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An experimental investigation on the effect of steel reinforcement on impact response of reinforced concrete plates

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ABSTRACT

An experimental investigation has been conducted to collect fundamental data and to develop more understanding of the effect of steel reinforcement distribution on the dynamic response of reinforced concrete plates. Five high strength concrete (HSC) plates are tested using free-fall low-velocity impact technique. A total of 10 impact tests are conducted, including two tests on each specimen. The impact loads are applied at the mid-point of the HSC plates by dropping a 475 kg steel weight from a constant height of 4.15 m. Two parameters are investigated namely: the main bottom steel reinforcement ratio (1.0, 2.0, and 3.0%); and the steel reinforcement arrangement (single or doubly reinforced plates). The top reinforcement of all doubly reinforced plates is kept constant as shrinkage reinforcement of 10 mm diameter spaced at 210 mm. The experimental results are evaluated focusing on the impact force characteristics and the impact behaviors of reinforced concrete plates. The test program was successful in providing a simple method for validating impact test setup using impulse–momentum theorem. Results showed that the change of reinforcement ratio and/or reinforcement arrangement has no significant effect on impulse and absorbed energy values for same impact loading condition. Additionally crack pattern and failure mode are found to be more dependent on the reinforcement arrangement rather than reinforcement ratio.

1. Introduction

Recently, it has been a growing trend to design some structures to resist both static and low-velocity impact loads. Low-velocity high mass impact loading conditions with velocities up to 10 m/s are the common impact scenarios for civil engineering. Typical low-velocity impact scenarios include transportation structures subjected to vehicle collisions, airport runway platforms during aircraft landing, and offshore structures subjected to ice and/or ship impact. Additionally, dynamic loading arising from natural hazards such as tornadoes and earthquakes are also related to low velocity impact.

Although numerous experimental investigations have been performed on impact behavior of reinforced concrete (RC) members, most of earliest studies are carried out by those associated with military and nuclear sectors. In such investigations, the impactor has small size hitting a massive target with high velocity in the range of 40–300 m/s. In this type of impact, the loading impulse acts over a very short time, much shorter than the natural period of structural member vibration by perhaps one or two orders of magnitude. As a result, the entire member has no time to respond globally and the failure of beams or plates is localized in the form of punching or bell-shaped ejection cone. However the resulting crack pattern and displacements map indicate that both flexural and shear failure are involved. For impact with higher velocity >1000 m/s, only local failures are developed. More details regarding high-velocity impact can be found elsewhere [1,2]. A worth of mention here is the results of these investigations are almost qualitative and often in form of impact-resistant empirical formulas [1]. Additionally, there is no standard test technique for impact loading condition [3]. Therefore, most of the developed empirical formulas from experimental investigations are applicable for certain condition and loading range [1,4].

RC member subjected to impact loading is a design concept that has not yet been fully developed for civil engineers. Additionally, current design codes did not suggest a clear method to analyze and predict possible failure mode of RC members under impact. As a result, several well-instrumented low-velocity impact experiments have been undertaken that aimed to understand the dynamic response of RC members as well as generate test data that used later to validate numerical studies, in particular, under drop-weight impact tests [4–11]. These low-velocity impact experimental investigations carried out on RC plates have revealed that: punching shear is the predominate failure pattern [4,7–9]; the impact punching capacity is twice the static one [8]; the supporting conditions have limited effect on RC plate response, failure pattern, impact capacity and maximum impact force [8,10,11]; the plate thickness has significant effect on impact capacity and maximum impact force [10];

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and reinforcement ratio has a significant effect in controlling spalling [9]. On the other hand, reinforcement ratio has little effect on maximum impact force [10].

High strength concrete is one of the main worldwide cementitious construction materials. As a result, it has been induced in several structures. Most of such structures are subjected to low-velocity impact loading conditions. In North Sea for example, there are eighteen HSC offshore platforms that are subjected to impact loads resulting from the high incident of heavy objects falling during the operation of offshore, and collision of supply ships and/or ice. This paper presents the details of a well-organized and equipped experimental investigation, aiming to investigate the effect of steel reinforcement distribution on the impact force characteristics and the impact behaviors of HSC plates, as well as generating precision impact test data that will be used later for the validation of ongoing numerical investigation by the authors.

2. Experimental investigation

2.1. Materials

The concrete mix used in this study is high-strength concrete with target 56-day cylinder-compressive strength of 80 MPa. This matrix includes ordinary Portland cement, quartzite sandstone, crushed granite of 14 mm maximum nominal size, 6% silica fume, and water:cement ratio of 0.35. This matrix is based on the composition developed by Marzouk [12]. In order to have identical concrete properties, all specimens are cast at the same time using single concrete batch; then all specimens are cured following same procedures, under moist burlap and plastic for 7 days. Afterwards, all specimens are taken out of their molds and placed to dry in laboratory air conditions until testing at the age of 56 days. CSA standard Grade 400 deformed steel bars are used as longitudinal reinforcement [13]. Three typical bar sizes of 10 M, 15 M, and 20 M are used in this study as specimens' reinforcement. The geometrical and materials properties are tested and summarized in Table 1. Each data point in the table is averaged from three specimens. The tested mechanical properties include: concrete standard compression cylinders and flexural of prisms, and coupon tests of steel reinforcement bars.

2.2. Test specimens

Five thin HSC plates with identical dimensions and reinforcement spacing are constructed and tested under free falling low-velocity impact test. The plates are 1950 mm square with a thickness of 100 mm. To address the effect of steel reinforcement distribution, two parameters are investigated namely: main bottom steel reinforcement ratio (1.0, 2.0, and 3.0%); and steel reinforcement arrangement (single or doubly reinforced plates). The variation in main bottom steel reinforcement ratios is achieved by increasing the bar size while reinforcement spacing is kept constant and is equal to 100 mm. Single and doubly reinforced plates are constructed as pairs with identical main bottom reinforcement. For doubly reinforced plates, the top reinforcement is kept constant, CSA Standard 10M bars with spacing 210 mm are used as minimal top reinforcement. All specimens are designed to collapse in bending-failure mode under mid-point static loading conditions with bending-shear capacity ratios range from 0.3 to 0.9. Details of individual specimen's reinforcement and their static bending and shear capacities are given in Table 2. Static flexural moment capacity P_{us} and punching-shear capacity V_{us} are calculated using conventional prediction equations. CSA A23.3 is followed to estimate ultimate static bending moment and punching-shear ultimate load of plates [13]. Additionally, the nominal flexural loads (P_{us}) are estimated using yield line theory [14]. Plates' identification, dimensions, reinforcement details, and cross sections are shown in Fig. 1.

Table 1
Properties of high-strength concrete and steel reinforcement.

High-strength concrete			
Density (kg/m^3)			2540
Compressive strength fc' (MPa)			83.10
Strain at peak stress ε_0			2.35×10^{-3}
Elastic modulus E_c (GPa)			30.22
Flexural strength f_r (MPa)			8.00
Steel reinforcement			
Bar size	10M	15M	20M
Diameter (mm)	11.29	15.95	19.53
Mass (kg/m)	0.775	1.560	2.345
Yield stress f_y (MPa)	433.40	435.00	451.20
Yield strain ε_y	2.0×10^{-3}	2.1×10^{-3}	2.3×10^{-3}
Ultimate strength f_{ult} (MPa)	621.70	618.30	629.10
Elastic modulus E_s (GPa)	201.10	204.24	198.60

Table 2
Steel reinforcement details and static capacities of test specimens.

Plate's ID	Bottom reinforcement		Top reinforcement		Static capacities		
	Dai./spacing (mm)	Ratio[a] (%)	Dai./spacing (mm)	Ratio[a] (%)	P_{us}[b] (kN)	V_{us}[c] (kN)	P_{us}/V_{us}[d]
HS-1-D	10M/100	1.00	10M/210	0.48	130	440	0.30
HS-2-D	15M/100	2.00	10M/210	0.48	240	400	0.60
HS-2-S	15M/100	2.00	–	–	240	400	0.60
HS-3-D	20M/100	3.00	10M/210	0.48	320	360	0.90
HS-3-S	20M/100	3.00	–	–	320	360	0.90

[a] Based on total section height = 100 mm, per direction.
[b] P_{us} = ultimate static flexural capacity.
[c] V_{us} = ultimate static punching capacity.
[d] P_{us}/V_{us} = flexural-punching capacity ratio.

2.3. Test set-up and instrumentations

The drop-weight impact frame system has been designed and fabricated at Ryerson University to generate a free-fall impact condition with a target capacity of 19.30 kJ. The schematic diagram of the setup and the test configuration is illustrated in Fig. 2. All specimens are tested under same loading and supporting conditions. Specimens are subjected to hard impact at their mid-point and simply supported at their four corners. The use of corner supports is selected to reduce the measurement of the reaction forces to specific points i.e. corners. In order to ensure hitting the specimens' mid-point, a tower frame with four vertical steel tracks is used to guide the mass. Two impact drops are applied to each specimen by dropping 475 kg weight from a constant height of 4.15 m, resulting 9 m/s theoretical impact velocity. The drop-weight is lifted to the desired height using an electrical crane. An electromagnet with a capacity of 600 kg (Fig. 2) attached to the crane is used to release the drop weight by switching off the magnet.

The drop-weight mass was manufactured by filling 400 mm square hollow structural steel (HSS) section of 750 mm high with concrete. Two 25 mm thick square steel plates are welded to the top and bottom ends of HSS section as end caps. The striking surface is flat and smooth with dimensions of 400 × 400 mm. It should be mentioned that the effect of the striking surface of the drop-weight on the dynamic response and failure mode of the RC members is very small under similar low velocity impact [5]. No damping materials are used in the contact zone during the tests since the use of damping materials inadvertently reduces the strain rate.

Previous study carried out by Soleimani and Banthia [15] showed that the reactions recorded by the support load cells for two identical impact tests without preventing vertical movements were