batches.

All slabs share the same kind of longitudinal reinforcement layout. T8, T10, and T13 reinforcing bars were used as longitudinal reinforcements to produce different longitudinal reinforcement ratios. R6 reinforcing bar was used as shear reinforcement. Three pieces of steel bars were tested

Fig. 2—Test setup: (a) rapid loading machine; (b) drop-weight system; and (c) supporting system.

Table 2—Properties of reinforcing bars

Reinforcing bar	Diameter, mm (in.)	Yield strength, MPa (ksi)	Ultimate strength, MPa (ksi)
T8	8 (0.31)	443 (64.3)	504 (73.1)
T10	10 (0.39)	576 (83.6)	655 (95.1)
T13	13 (0.51)	605 (87.8)	690 (100.1)
R6	13 (0.51)	282 (40.9)	392 (56.9)

using a tensile test machine for each type of reinforcing bar. The properties of the steel bars are summarized in Table 2. To predict the failure mode of specimens during static test, the flexure resistance capacities of slabs were estimated using yield line theory, and the shear resistant capacities of slabs were evaluated according to ACI 318-08.¹⁸ The estimated slab capacities and failure mode are summarized in Table 1.

Experimental procedure and test setup

The experimental program was divided into two phases. In phase one, the six types of specimens described in the last part were tested under static loading rate (0.0004 m/s [0.0013 ft/s]), medium loading rate (0.4 m/s [0.13 ft/s]), and high loading rate (2 m/s [0.66 ft/s]); each test was identified by adding the loading rate (S/M/H) in front of the specimen's name. The slabs were loaded by the rapid loading machine shown in Fig. 2(a). A 200 mm (7.9 in.) diameter circular loading plate was placed in the center of the tested slab to increase the loading area of rapid loading machine. The maximum loading displacement was fixed at 7 cm (2.8 in.) for all the tests.

In phase two, the low-velocity impact experiment was carried out. During the impact test, the six types of specimens were impacted using the free drop machine shown in Fig. 2(b). The drop height of the drop hammer was 1.5 m (4.9 ft) and the corresponding impact velocity was 5.425 m/s (17.8 ft/s). For comparison purpose, a 500 kg (1102 lb) drop hammer with 200 mm (7.9 in.) diameter flat nose was used to impact the center of the slab specimen and the impacted area on the slab is the same as the loading area of the rapid loading test. To differentiate the impact test from rapid loading test, each impact test was identified by adding "I" in front of the specimen's name.

The same supporting system shown in Fig. 2(c) was used for static-/medium-/high-loading-rate testing and impact testing. A 1200 x 1200 mm (47.2 x 47.2 in.) size steel support was constructed using a series of H steel beams which were fixed into the strong floor with high-tension bolts. Four thin steel plates with a width of 100 mm (3.9 in.) and length of

Fig. 3—Arrangement of displacement sensors and accelerometers.

980 mm (38.6 in.) were installed above the H beams and the clean slab span was 1000 mm (39.4 in.). The specimen was bolted to the support with 24 high tension bolts. The diameter of the high-tension bolts is 18 mm (0.71 in.), which is 2 mm (0.08 in.) less than the diameter of the holes left on the slab specimens. Therefore, the friction between slab and bolts can be ignored. On top of the slab, twenty-four 100 mm (3.9 in.) square steel plates were installed together with the bolts to confine the top surface of the specimen.

Instrumentation

Various kinds of sensors were installed to monitor the experiment. In the static-/medium-/high-loading-rate test, a load cell with the capacity of 980 kN (220 kip) was installed to the rapid loading machine to record the load. Two laser-type displacement sensors were installed to capture the displacement distribution of slab during test. Four accelerometers with the capacity of 1000 times gravity were installed to capture the acceleration distribution of slabs. The arrangement and designation of these sensors are given in Fig. 3. All these sensors were mounted to measure the response of slab's top surface. Moreover, 12 strain gauges were installed at both top and bottom layers of reinforcement mats. Four additional strain gauges were installed in the shear reinforcement for

Fig. 4—Load-displacement curves.

those slabs with stirrups. The arrangement and designation of strain gauges is shown in Fig. 1.

During the impact test, two changes were made on the above instrumentation plan. First, because there is no load cell on the impact machine, two accelerometers were attached to the dropping hammer to record the acceleration history of the hammer, which can be used for calculating impact force history. Moreover, due to safety consideration of equipment, the D2 displacement sensor was relocated to D2' positions. The arrangement of other sensors was exactly the same as static-/medium-/high-loading-rate test.

EXPERIMENTAL RESULTS AND DISCUSSION OF STATIC-, MEDIUM-, AND HIGH-LOADING-RATE TESTS

Load-displacement relationship

The load-versus-loading point displacement curves of different specimens are shown in Fig. 4. The cable of data logger was cut off during test M-15-0.25, and its corresponding result was not recorded. Therefore, the response of test M-15-0.25 is not reported in this paper. It is obvious that a higher loading rate would lead to a higher maximum load-carrying capacity of specimen. The maximum strengths and dynamic amplification factors (DAF, defined as the ratio

of a specimens' maximum strength at any loading rate to its maximum static strength) of tested specimens are summarized in Fig. 5. The maximum strengths of specimens are enhanced by 15 to 54% at medium loading rate and 42 to 73% at high loading rate comparing with their static strengths. The average dynamic amplification factor under medium loading rate and high loading rate were calculated to be 1.3 and 1.5, respectively. Studying the result, it was found that specimens with more longitudinal reinforcement have bigger DAFs than those specimens with less longitudinal reinforcement. For example, Specimen 15-0.66 has the largest DAFs of 1.52 and 1.7 under medium and high rate loadings. Comparatively, Specimen 15-0.25 has the smallest DAF of 1.3 for high loading rate.

During all tests, the load on the slab increased sharply when the slab was initially loaded and quickly reached its maximum value with limited displacement. Additionally, the stiffness of specimens during this stage was found to increase as loading rate increases, and this phenomenon becomes obvious during high-loading-rate tests where the stiffness of the specimen is much higher than those loaded statically. After reaching the maximum load, the responses of slabs can be categorized into two kinds depending on whether they have shear reinforce-

Fig. 5—Maximum strength and DAF. (Note: 1 m/s = 3.28 ft/s.)

Fig. 6—Energy absorption capacity and DEAF. (Note: 1 m/s = 3.28 ft/s.)

ment or not. For slabs without shear reinforcement, their loads fell suddenly to very low values after peak point which imply shear failure mode. After that, their residual strengths began to increase again at a very low rate and finally reached their second peaks. For slabs with shear reinforcement, although shear failure mode was still dominant, a much more ductile behavior could be observed than those without shear reinforcement. Their loads dropped more mildly and maintained relatively high magnitudes of residual strengths at large displacement compare with specimens without shear reinforcement.

Energy absorption capacity

In addition to load-carrying capacity, energy absorption capacity is another important specimen property which enables assessment of the performance of slab from an energy aspect. The energy absorption capacity of a slab specimen can be easily obtained by defining a failure criteria and integrating its load-displacement curve.

Shear failure mode was found on all the specimens during the conducted experiment. Specimens are considered as failed once their strengths dropped below 80% of their maximum load-carrying capacity. The energy absorption capacities of slabs are calculated by integrating their load-displacement curves until shear failure points. The energy absorption capacity of a slab and the corresponding dynamic energy amplification factor (DEAF, defined as the ratio of specimens' energy absorption capacity at any loading rate to its static energy absorption capacity) are given in Fig. 6. It can be observed that an increase in any of the slab's thickness, longitudinal reinforcement ratio, or shear reinforcement ratio can improve the energy absorption capacity of slab. Shear reinforcement ratio is the most effective among them because it not only provides extra shear resistance, but also enhances the rigidity of slab through its confining effect. The energy absorption capacity of

slab also increases with increasing loading rate. The dynamic energy amplification factor of the tested specimens ranges from 1.23 to 1.94 for medium loading rate and 1.83 to 2.79 for high loading rate. On average, slab's DEAFs were calculated to be 1.56 for medium loading rate and 2.34 for high loading rate.

Inertial effect

To assess the inertial effect of slabs under different loading rates, the measured acceleration data were used to evaluate the generated inertial force of slab. A simple integration approach is proposed to fully use the recorded acceleration points to estimate the inertial force of slab. As shown in Fig. 3, a quarter of the slab is divided into four tributary integration areas according to the positions of accelerometers. For area I1, a uniformly distributed acceleration is assumed with the value of the A1 sensor. For each of the remaining fan areas, the acceleration is assumed to have a linear distribution and the values of its inner or outer boundary is the same as the accelerometer that installed in the boundary. Zero acceleration was assumed in the supported regions and slab corners. By assuming symmetric slab acceleration distribution, the inertial force of slab can be calculated by summing the integrated inertial forces of the four tributary areas and multiplying this sum by 4. Similar inertial force history was found for all specimens under the same loading rate. Therefore, the measured acceleration data and calculated inertial forces of test M-15-0.39 and H-15-0.39 are given in Fig. 7 to show the typical inertial force history. The maximum inertial forces (absolute value) are summarized in Table 3.

For medium-loading-rate tests, inertial force becomes significant during the period when the specimen's strength is reducing. In most instances, the inertial force is too small to affect the slab response and the measured load force. Comparatively, large and widespread inertial forces

Fig. 7—Acceleration histories and integrated inertial force histories (Specimen 15-0.39). (Note: $1g = 9.81 \text{ m/s}^2 = 32.2 \text{ ft/s}^2$.)

are found during high-loading-rate tests. Due to the high velocity of the loading plate, the slab was accelerated downward and upward (negative) inertial force was generated at very early loading stage. Accordingly, the slab stiffness is exaggerated by the generated inertial force. In the region where the slab reaches its maximum strength, the whole inertial force comprises a small amount of upward inertial force in the loading area (A1) and large amount of downward inertial force in the remaining area (A2, A3). It should be noted that the downward inertial force is not induced by the loading plate, but by the restoring force in those areas. Because the link between loading area and its surroundings was severely weakened due to the formation process of punching shear cone, the downward inertial force in the surrounding areas was more likely to be balanced by the support reaction force and may not effectively interrupt the measured maximum strength. However, the available experimental data is not enough to quantify the exact influence of the observed downward inertial force on the measured load.

Deflected shapes

In this section, the displacement history measured by Sensors D1 and D2 were used to plot the deflected shape along the midline of slab. Uniform displacement distribution with the value measured by D1 is assumed in the loading area and zero displacement is assumed in the supported region. By assuming symmetric displacement response of slab, the deflected shape can be plotted via linking the data points with straight lines. Figure 8 shows the deflected shapes of Specimen 15-0.39 during static-, medium-, and high-loading-rate tests. For each loading rate, a new deflected shape was plotted every time a slab's middle point moved 2 mm (0.08 in.). Obvious punching shear failure mode can be observed from the deflected shapes of Specimen 15-0.39, irrespective of loading rate. The exact shear failure points are characterized by the rebound of unloaded slab area which indicate the full

Table 3—Maximum inertial forces

Specimen	Medium loading rate		High loading rate	
	Maximum inertial force, kN (kip)	Corresponding midspan displacement, mm (in.)	Maximum upward inertial force, kN (kip)	Corresponding midspan displacement, mm (in.)
10-0.59	50 (11.3)	13.9 (0.55)	102 (23.0)	1.0 (0.04)
15-0.25	—	—	186 (41.9)	0.67 (0.026)
15-0.39	62 (14)	10.3 (2.32)	136 (30.6)	0.85 (0.033)
15-0.66	57 (12.8)	7.9 (1.78)	129 (29.1)	0.69 (0.027)
15-0.39-0.28	33 (7.4)	55.5 (12.5)	136 (30.6)	0.65 (0.026)
15-0.39-0.56	60 (13.5)	64.7 (14.6)	126 (28.4)	0.55 (0.022)

formation of punching shear cone and its separation with nearby concrete. The same failure mode was found for all the remaining specimens by observing their deflected shapes. By summarizing the failure points of all the specimens, it was found that the punching shear failure usually happens slightly after reaching a specimen's maximum strength and the corresponding failure strengths ranged from 60 to 99% of specimen's maximum strength. This result verifies the shear failure criteria (80% of specimen's maximum strength) proposed earlier for assessing a specimen's energy absorption capacity.

Strain, failure mechanism, and corresponding strain rate

To illustrate strain development and corresponding failure mechanism, the strain histories of selected date points along the midline of Specimen 15-0.39 under different loading rates are plotted in Fig. 9. Similar strain histories can be seen in spite of loading rate. Rapid tensile strain increase and yielding of bottom reinforcement can be observed at a very early loading

Fig. 8—Deflected shapes under different loading rates (Specimen 15-0.39).

stage (about 2 mm [0.08 in.] midpoint displacement). Yielding points are found in the sequence of B1, B2, and B3 which means a gradually globalized response of bottom reinforcement. Meanwhile, the strain of the top reinforcement is still small and no yielding point can be found due to the limited slab deformation. Accompanied with a further increase of displacement, the strength of the specimen continues increasing despite the yielding of bottom reinforcement, indicating the extra strength is mainly contributed by concrete. As discussed earlier, a fully formed punching shear cone and punching shear failure happens just after specimen reaches its maximum strength. A sudden drop of tensile strain of both bottom and top reinforcements can be found at the same time. After that, the loading plate continues its movement and the strain of reinforcement increases again. Yielding of top reinforcement also happens during this period. Because concrete of loading area has failed already at this stage, the residual strength of specimen is solely controlled by reinforcement. Similar strain histories are found in a slab's diagonal direction. By analyzing all the collected strain data, it is found that all kinds of specimens share the same type of strain behavior and failure mechanism described earlier. Additionally, by studying strain histories of shear reinforcements of those slabs with stirrups, it is found that the yielding of shear reinforcement usually happens when a specimen reaches its maximum strength, which proves the effectiveness of shear stirrups in enhancing slab's punching shear strength. Based on earlier discussion, the general failure process of slabs is sketched in Fig. 10.

The strain rates of reinforcement were calculated by differentiating corresponding strain histories in the time domain. The maximum strain rates of B1/B4 data points of all the tested specimens are summarized in Table 4. The results show that the maximum strain rate is strongly affected by loading rate. The average maximum strain rates are 0.75 s^{-1} and 4.35 s^{-1}

for medium- and high-loading-rate tests. For the purpose of providing more detailed information on the relation between loading rate and strain rate. The distribution of strain rates of T1, T2, B1, and B2 of Tests S-15-0.39, M-15-0.39, and H-15-0.39 are also plotted in Fig. 9. It was found strain rate increases in a whole scale when loading rate increases. The strain rate of medium- and high-loading-rate tests are mainly distributed in the order from 10^{-3} s^{-1} to 10^0 s^{-1} . It is generally accepted that strength enhancement effect on both steel and concrete becomes significant when strain rates go beyond 10^{-2} s^{-1} . Accordingly, it can be concluded that the strain rate effect plays an important role in boosting the strengths of the tested specimens under medium- and high-loading-rate tests. However, further analytical evaluation using the recorded strain rate data needs to be conducted to quantify the exact contribution of strain rate effect to the observed strength increase.

Crack pattern and damage

All the specimens were observed to share the same type of damage and crack development mode as shown in Fig. 11. On the front surface, except for a hole drilled by the loading plate in the loading area, the remaining slab area is nearly intact and no crack can be observed. On the bottom surface, radial and circumferential cracks can be found, which are indicative of slab's flexure and punching shear behaviors respectively. Obvious concrete scabbing can be seen at the bottom surface, which mainly initiates between outmost circumferential crack and the loading area. The concrete of the loading area is found to be fully separated from nearby concrete and forms a punching shear cone. The punching shear cone is severely cracked but still manages to hang on to the reinforcements. It is believed that at the final loading stage, the punching shear cone is too weak to transfer large amount of load to bottom reinforcement. By observing the exposed steel bars, global-

Fig. 9—Strain histories and corresponding strain rate under different loading rates (Specimen 15-0.39).

Table 4—Maximum strain rate of B1/B4 data point

Specimen	Static loading rate, s^{-1}	Medium loading rate, s^{-1}	High loading rate, s^{-1}	Impact, s^{-1}
10-0.59	0.0015	0.33	6.3	9.15
15-0.25	0.0010	—	4	5.01
15-0.39	0.0029	0.95	3.06	5.85
15-0.66	0.0018	0.85	3.18	2.65
15-0.39-0.28	0.0008	0.36	6.5	5.4
15-0.39-0.56	0.0026	1.27	3.07	4.8

ized bending is found on bottom reinforcements. Comparatively, the deformation of top reinforcement is centralized in the loading area. However, the top steel reinforcement in the loading area is more severely bent than bottom reinforcement and fracture of top reinforcing bar is found in Test M-10-0.59.

The final damages of various specimens under high loading rate are presented in Fig. 12. Not much difference in final damage status can be seen when comparing specimens with different depth and longitudinal reinforcement ratios.

However, shear reinforcement is observed to be effective in reducing concrete scabbing.

EXPERIMENTAL RESULTS OF IMPACT TEST AND COMPARISON TO HIGH-LOADING-RATE TEST

Crack patterns and damage

As shown in Fig. 13, the specimens tested under impact loading were found to have very similar crack pattern and damage style compared to those under high-loading-rate testing. On the front surface, the loading area of a specimen was penetrated by the loading hammer while remaining area is nearly undamaged. The penetration depths of impacted specimens were measured after testing and summarized in Table 5. Taking Test I-15-0.39 as reference, the penetration depth increased by 26% and 71% for Tests I-15-0.25 and I-10-0.59, respectively, and reduced by 33%, 78%, and 94% for Tests I-15-0.66, I-15-0.39-0.28, and I-15-0.66, respectively. On the bottom surface, radial and circumferential cracks were found on all specimens. For specimens without shear reinforcement, circumferential cracks were fully developed. Concrete scabbing initiated along these circumferential cracks

Fig. 10—General failure process of slabs: (a) yielding of bottom reinforcement and global slab response at very early loading stage; (b) shear failure and full formation of punching shear cone just after reaching slab's maximum strength; and (c) residual strength of slab is mainly contributed by steel reinforcement.

Fig. 11—Typical damages on top and bottom surfaces of slab (Specimen 15-0.66).

and steel bars were exposed. For Test I-15-0.39-0.28, circumferential cracks formed as well. However, only light concrete scabbing happened in a limited area and no steel bar was exposed. The damage to the specimen in Test I-15-0.39-0.28 was quite limited in that diagonal flexural cracking dominated the crack pattern and no concrete scabbing could be observed.

Using the same method described earlier in the high-loading-rate test, the deflected shapes of specimens during impact testing are plotted using data collected from displacement sensors. For discussion purpose, the deflected shapes in Tests I-15-0.66 and I-15-0.39-0.56 are presented in Fig. 14. The exact punching shear failure point defined previously in the high-loading-rate test is the full formation of the punching shear cone, which is characterized by reversed movement between the loading area and its surroundings. The same principle is used for impact tests to determine whether punching shear failure happens during test. It can be seen that the unloaded area of Test I-15-0.66 reaches its maximum deformation and begins to rebound at 2.8 ms. In the meantime, the loading area continues its downward movement at a relatively high rate. The same behavior is found in Tests I-10-0.59, I-15-0.39, and I-15-0.66. Therefore, these slabs can be considered as failed. For Test I-15-0.39-0.56, loaded and unloaded areas reach their maximum displacement at 5.9 ms and begin to rebound together. Therefore, Test I-15-0.39-0.56 did not fail during the test. The loaded and unloaded areas of Test I-15-0.39-0.28 also reached their maximum displacement at nearly the same instant. However, a 2.5 ms lag is found between the rebound times of load and unloaded areas. Although this specimen is not failed, this phenomenon indicates the severely weakened link between the loaded and unloaded regions.

Absorbed energy

The absorbed energy of specimens during impact testing is calculated according to the impact and rebound velocities of the dropping hammer. The rebound velocity is obtained by differentiating the recorded displacement history of the dropping hammer. The absorbed energy together with

Fig. 12—Damage to bottom surface of slabs tested under high-rate loading.

Table 5—Summary of impact experiment

Test	PD, mm (in.)	V_i , m/s (ft/s)	V_r , m/s (ft/s)	E_a , J (ft·lbf)	E_c , J (ft·lbf)	E_a/E_c	Estimated punching shear failure	Observed punching shear failure	$F \cdot t$, N·s (lbf·s)	$M \cdot \Delta V$, kg·m/s (lbf·s)
I-10-0.59	46.3 (1.82)	5.425 (17.8)	0.956 (3.14)	7129 (5257)	3368 (2484)	2.12	Fail	Fail	3300 (742)	3190 (717)
I-15-0.25	33.9 (1.33)		0.744 (2.44)	7219 (5324)	3937 (2903)	1.83	Fail	Fail	3134 (705)	3085 (694)
I-15-0.39	27.0 (1.06)		1.216 (3.99)	6988 (5153)	4185 (3086)	1.67	Fail	Fail	3391 (762)	3321 (747)
I-15-0.66	18.0 (0.71)		1.256 (4.12)	6963 (5135)	4477 (3302)	1.56	Fail	Fail	3489 (784)	3341 (767)
I-15-0.39-0.28	6.0 (0.24)		1.186 (3.89)	7006 (5167)	8139 (6002)	0.86	Not fail	Not fail	3354 (754)	3306 (743)
I-15-0.39-0.56	1.7 (0.07)		1.698 (5.57)	6637 (4895)	12907 (9518)	0.51	Not fail	Not fail	3703 (832)	3562 (800)

Notes: PD is penetration depth; V_i is impact velocity; V_r is rebound velocity; E_a is absorbed energy; E_c is energy absorption capacity (from high-loading-rate test); $F \cdot t$ is impulse; and $M \cdot \Delta V$ is change of momentum of drop hammer.

Fig. 13—Damage to bottom surface of slabs tested under impact loading.

Fig. 14—Comparison of deflected shapes between slab without reinforcement (Test I-15-0.66) and slab with reinforcement (Test I-15-0.39-0.56).

other experimental details are also presented in Table 5 and compared with the energy absorption capacities of slabs under high-loading-rate testing. It is found that the punching shear failure of specimens under impact loading is well-predicted using the energy absorption capacity of specimens tested under high loading rate.

Strain and corresponding strain rate

By examining the recorded strain histories, it was found that the strain behavior and damage process of impacted specimens are nearly the same as the specimens tested during the high-

loading rate test. Yielding of bottom reinforcements happened in all specimens at the very beginning of impact. For specimens without shear stirrups, yielding of top reinforcements was observed after punching shear failure point. For specimens with shear reinforcements, no yielding of top reinforcement was found due to the limited deformation and penetration depth.

The maximum strain rates of impact tests are listed in Table 4 and compared with the maximum strain rates of the high-loading-rate test. Additionally, the strain rate distribution of Tests H-15-0.39 and I-15-0.39 are plotted in time domain in Fig. 15. It was found that the maximum strain

Fig. 15—Comparison of strain rate distribution between high-loading-rate test (H-15-0.39) and impact test (I-15-0.39).

Fig. 16—Impact force and inertial force during impact test.

rates of the impact test and the high-loading-rate test are in the same order of 10^0 s^{-1} . Moreover, the strain rates of both tests are mainly ranged from 10^{-2} s^{-1} to 10^0 s^{-1} . The similarity in strain rate between impact test and high-loading rate tests indicates similar strain rate effect on specimen materials.

Impact force and inertial effect

As mentioned earlier, two accelerometers were attached to the drop hammer. The impact force history was then calculated by multiplying the measured acceleration history with the mass of drop hammer. Additionally, the inertial force of specimen during impact test was calculated using the same

integration method of rapid loading test illustrated earlier. The impact force history and corresponding inertial force are given in Fig. 16. For all the specimens, impact force and inertial force rose immediately and reached their maximum values at the very beginning of impact. After that, the impact force reduced and formed a long tail. Accompanied with the reduction of impact force, inertial force also dropped and gradually dissipated. Compared with the high-loading-rate test, the induced inertial force under impact load was more significant and interruptive which made it very difficult to directly relate the measured impact force with the true resistance of slab.

The impulse of each impact test was evaluated by integrating the corresponding impact force history. Additionally, the change of momentum of the drop hammer during each test was calculated using the drop hammer's mass and impact and rebound velocities. The impulse and change of drop hammer's momentum are listed in Table 5. It can be seen that in each test, the impulse is nearly same as the change in the momentum of drop hammer.

CONCLUSIONS

The results of this study support the following conclusions:

1. Both load-carrying and energy absorption capacities of RC slabs are found to increase when the loading rate increases. Higher loading rate can also lead to higher specimen stiffness at initial loading stage. The maximum strain rate approximately increased 100 times from static loading rate to medium loading rate and another 10 times from medium loading rate to high loading rate. Inertial force also rises when loading rate increase. However, the inertial effect did not become significant until a high loading rate.

2. Punching shear failure mode was observed for all the specimens that failed during experiment irrespective of loading rate and loading type. A similar damage process was found for both high loading rate test and impact test. Yielding of bottom reinforcement happens at very early loading stages. The punching shear failure of specimens is evident from the full formation of punching shear cone and its separation with nearby concrete. The residual strength of slab is mainly contributed by top reinforcements whose yielding usually happened after punching shear failure.

3. Both longitudinal and transverse reinforcements are effective in enhancing the maximum strength of specimens. However, the benefits to a slab's energy absorption capacity and impact resistance made by longitudinal reinforcement are limited compared with shear reinforcement. The experimental results show that the damage of slab under both high-rate and impact loadings can be efficiently reduced by adding shear stirrups.

4. Similar crack patterns, damage, and failure processes of specimens were found through the comparison between high-loading-rate testing and impact testing. Additionally, similar strain rates were observed not only in maximum value but also on an average level, which would lead to similar strain rate effects on specimen's materials. The punching shear failure of impacted slabs was very well-predicted using the energy absorption capacities from the high-loading-rate test. In sum, the high-loading-rate test can produce similar slab behavior and strain rate as a low-velocity impact problem. The load and energy capacities of slabs can be easily and accurately obtained from displacement controlled high loading rate test. The high-loading test can be considered a supplementary approach for studying impact problem.

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