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Behavior of Reinforced Concrete Slabs under Low-Velocity Impact

by Yao Xiao, Bing Li, and Kazunori Fujikake

Fifteen 1200 x 1200 x 150 mm (47.2 x 47.2 x 5.9 in.) reinforced concrete (RC) slabs were tested under low-velocity impact loadings. These slabs were fixed on their four sides and vertically impacted by a drop-weight system. The influences of impact energy, diameter of impacted area, and nose shape of impactor on the damage of RC specimens are studied. The damage of slabs under low-velocity impact increases with increasing impact energy. Moreover, punching shear failure mode was observed for all the specimens that failed during the test. Besides experimental work, three-dimensional (3-D) finite element (FE) analysis was conducted using the LS-DYNA software to help determine the impact energy that would cause punching shear failure of RC slabs. In the FE model, 3-D elements with strain-rate-sensitive material models were used to model concrete and steel reinforcement. The support and impactor were idealized as rigid body. Based on the results from FE analysis, two dimensionless empirical equations are proposed in term of various parameters to assess the energy capacity of slab under low-velocity impact.

Keywords: energy capacity; low-velocity impact; LS-DYNA; reinforced concrete slab.

INTRODUCTION

Reinforced concrete (RC) structures may be subjected to impacts at low velocities during their service lives. Typical scenarios include impact from debris brought by tsunami or flood, impact from falling objects during earthquake, collision from vehicles, and so on. The impact load, which is characterized by the application of a force of short duration but high intensity,¹ can generate high strain rate, significant inertial effect, and stress wave on RC, thereby leading to a dynamic structural response that is different from the static performance of structures. Therefore, it is important to understand the behavior of RC structures subjected to impact loading to facilitate the corresponding design and evaluation works.

Most past research on the impact problem of RC slabs focuses on high-velocity impact (impact velocity > 100 m/s [328 ft/s]). For example, Dancygier et al.² and Sugano et al.^{3,4} experimentally studied the damage of RC slabs under high-velocity impact. Ågårdh and Laine⁵ used the finite element (FE) method to numerically study the performance of RC slabs under high-velocity impact. In these studies, localized behaviors such as spalling of concrete, scabbing of concrete, local penetration, and perforation were found to dominate slab response. Based on the experimental database of high-velocity impact, a number of empirical equations for evaluating localized damage indexes such as penetration depth, scabbing limits, and perforation limits were proposed.⁶⁻⁸ When it comes to low-velocity impact (impact

velocity < 15 m/s [49 ft/s]) on RC slabs, limited studies are available. Zineddin and Krauthammer⁹ tested nine 3353 x 1524 x 90 mm (132 x 60 x 3.5 in.) RC slabs under impact loads with the impact velocities range from 1.7 to 3.5 m/s (5.6 to 11.5 ft/s). Chen and May¹⁰ tested four 800 x 800 x 76 mm (31.5 x 31.5 x 3 in.) and two 2300 x 2300 x 150 mm (90.6 x 90.6 x 5.9 in.) RC slabs under impact loads with the impact velocities range from 6.5 m/s to 8.7 m/s (21.3 to 28.5 ft/s). Eight 1800 x 1800 x 130 mm (70.9 x 70.9 x 5.1 in.) fiber-reinforced RC slabs were tested by Hrynyk and Vecchio¹¹ under 8 m/s (26.2 ft/s) impact loads. In addition to local behavior, obvious global behavior was also observed during these low-velocity impact tests. Despite the contribution of these works, the current experimental database is still limited for gaining a comprehensive understanding on this field. Therefore, to gain a greater understanding of the behavior of RC slabs subjected to low-velocity impact, an experimental program was designed and conducted. Both the local and global behaviors of slabs are presented and discussed. The induced strain rate and inertial effect are presented as well. In addition, influences of the diameter and nose shape of impactor, impact energy, and impact momentum on slab response are also examined.

The evaluation of the maximum load-carrying capacity of RC members under impact loading has long been a challenge for engineers. In some research, the maximum impact force or maximum support reaction force were related with the load-carrying capacity of tested specimens.^{12,13} However, both impact and support reaction forces obtained from impact test comprise large amount of inertial force, and therefore cannot accurately represent the actual load-carrying capacity of slab. On the other hand, determining the energy capacity of RC members under impact has also achieved limited success as the impact energy needs to be gradually adjusted through a series of trial tests to determining the exact impact energy that could fail the designed specimen. In some past studies, the RC targets were impacted repeatedly until failure with relatively small impact energies and the corresponding impact energy capacity was calculated by summing up the impact energies of these repeated impacts.^{14,15} However, this method tends to overestimate the energy capacity of RC members, as during each impact, a portion of impact energy was dissipated through structural damper without causing damage to the specimen. There-

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fore, considering the difficulty of experimentally assessing the energy capacity of tested specimens, a 3-D nonlinear FE analysis was performed using the LS-DYNA software. The proposed modeling method is first verified with the experimental results and then been used for a series of parametric studies. To evaluate the energy capacity of RC slabs under low-velocity impact, the impact energy is gradually adjusted during the analysis to find the amount of impact energy that just enough to fail the modeled RC member.

RESEARCH SIGNIFICANCE

Current understanding of the behavior of RC slabs subjected to low-velocity impact is still limited. In this paper, an impact experimental program is conducted to study

Fig. 1—Size and reinforcement layout of slab specimens.

the effects of impact energy, impactor's diameter, and nose shape on slab damage and response. These test results and corresponding discussion can enhance the understanding of the behavior of RC slabs under impact loading. Additionally, an FE analysis is conducted to investigate the influences of various parameters on the energy capacities of RC slabs. Empirical equations are proposed for predicting the energy capacity of RC slabs. The FE analysis and the proposed empirical equations can shed some light on evaluating the damage of RC slabs under impact loading.

EXPERIMENTAL INVESTIGATION

Specimens and material property

Fifteen RC slabs with the design shown in Fig. 1 were made for this experimental program. These 1200 mm (47.2 in.) square, 150 mm (5.9 in.) thick slabs were doubly reinforced with 10 mm (0.39 in.) diameter reinforcing bars with a clear cover of 18 mm (0.71 in.) and the corresponding reinforcement ratio is 0.39% (based on one layer of reinforcement). Twenty-four 20 mm (0.79 in.) diameter holes were made with polyvinyl chloride (PVC) pipes on four sides of each slab, which were used for fixing the slab into a support system with bolts. Three pieces of reinforcing bars were cut to a length of 250 mm (9.8 in.) and tested using tensile testing machine. The average yield and ultimate strengths of the tested reinforcing bars are 576 and 655 MPa (83.5 and 95.0 ksi). These 15 slabs were casted in one batch. Three concrete cylinders 150 mm (5.9 in.) in diameter and 300 mm (11.8 in.) in height were made with the same concrete during slab casting. These cylinders were then tested using a compression machine at their 28 days; their average compressive strength is 42.3 MPa (6.1 ksi). The maximum aggregate size of concrete is 10 mm (0.39 in.). The flexural capacity of the designed specimen was calculated to be 268 kN (60.3 kip) based on yield line theory (the assumed yield lines are depicted by dash lines in Fig. 1). The shear capacities of the designed specimen were assessed

Table 1—Details of experimental program

Designation of test	M , kg (lb)	h , m (ft)	V_i , m/s (ft/s)	E_i , J (ft·lbf)	M_i , kg·m/s (lbf·s)	d , cm (in.)	Nose shape
10H-a	200 (441)	3 (9.84)	7.67 (25.2)	5886 (4341)	1534 (345)	10 (3.94)	Hemispherical
10H-b	300 (661)	2 (6.56)	6.26 (20.5)	5886 (4341)	1878 (423)		
10H-c	300 (661)	1.33 (4.36)	5.11 (16.8)	3914 (2886)	1534 (345)		
10H-d	500 (1102)	1.2 (3.94)	4.85 (15.9)	5886 (4341)	2425 (546)		
10H-e	500 (1102)	0.48 (1.57)	3.07 (10.1)	2354 (1736)	1534 (345)		
10F-a	200 (441)	3 (9.84)	7.67 (25.2)	5886 (4341)	1534 (345)	10 (3.94)	Flat
10F-b	300 (661)	2 (6.56)	6.26 (20.5)	5886 (4341)	1878 (423)		
10F-c	300 (661)	1.33 (4.36)	5.11 (16.8)	3914 (2886)	1534 (345)		
10F-d	500 (1102)	1.2 (3.94)	4.85 (15.9)	5886 (4341)	2425 (546)		
10F-e	500 (1102)	0.48 (1.57)	3.07 (10.1)	2354 (1736)	1534 (345)		
20F-a	200 (441)	3 (9.84)	7.67 (25.2)	5886 (4341)	1534 (345)	20 (7.87)	Flat
20F-b	300 (661)	2 (6.56)	6.26 (20.5)	5886 (4341)	1878 (423)		
20F-c	300 (661)	1.33 (4.36)	5.11 (16.8)	3914 (2886)	1534 (345)		
20F-d	500 (1102)	1.2 (3.94)	4.85 (15.9)	5886 (4341)	2425 (546)		
20F-e	500 (1102)	0.48 (1.57)	3.07 (10.1)	2354 (1736)	1534 (345)		

Notes: M is mass of impactor; h is drop height; V_i is impact velocity; E_i is impact energy; M_i is impact momentum; and d is diameter of impactor.

Fig. 2—Different noses installed to impactor: (a) 10 cm (3.94 in.) diameter hemispherical nose; (b) 10 cm (3.94 in.) diameter flat nose; and (c) 20 cm (7.87 in.) diameter flat nose.

according to ACI 318-14.¹⁶ The calculated shear capacities are 196 kN (44.1 kip) (assuming 100 mm [3.9 in.] diameter circular loading area in the slab center) and 282 kN (63.4 kip) (assuming 200 mm [7.9 in.] diameter circular loading area in the slab center). Comparing the calculated flexure and shear capacities of specimen, it is found the specimen is predicted to have a shear failure mode under static loading when the diameter of loading area is 100 mm (3.9 in.), but a flexure failure mode when the diameter of loading area becomes 200 mm (7.9 in.).

Test procedure and test setup

The details of this experimental program are presented in Table 1. These 15 slab specimens were tested in three groups named 10H, 10F, and 20F according to the nose shape and diameter of the impactor. As shown in Fig. 2, 10 cm (3.9 in.) diameter hemispherical nose (10H), 10 cm (3.9 in.) diameter flat nose (10F), and 20 cm (7.9 in.) diameter flat nose (20F) were used for these three groups. In each group, five slabs were impacted under different drop weights or drop heights, which were carefully chose to produce same impact energy or impact momentum. The tests named a, b, and d had the same impact energy, and the tests named a, c, and e shared the same impact momentum. The slab specimens were loaded using the drop weight system shown in Fig. 3(a) whose maximum drop weight and height are 500 kg (1102 lb) and 3 m (9.84 ft). The drop weight system has a track to guide the movement of the drop weight to ensure it hits the target vertically.

The supporting system shown in Fig. 3(b) was used for this impact experiment. This 1200 x 1200 mm (47.2 x 47.2 in.) steel support was constructed using a series of H steel beams, which were fixed into the strong floor with high-tension bolts and can be considered with enough rigidity during test. Four thin steel plates with the width of 100 mm (3.9 in.) and length of 1000 mm (39.4 in.) were installed above the H beams to increase the clear span of the support to 1 m (39.4 in.). The slab specimen was bolted to the support with 24 high-tension bolts. 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

(a)

(b)

Fig. 3—Test setup: (a) drop-weight system; and (b) supporting system.

the specimen. These bolts were lightly fastened to prevent it from generating stress on the specimen.

Instrumentation

Different kinds of sensors were installed during the test to capture the response of the tested slabs. The arrangement of displacement sensors and accelerometers are given in Fig. 4. Two laser-type displacement sensors with the sampling rate of 50 kHz and three accelerometers with the capacity of 1000 times gravity and measuring frequency of 10 kHz were

installed along the midline of the top surface of slab specimens to capture its displacement and acceleration distributions. The collected acceleration data can also be used for assessing the induced inertial effect of slabs. Another two accelerometers with the same measuring capacity and frequency were attached to the impactor to record its acceleration history, which could be used for calculating the impact force. It should be noted that, to reduce the noise, all the raw data from accelerometers were filtered using an FFT low-pass filter with a cutoff frequency of 1250 Hz. The cutoff frequency was determined based on the following principles: 1) in the corresponding power spectrum, the cutoff frequency should include most of the high-amplitude part; and 2) the impulse (applied to the slab by the drop weight, calculated using acceleration history of the drop weight) calculated with filtered data should not change so much compare with the impulse calculated with raw acceleration data. Six strain gauges were installed to both top and bottom layers of reinforcement mats to capture the strain of

reinforcement. The arrangement of strain gauges is shown in Fig. 1.

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

Crack patterns and damage

The damages on the front and bottom surfaces of tested slab specimens are shown in Fig. 5 and Fig. 6, respectively. In the front surface, except for a hole drilled by the drop weight in the impacted area, the remaining slab area was nearly intact. For each specimen, the drilled hole had the same diameter and shape as the nose of the impactor and its corresponding penetration depth was measured after test and listed in Table 2. In general, the penetration depth was found to increase when impact energy increases despite the equivalence of impact momentum. Difference of penetration depth was not significant among tests a, b, and d, which have the same impact energy. The average penetration depths are 16.6, 17.8, and 8.8 mm (0.65, 0.70, and 0.35 in.) for 10H, 10F, and 20F groups. This result indicates that penetration depth decreases when the diameter of loading area increases. Considering the influence of impactor's nose shape, it is found that the hemispherical nose can penetrate slabs with relatively small impact energy, while the flat nose causes larger penetration depth than the hemispherical nose when the impact energy is large.

Similar to the front surface, damage on the bottom surface of slab also increased with increasing impact energy. For tests 10H-e, 10F-e, and 20F-e, only light radial cracks, which are indicative of slab's flexural behavior, were found on the bottom surfaces of the tested specimens. For tests 10H-c, 10F-c, and 20F-c, in addition to radial cracks, circumferential cracks that are indicative of slab's punching shear behavior were also observed. Comparing with 20F-c, the damage to 10H-c and 10F-c is more severe that light concrete scabbing can be observed. With the further increase of impact energy (tests a, b, and d), the width of circumferential cracks increased and more severe concrete scabbing were seen, which are representative of typical punching shear failure mode. The concrete scabbing mainly initiated between the outmost circumferential cracks and the loading area. Reinforcing bars in the scabbing region were exposed and bent. In the loading area, the concrete was severely crushed but still hung on the reinforcement. The slab area surrounded by the exterior circumferential crack is defined as damaged area and the diameter of the damaged area was measured for each specimen and listed in Table 2. The average diameters

Fig. 4—Arrangement of displacement sensors and accelerometers.

Fig. 5—Typical damage on front surface of specimens.

Fig. 6—Damage on bottom surface of specimens: (a) 10H group; (b) 10F group; and (c) 20F group.

Table 2—Input parameters of material models

Concrete, CSCM model	Mass density, kg/m ³ (lb/ft ³)	Compression strength, MPa (ksi)	Maximum aggregate size, mm (in.)	Yield stress, MPa (ksi) Poisson's ratio	
	2400 (150)	25 to 45 (3.63 to 6.53)	10 (0.39)		
Steel reinforcement (piecewise linear isotropic plasticity model)	Mass density, kg/m ³ (lb/ft ³)	Young's modulus, MPa (ksi)	Plastic strain to failure, 10 ⁻⁶	576 (83.54) 0.3	
	7850 (490)	2×10^5 (2.9×10^4)	3300

Fig. 7—Comparison of deflected shapes of slabs under different impact energies.

Fig. 8—Strain histories of top and bottom reinforcements of Tests 20F-d, 10F-d, and 10H-d.

of damaged areas for group 10H, 10F, and 20F are 695, 735, and 872 mm (27.4, 28.9, and 34.3 in.) respectively. In sum, the damage of slabs under impact load is strongly related to impact energy.

Deflected shapes

In this section, the measured displacement histories of D1 and D2 data points are used to plot the deflected shape along the midline of the front surface of the tested slab. Uniform displacement 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 is plotted via linking the measured data points with straight lines. For example, the deflected shapes of slabs during the tests of 20F-e, 20F-c, and 20F-d are plotted at an interval of 1.5 ms (millisecond) and shown in Fig. 7. For 20F-e, an elastic flexural behavior could be observed that the impact caused a global deformation on the front surface of slab. After reaching its maximum displacement around 6 ms, the slab began to rebound and the residue deformation was very limited. For test 20F-c, the global flexural response could be seen in the early loading stage. Additionally, the punching shear behavior of impacted slab was also observed that the deflection of the impacted region increased much more rapidly than the deflection of unloaded area. This punching shear behavior was accompanied with the development of shear cracks and the formation of the punching shear cone. After 4.5 ms, the unloaded area began to rebound while the loaded area continued its downward movement for another few millimeters and then rebounded at 7.5 ms. This phenomenon suggests a severely weakened concrete link between the loaded and unloaded

slab areas due to the formation process of the punching shear cone. For test 20F-d, the impact energy was further increased and a typical punching shear failure mode could be observed from the deflected shape. The exact punching shear failure point was characterized by the obviously reversed movement between the loaded and unloaded area, which indicated the full formation of punching shear cone and its separation with surrounding concrete. This principle of determining the punching shear failure points is used for other specimens and their failure situations are summarized in Table 2. For specimens with similar deflected shapes as 20F-c, they were at the brim of punching shear failure because the impacted area still had certain connections with surrounding concrete. Therefore, these specimens are categorized as “about to fail.” From Table 2, it can be found that 10 cm (3.9 in.) diameter flat nose impactor requires the least energy to cause punching shear failure on the designed specimen. Comparatively, slab impacted by 20 cm (7.9 in.) diameter flat nose impactor has a longer shear perimeter than that impacted by 10 cm (3.9 in.) diameter flat nose impactor and therefore possesses a better capability in resisting punching shear failure.

Strain histories of steel reinforcements and damage process

To illustrate the strain development of reinforcement, the recorded strain histories of Tests 20F-d, 10F-d, and 10H-d are plotted in Fig. 8. In each plot, the times of punching shear failure and rebound of impactor are marked with vertical lines. For 20F-d, tensile strain increased rapidly in the bottom reinforcement at very early loading stage. Yielding points of bottom reinforcement were found in the sequence

Fig. 9—Time histories of impact, inertial, and reaction forces.

of B1, B2, and B3, which indicates a global flexural response of impacted specimen. Meanwhile, no yielding of top reinforcement could be seen due to the limited slab deformation. During the same period, inclined shear cracks also initiated in the impacted region and began to propagate. Once the shear cracks had fully developed, punching shear failure happened and the severely damaged concrete in the loading area was unable to transfer load to the bottom reinforcement, which led to a sudden release of strain in the bottom reinforcement. On the contrary, the strain on the top reinforcement continues to increase after the failure point and the residue impact was mainly resisted by the top reinforcement. In general, the strain behavior and damage process of 10F-d and 10H-d are similar to 20F-d. That is: 1) yielding

of bottom reinforcement and bending behavior at the early stage of impact; 2) failure of specimen was governed by the failure of concrete irrespective of reinforcement strain; and 3) strain of top reinforcement continued to increase after the failure point.

Despite the mentioned similarity, the strain of the T1 data point, which represents mass penetration of the tested specimen, was very different among these three tests. For 20F-d, yielding of T1 happened after shear failure of the specimen. For 10F-d, yielding of T1 happened at the instant of shear failure. For 10H-d, T1 yielded much earlier before the bending behavior and shear failure of the specimen. Due to stress concentration, the hemispherical nose impactor can easily penetrate concrete targets. On the other hand, impact

Fig. 9 (cont.)—Time histories of impact, inertial, and reaction forces.

energy and force are not transferred efficiently for the hemispherical nose impactor due to the limited impact area. This is believed to be the reason the hemispherical nose impactor penetrates the slab with relative small impact energy but requires more impact energy to fail it than the flat nose impactor. The observed difference among the strain histories of T1 point suggested that mass penetration does not correlate well with the development of shear cracks and the formation of punching shear cone and as such, penetration depth should not be used as the sole index to determine the damage of impacted targets. The strain rate of reinforcement was calculated by differentiating the measured strain histories and the maximum strain rate of B1 point ranged from 1.3 s^{-1} to 3.2 s^{-1} for all the tests.

Ratio between imparted energy and impact energy

As mentioned earlier, accelerometers were attached to the impactor to measure its acceleration history. By integrating the measured acceleration history in time domain, the velocity history of impactor was obtained and the rebound velocity could be determined. Once the rebound velocity of impactor is known, the energy imparted to slab can be calculated via subtracting the residue kinetic energy of impactor from the impact energy. The calculated rebound velocities, absorbed energies, and its ratio over impact energies of

different tests are listed in Table 2. The accelerometers of Tests 20F-a and 20F-b were damaged during the test and therefore no result is presented for these two tests.

It is found that the ratio between imparted energy and impact energy is strongly related with the damage lever of tested specimens. For the tests of 10H-e, 10F-e and 20F-e where specimens were slightly damaged, approximately 80 to 90% of the impact energy was imparted to tested slabs. For the remaining tests, 95 to 98% of the impact energy was imparted to the tested slabs. This phenomenon is expected because for the less damaged slabs, more impact energy is stored through the temporary elastic deformation of slab. This stored energy will return to the impactor when the elastic deformation recovers. On the contrary, severely damaged slabs have already entered their plastic stage and more impact energy is dissipated in the format of permanent deformation or fracture damage and limited energy can return to the impactor.

Impact force and inertial effect

The acceleration history of impactor is multiplied with its mass during each test to calculate the corresponding impact force history. The calculated impact force histories are shown in Fig. 9. The impact force histories of tests 20F-a and 20F-b are not presented herein because the accelerom-

Fig. 10—Quarter FE model of RC slab: (a) mesh of concrete; and (b) beam elements of reinforcement.

eters were damaged during these two tests and no acceleration data was recorded. The impact force histories of different tests are similar in shape, which comprises a head part with high magnitude but short duration and a tail part with lower magnitude but longer duration. The maximum impact forces during different tests are listed in Table 2. It can be seen that the maximum impact force increases when the contact area between the impactor and specimen increases such that the average maximum impact forces of 10H, 10F, and 20F groups are 390, 632, and 726 kN (87.7, 142.1, and 163.2 kip), respectively. In each group, the maximum impact force is found to increase when impact energy increases, and similar maximum impact force was observed for tests a, b, and d, which have the same impact energy. However, it is worth mentioning that the maximum impact force usually happens around approximately 1 ms after impact that the damage and deformation of specimens is very limited in the meantime. Therefore, no direct relation can be observed between the maximum impact load and the resistance capacity of specimen.

To assess the inertial effect during the impact test, a simple integration approach is proposed to fully use the recorded acceleration data to estimate the inertial force of slab. As shown in Fig. 4, a quarter of the slab is divided into four tributary integration areas according to the positions of accelerometers. For Area II, 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 is assumed in the supported regions and slab corners. By assuming symmetric slab acceleration distribution, the inertial force of slab can be calculated by summing up the integrated inertial forces of the four tributary areas and multiplying this sum with 4. When ignoring damping force, the difference between impact force and support reaction force is mainly balanced by inertial force during impact. Therefore, the support reaction force is roughly estimated via subtracting inertial force from the impact force. The estimated inertial forces and reaction forces are plotted in Fig. 9 as well. As can be seen, the slab gained significant downward acceleration immediately after impact and upward (negative) inertial force was induced. At this stage, the impact load is mainly balanced by the generated inertial force. As a result, the maximum impact load cannot be considered the slab's resistance capacity. Accompanied with the increase of slab deformation, the reaction force increased and reversely accelerated the slab. Once the reaction force surpassed the impact load, inertial force

became downward (positive) to balance the reaction force. Therefore, it can be concluded that the inertial effect is significant and interruptive during the impact test, which makes it difficult to directly relate the measured impact or reaction force with the true impact resistance of tested specimen.

FINITE ELEMENT ANALYSIS OF RC SLABS SUBJECTED TO LOW-VELOCITY IMPACT

In the experimental part, a close relation has been observed between impact energy and slab damage. Considering the difficulty of abstracting the load-carrying capacity of slab from impact experiment, it is desired to obtain the energy capacity of the slab in resisting punching shear failure to satisfy the engineering need. Therefore, finite element simulation of the slab impact problem was conducted to numerically study the energy capacity of the slab under impact load.

Details of FE modeling

LS-DYNA was employed to conduct this FE analysis due to its calculation efficiency and proven effectiveness in simulating high strain rate scenarios such as impact and impulse problems. Figure 10 shows the three-dimensional (3-D) FE model of the tested slabs. Due to geometric symmetry, only one-quarter of the impact system was modeled to reduce the calculation efforts. Translational restrains were assigned to both the symmetry planes in their normal direction. In this model, the concrete, impactor, and support were discretized by an eight-node hexahedron element with Lagrange interpolation function. The mesh size for concrete elements was approximately 10 mm (0.39 in.) in each direction and the corresponding aspect ratio is approximately 1. The 3-D beam element with three nodes (one-direction node defining the normal direction of the beam element) was used for modeling the steel reinforcement. These beam elements shared the same nodes and boundaries with the concrete element and therefore perfect bond between concrete and steel reinforcement was assumed in this model. This assumption is reasonable for the impact problem because concrete members usually fail within several or tens of milliseconds after impact and this amount of time is usually not enough for developing significant bond slip between concrete and reinforcing bars. To better represent the experimental boundary condition, the support was modeled explicitly, which contains two steel strips beneath the slab and six steel plates confining the top surface of the slab. The steel strips and plates are connected with steel bars that insert through the slab. These two steel strips were fully fixed and no restraint was assigned to the slab in the supported region. With the described modeling method, contact would happen

Table 3—Summary of experimental results

Designation of test	<i>PD</i> , mm (in.)	<i>DA</i> , mm (in.)	Punching shear failure	<i>V_r</i> , m/s (ft/s)	<i>E_a</i> , J (ft-lbf)	<i>E_a/E_i</i>	<i>MIF_{test}</i> , kN (kip)	<i>MIF_{FEM}</i> , kN (kip)
10H-a	17.5 (0.68)	603 (23.7)	Yes	1.28 (4.20)	5390 (3975)	0.97	415 (93.3)	395 (88.8)
10H-b	26.5 (1.04)	815 (32.1)	Yes	1.08 (3.54)	5711 (4212)	0.97	452 (102)	349 (78.46)
10H-c	13.5 (0.53)	707 (27.8)	About to fail	1.04 (3.41)	3763 (2775)	0.96	397 (89.3)	326 (73.3)
10H-d	21.4 (0.84)	654 (25.7)	Yes	0.88 (2.89)	5688 (4195)	0.97	389 (87.5)	375 (84.3)
10H-e	4.3 (0.17)	—	No	0.93 (3.05)	2139 (1577)	0.91	297 (66.8)	316 (71.0)
10F-a	23.7 (0.93)	761 (30.0)	Yes	1.31 (4.30)	5577 (4113)	0.97	694 (156)	646 (145)
10F-b	26.6 (1.05)	703 (27.7)	Yes	1.05 (3.44)	5721 (4219)	0.97	651 (146)	636 (143)
10F-c	9.8 (0.39)	610 (24.0)	Yes	0.72 (2.36)	3846 (2836)	0.98	603 (136)	584 (131)
10F-d	28.1 (1.11)	871 (34.3)	Yes	0.99 (3.25)	5636 (4156)	0.96	672 (151)	627 (141)
10F-e	0.7 (0.03)	—	About to fail	1.07 (3.51)	2071 (1487)	0.88	538 (121)	556 (125)
20F-a	10.3 (0.41)	853 (33.6)	Yes	—	—	—	—	—
20F-b	18.6 (0.73)	755 (29.7)	Yes	—	—	—	—	—
20F-c	3.6 (0.14)	878 (34.6)	About to fail	0.9 (2.95)	3802 (2804)	0.97	680 (153)	757 (170)
20F-d	11.3 (0.44)	901 (35.5)	Yes	0.71 (2.33)	5757 (4246)	0.98	794 (179)	846 (190)
20F-e	None	—	No	1.34 (4.40)	1908 (1407)	0.81	705 (158)	670 (151)

Notes: *PD* is penetration depth; *DA* is diameter of damaged slab area; *V_r* is rebound velocity; *E_a* is absorbed energy; *MIF_{test}* is maximum impact force in test; *MIF_{FEM}* is maximum impact force in FEM.

Fig. 11—Comparison of tested and simulated impact forces (20F-e, 20F-c, and 20F-d).

between the impactor and the slab or between the support and the slab. The algorithm “Contact Automatic Surface to Surface” in LS-DYNA was chosen to model the contact during analysis.

The Continuous Surface Cap Model (CSCM) constitutive model was used for modeling the constitutive behavior of concrete. This model was based on isotropic constitutive equations and contains a continuous yield surface that was formulated in terms of three stress invariants of the deviatoric stress tensor. This yield surface can account for ductile and brittle damages with a damage parameter ranging from zero (undamaged) to one (fully damaged). Strength softening of concrete was also considered with a softening function. This model also allows element erosion once the damage parameter reaches 1. Therefore, fully damaged concrete elements were deleted from the FE model and the concrete damage could be visualized. Strain rate effect was also included in this model to account for the strength enhancement of concrete under high strain rate.

The Piecewise Linear Isotropic Plasticity Model was chosen to model the constitutive relationship of steel reinforcement. This model could consider strength hardening of steel after its yielding and allows the user to define

stress-versus-strain curves under various strain rates. In this paper, the strength enhancement ratio of steel under different strain rates proposed by Malvar¹⁷ and Li et al.¹⁸ was chosen for defining these curves. The input parameters of the material models for concrete and steel reinforcement are listed in Table 2.

The support and impactor were modeled with the rigid material model. In this model, the support and impactor were idealized as rigid body that their deformation was ignored. Detailed formulation and explanation of all the materials models mentioned previously could be found in the LS-DYNA theory manual.¹⁹

Verification of FE analysis results

To prove the effectiveness of the modeling method described previously, FE analysis was conducted for all 15 impact tests of the present study. The simulated maximum impact forces were listed in Table 3 and compared with the experimental results. As an example, the simulated impact force histories; displacement histories of D1 and D2 points; and crack patterns of Tests 20F-c, 20F-d, and 20F-e are presented in Fig. 11, Fig. 12, and Fig. 13. It can be observed that the simulated impact forces and crack patterns

Fig. 12—Simulated displacement histories of D1 and D2 points.

Fig. 13—Simulated slab damage: (a) 20F-e; (b) 20F-c; and (c) 20F-d.

Table 4—Variation in mass

m_i , kg (lb)	m_s , kg (lb)	m_i/m_s	V_i , m/s (ft/s)	E_i , J (ft·lbf)	d , cm (in.)	Nose shape	MIF , kN (kip)	MMD , mm (in.)	RMD , mm (in.)	T_{MMD} , ms
100 (220)	540 (1190)	0.19	8.66 (28.4)	3750 (2765)	20 (7.87)	flat	772 (174)	6.26 (0.25)	5.3 (0.21)	1.8
300 (661)		0.56	5 (16.4)				750 (169)	6.42 (0.25)	5.1 (0.20)	2.5
500 (1102)		0.93	3.87 (12.7)				735 (165)	6.07 (0.24)	4.8 (0.19)	2.8
700 (1543)		1.3	3.27 (10.7)				679 (153)	6.03 (0.24)	4.5 (0.18)	3.4
1000 (2204)		1.85	2.74 (8.99)				658 (148)	5.75 (0.23)	4.3 (0.17)	3.7

Note: d is diameter of impactor.

match well with the experimental results. In the experimental part, the punching shear failure was defined as the obviously reversed movement between the impacted area and its surroundings. The same principle is used in this FE analysis. More precisely, the punching shear failure is defined to happen if the D1 (midpoint of slab) did not rebound together with D2 (245 mm [9.6 in.] from the midpoint) and continued its downward movement for more than 3 mm (0.19 in.). From Fig. 12, it is observed that 20F-d failed while 20F-e and 20F-c did not. In Fig. 13, it can be found that the inclined shear cracks were fully developed in the loading area for 20F-d and led to punching shear failure. For 20F-c, shear cracks were partially formed. For 20F-e, no obvious shear crack could be observed. By comparing the numerical results with experimental data of the remaining cases, it was found that the simulated extent of damage of all 15 tests accord nicely with the experimental results.

Influence of mass ratio on response of RC slab

After proving the effectiveness of the FE simulation method, FE analysis was conducted to study the influence of mass ratio on the response of the RC slab. In the experimental part, 200, 300, and 500 kg (441, 661, and 1102 lb) impactors were used to impact the slab specimens whose weights were 540 kg (1190 lb), and the corresponding ratios between impactor mass (m_i) and slab mass (m_s) were 0.37, 0.56, and 0.93. In this part, the numerical study was conducted to include a wider range of mass ratio. Details of this analysis are summarized in Table 4. Similar to the experimental part, the impact energy was fixed for different cases. The property of the RC slab was the same as the specimens used in the experiment.

The influence of mass ratio on the midspan deflection of the bottom surface of RC slabs is shown in Fig. 14. The maximum impact force (MIF), maximum midspan deflection (MMD), residue midspan deflection (RMD), and time

of reaching the maximum midspan deflection (T_{MMD}) are summarized in Table 5. The results show that the maximum impact force and residue midspan deflection decrease when the ratio between m_i and m_s increases. The maximum midspan deflection increases when the mass ratio increased from 0.19 to 0.56, but then decreases with the further increase of mass ratio. The time required for the slab to reach its maximum midspan deflection increases together with mass ratio. However, it should be noted that the differences of these results made by varying the mass ratio was in general very small and insignificant when the impact energy is fixed.

Fig. 14—Influence of mass ratio on midspan deflection (bottom surface) of RC slab.

Table 5—Details of parametric study program

Designation	Dimension of slab, cm (in.)	f_c , MPa (ksi)	DR, mm (in.)	ρ , %	E_{s-FEA} , J (ft-lbf)			E_{s-Equ} , J (ft-lbf)		
					$d = 5$ cm (2.0 in.)	$d = 10$ cm (3.9 in.)	$d = 20$ cm (7.9 in.)	$d = 5$ cm (2.0 in.)	$d = 10$ cm (3.9 in.)	$d = 20$ cm (7.9 in.)
15-25-0.25	120 x 120 x 15 (47.2 x 47.2 x 5.9)	25 (3.63)	8 (0.32)	0.25	1634 (1205)	2166 (1597)	2774 (2046)	1606 (1184)	1956 (1442)	3066 (2261)
15-25-0.39		25 (3.63)	10 (0.39)	0.39	1634 (1205)	2166 (1597)	3038 (2240)			
15-25-0.66		25 (3.63)	13 (0.51)	0.66	1838 (1355)	2522 (1860)	3314 (2444)			
15-35-0.25		35 (5.08)	8 (0.31)	0.25	2166 (1597)	2400 (1770)	4374 (3226)	2249 (1656)	2739 (2020)	4292 (3165)
15-35-0.39		35 (5.08)	10 (0.39)	0.39	2282 (1683)	2646 (1951)	4538 (3347)			
15-35-0.66		35 (5.08)	13 (0.51)	0.66	2400 (1770)	2774 (2046)	4704 (3469)			
15-45-0.25		45 (6.53)	8 (0.32)	0.25	2646 (4.2)	3038 (2240)	4704 (3496)	2891 (2132)	3521 (2597)	5518 (4069)
15-45-0.39		45 (6.53)	10 (0.39)	0.39	2646 (1951)	3174 (2321)	5046 (3721)			
15-45-0.66		45 (6.53)	13 (0.51)	0.66	2904 (2141)	3602 (2656)	5400 (3982)			
10-25-0.21	120 x 120 x 10 (47.2 x 47.2 x 3.9)	25 (3.63)	6 (0.24)	0.21	938 (692)	1442 (1063)	2522 (1860)	503 (371)	1450 (1069)	2525 (1862)
10-25-0.38		25 (3.63)	8 (0.32)	0.38	938 (692)	1442 (1063)	2522 (1860)			
10-25-0.59		25 (3.63)	10 (0.39)	0.59	938 (692)	1634 (1205)	2522 (1860)			
10-35-0.21		35 (5.08)	6 (0.24)	0.21	1176 (867)	1838 (1355)	3456 (2549)	704 (519)	2030 (1497)	3535 (2607)
10-35-0.38		35 (5.08)	8 (0.32)	0.38	1176 (867)	1944 (1434)	3602 (2656)			
10-35-0.59		35 (5.08)	10 (0.39)	0.59	1262 (931)	2053 (1514)	3602 (2656)			
10-45-0.21		45 (6.53)	6 (0.24)	0.21	1442 (1063)	2774 (2046)	4214 (3108)	906 (668)	2610 (1925)	4545 (3352)
10-45-0.38		45 (6.53)	8 (0.32)	0.38	1536 (1133)	2774 (2046)	4374 (3226)			
10-45-0.59		45 (6.53)	10 (0.39)	0.59	1634 (1205)	2646 (1951)	4538 (3347)			

Notes: f_c is compressive strength of concrete; DR is diameter of reinforcing bars; ρ is reinforcement ratio; E_{s-FEA} is minimum impact energy for punching shear failure obtained in FE analysis (using 300 kg [661 lb] impactor); and E_{s-Equ} is minimum impact energy for punching shear failure estimated using Eq. (1).

Parametric study on energy capacity of RC slab

A parametric investigation is presented in this section to include more variables that were not covered in the experimental study and to learn how they affect the energy capacity and angle of shear cracks of the RC slab. The variables considered in this study are compressive strength of concrete (f_c : 25, 35, and 45 MPa [3.63, 5.08, and 6.53 ksi]), longitudinal reinforcement ratio (ρ : 0.21 to 0.66%), slab thickness (H : 10 and 15 cm [3.9 and 5.9 in.]) and diameter of impactor (d : 5, 10, and 20 cm [2, 3.9, and 7.9 in.]). The weight of the impactor is fixed at 300 kg (661 lb) and only the flat nose impactor is used. Details of this parametric study program and specimen characteristics are summarized in Table 5. It should be noted that the reinforcement in this parametric study has the same layout as Fig. 1 and the difference in reinforcement ratio among different cases is made by varying the diameter of reinforcing bars. The yield and ultimate strengths of reinforcement were 576 and 655 MPa (83.5 and 95.0 ksi). A total of 54 cases were analyzed. In each case, a relatively small impact velocity was assigned at first. If the specimen did not fail with the assigned impact velocity, the analysis will be conducted again with a new impact velocity that is 0.1 m/s (0.33 ft/s) higher than the previous one. The analysis will stop when the punching shear failure could be observed from the displacement histories of D1 and D2 points and the corresponding impact velocity was used for calculating the impact energy that just enough to cause punching shear failure E_s .

Effects of longitudinal reinforcement ratio and compressive strength of concrete on E_s —Figure 15 illustrates the

Fig. 15—Influence of ρ and f_c on E_s .

effects of longitudinal reinforcement ratio and compressive strength of concrete on the energy capacity of RC slabs in resisting punching shear failure. The enhancement on E_s made by increasing the longitudinal reinforcement ratio was observed to be very limited. For a 10 cm (3.9 in.) thick slab, E_s was, on average, enhanced by 6% when the reinforcement ratio increased from 0.21 to 0.59%. For the 15 cm (5.9 in.) thick slab, E_s was, on average, enhanced by 14% when the reinforcement ratio increased from 0.25 to 0.66%. The enhancement on E_s brought by increased longitudinal reinforcement ratio is expected because bending behavior and yielding of reinforcement happens at the early stage of impact. However, this bending behavior and corresponding global deformation are limited before the shear failure of the slab and therefore prevents the longitudinal reinforcement in dissipating more impact energy. It should also be noted that only lightly reinforced slabs were considered in this analysis. If the slabs were highly reinforced, they were likely to have more pronounced flexural response and global deformation, which would enable the reinforcement in consuming more energy under impact loading.

E_s was found significantly affected by the compressive strength of concrete in Fig. 15. On average, E_s was enhanced by 33% when f_c increased from 25 to 35 MPa (3.63 and 5.08 ksi) and another 25% when f_c increased from 35 to 45 MPa (5.08 to 6.53 ksi). These results suggest an approximately linear relationship between E_s and f_c . As introduced in the experimental study, the punching shear failure of RC slabs under impact loading was governed by the failure of concrete in the impacted region. This phenomenon explains why, compared with the longitudinal reinforcement ratio, the strength of concrete is more influential on E_s .

Effects of diameter of impactor and slab thickness on E_s —Diameter of impactor and slab thickness are the two parameters that affect the amount of concrete participated

in carrying the impact-induced shear force. Therefore, an increase of diameter of impactor or slab thickness shall boost the energy capacity of RC slabs in resisting shear failure. The effects of d and H on E_s are shown in Fig. 16. E_s was on average increased by 67 and 70% when d increased from 5 to 10 cm (2.0 to 3.9 in.) and from 10 to 20 cm (3.9 to 7.9 in.). When it comes to slab thickness, the average E_s of 15 cm (5.9 in.) thick slabs was found to be 46% higher than the average E_s of 10 cm (3.9 in.) thick slabs.

Effects of diameter of impactor and slab thickness on angle of shear cracks

In addition to the energy capacity of RC slabs, angle of shear cracks is another important index that could be used to predict the damaged area of RC slabs under impact loading. The influence of diameter of impactor and slab thickness on the angle of shear cracks are plotted in Fig. 17. The angles of shear cracks are summarized in Table 6. The average angles of shear cracks for 10 cm (3.9 in.) thick slabs and 15 cm (5.9 in.) thick slabs are 41.6 and 42.6 degrees, respectively. The angle of shear cracks decreases when the diameter of impactor increases, and this phenomenon is less pronounced when slab thickness increase.

Proposed empirical equations for estimating minimum impact energy for punching shear failure of RC slabs

The minimum impact energies for punching shear failure E_s obtained from the aforementioned parametric study are summarized in Table 5. For clearer visualization, these results are again plotted in Fig. 18. To quantify the relationship between different parameters and E_s , two dimensionless empirical equations were proposed as follows for estimating the minimum impact energy required for punching shear failure of lightly reinforced RC slabs.

Fig. 16—Influence of d and H on E_s .

Fig. 17—Influence of H and d on angle of shear cracks.

$$\frac{E_s}{d^3 f_c} = \left[1.65 \frac{H}{d} - 4.53 \left(\frac{H}{d} \right)^2 + 3.47 \left(\frac{H}{d} \right)^3 \right] 10^{-4} \quad (\text{SJ units})$$

$$\frac{E_s}{d^3 f_c} = \left[1.37 \frac{H}{d} - 3.77 \left(\frac{H}{d} \right)^2 + 2.89 \left(\frac{H}{d} \right)^3 \right] 10^{-2} \quad (\text{U.S. customary units})$$

for $0.5 \leq \frac{H}{d} < 1$ (1a)

$$\frac{E_s}{d^3 f_c} = \left[2.05 - 2.72 \frac{H}{d} + 1.25 \left(\frac{H}{d} \right)^2 \right] 10^{-4} \quad (\text{SJ units})$$

$$\frac{E_s}{d^3 f_c} = \left[1.71 - 2.27 \frac{H}{d} + 1.04 \left(\frac{H}{d} \right)^2 \right] 10^{-2} \quad (\text{U.S. customary units})$$

for $1 \leq \frac{H}{d} \leq 3$ (1b)

These two equations were plotted in Fig. 19 and were obtained through regression analysis of the FE results. In the proposed equation, the influence of the reinforcement ratio was excluded and the E_s was assumed proportional to the compressive strength of concrete. The dimensional parameters E_s , f_c , d , and H were substituted with the dimensionless parameters of $E_s/(d^3 f_c)$ and H/d . The impact energy for punching shear failure estimated using the proposed empirical equations are compared with the FE results in Table 5. It can be seen that, in most cases, the estimated results accord well with the FE results. It should be noted that these proposed empirical equations are not suitable for predicting the shear failure energy capacity of highly reinforced concrete slabs in which the influence of longitudinal reinforcement ratio may not be ignored. Additionally, highly reinforced concrete

Table 6—Angle of shear cracks

	$H = 10 \text{ cm (0.39 in.)}$			$H = 15 \text{ cm (0.59 in.)}$		
	$d = 5 \text{ cm (0.20 in.)}$	$d = 10 \text{ cm (0.39 in.)}$	$d = 20 \text{ cm (0.79 in.)}$	$d = 5 \text{ cm (0.20 in.)}$	$d = 10 \text{ cm (0.39 in.)}$	$d = 20 \text{ cm (0.79 in.)}$
θ , degrees	59	42.3	23.5	49.1	43.2	35.5

Note: θ is angle of shear cracks.

Fig. 18—Minimum impact energy for punching shear failure: (a) slab depth = 10 cm (3.9 in.); and (b) slab depth = 15 cm (5.9 in.).

Fig. 19—Dimensionless equations for estimating E_s .

slabs are more likely to fail in flexure under low-velocity impact than lightly reinforced concrete slabs.

CONCLUSIONS

The main purpose of this paper is to investigate the behavior of RC slabs under low-velocity impact through experiment and finite element analysis. The results presented in this paper support the following conclusions.

1. The damage of slabs under low-velocity impact increases with increasing impact energy. The change of mass and drop height of impactor do not affect the slab damage so much as long as the impact energy is fixed. Therefore, in the domain of low-velocity impact, it is possible to directly relate the impact energy with the slab response and damage without knowing the exact velocity and mass of impactor. Compared to the flat nose shape impactor, the hemispherical nose shape impactor can cause penetration on RC slabs with relatively small impact energy but requires more impact energy to cause punching shear failure on them. In addition, more impact energy is required to fail RC slabs when the diameter of impactor increases.

2. Although some specimens were designed to have a flexural failure mode under static loading, punching shear failure mode was observed for all the tested specimens and during the subsequent FE analysis. The corresponding damaged process could be summarized as: 1) globalized flexural response at the early loading stage; 2) shear cracks initiate and propagate to form the punching shear cone, punching shear failures happens when the punching shear cone is fully developed and separated from its surrounding concrete; and 3) concrete in the loading area was crushed after punching shear failure and the residue impact of slab was mainly resisted by the top reinforcement.

3. The impact force reaches its maximum value immediately after impact and was not found in the same phase of the punching shear failure of impacted slab. Large inertial forces were found during impact, which was coupled with both impact and support reaction forces. Therefore, the impact force or support reaction force cannot be directly considered as the true resistance capacity.

4. Results from the finite element analysis show that an increase in any of concrete strength, diameter of impacted area, and slab thickness can effectively boost the energy capacity of a lightly reinforced concrete slab, whereas the effect of longitudinal reinforcement ratio was limited. Additionally, the angle of shear cracks was on average 42 degrees, which decreases when the diameter of the impactor increases. Based on regression analysis of the FE results, two empirical equations were proposed for assessing the impact energy for punching shear failure of lightly reinforced concrete slabs, which could be used for initial design or quick check of slab's ability in resisting low-velocity impact. However, verification involving more experiments and a wider range of parametric study are required to further update the proposed equations to enhance its accuracy and application range.

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