Engineering Failure Analysis 56 (2015) 233–243

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Failure behaviors of reinforced concrete beams subjected to high impact loading

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ARTICLE INFO

Article history:
Received 26 September 2014
Received in revised form 7 February 2015
Accepted 12 February 2015
Available online 25 February 2015

Keywords:
Falling-weight impact test
Impact loading
Reinforced concrete beam
Residual deflection
Loading rate

ABSTRACT

To attain a better understanding of the failure behavior of reinforced concrete (RC) beams under impact load, series of high speed impact experiments were performed using an instrumented drop-weight impact machine. The test program was successful in providing a substantial volume of test data including impact loads, mid-span deflections, crack profiles and strains. These data was analyzed, focusing on the impact load characteristics and the impact behaviors of RC beams. Various characteristic values and their relationships were investigated such as the drop height, the static flexural load-carrying capacity, the input impact energy and the beam response values. Two empirical formulas were proposed to estimate the maximum and residual deflection of the beam based on the static flexural load-carrying capacity and the input impact energy. The applicability of the proposed equations was confirmed by comparison with the experimental results obtained by other researchers.

1. Introduction

In addition to static loads, many reinforced concrete (RC) structures are often subjected to short-duration dynamic loads. These loads can originate from impacts by missiles, impulsive loads due to air blasts, falling heavy loads and earthquakes etc. In all these cases, it is of fundamental importance to understand the effect of loading rate on structures. The dynamic behavior of the structures under impact is generally very complex and closely related to the type of structure and the characteristic of material used in the structure. Furthermore, many problems concerning the structural impact and dynamic material properties of RC are unsolved yet. RC structures are composite constructs, composed of plain concrete and steel reinforced. The strength characteristics of plain concrete and reinforcement are known to be enhanced due to increasing loading rate [1,2]. However, current researches on the properties of RC subjected to varying rates of loading are still considered to be in their infancy.

Over the past few decades, several studies have been reported in the area of reinforced concrete members subjected to dynamic loading [3–10], which is often generated by impact. Impact behavior of beams was studied by Seabold [11], Takeda and Tachikawa [12], Hughes and Beeby [13], Banthia [14], and Ragan [15]. A general tendency towards increase in the absorbed energy at high loading rates has been reported from these tests. However, under certain circumstances, a tendency towards reduced ductility resulting from a different mode of failure has been reported in impact tests on beams [11,13,15].

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http://dx.doi.org/10.1016/j.engfailanal.2015.02.006
1350-6307/

Fujikaka et al. [16] carried out a drop-weight impact test of twelve specimens of RC beams with different impact velocities ranging from 0.15 m/s to 2.4 m/s. The influence of drop height and the amount of longitudinal reinforcement on the impact responses of the RC beams were investigated. The results indicated the maximum impact load, the impulse and the maximum mid-span deflection increase as the drop height increases. Soleimani et al. [17] performed impact experiments of seven beams with statically flexural failure mode under different impact velocities ranging from 2.8 m/s to 6.26 m/s. It was found that beyond a certain impact, the flexural load capacity of RC beams remains constant; further increase in stress rate does not increase their load carrying capacity.

Series of low speed impact experiments of reinforced concrete beams were performed with varying span lengths, cross section and main reinforcement by Tachibana et al. [18]. The experimental results were evaluated focusing on the impact load characteristics and the impact behaviors of reinforced concrete beams. Under the maximum impact velocity 7 m/s, Kishi and Mikami [19] conducted falling-weight impact tests on a total of 36 beams with varying section parameters, and the key factors for better representing the impact behavior of the beams were investigated.

In order to study the behavior of RC beams subjected to high impact loading, a drop-weight impact test was performed on eighteen specimens of RC beams with statically flexural failure mode in this paper. The impact velocities ranged from 6 m/s to 13 m/s, and loads, deflections and strains were monitored throughout the tests. The influence of drop height, the amount of longitudinal reinforcement and concrete strength on the impact responses of the RC beams was investigated. Two empirical equations were derived based on the experimental results. By using these equations, the static flexural load-carrying capacity of an RC beam might be determined by specifying the limit state with the maximum and residual deflections of the beam. Finally, the formulas were confirmed from comparison with the experimental results obtained by other researchers.

2. Experimental overview

2.1. Material properties

The mix proportion of the concrete used to cast the RC beam is tabulated in Table 1. The aggregates had a maximum size of 10 mm. All tests were performed within 3 days after 60 days of casting. The concrete compression strength was determined from the average of three 150 × 150 × 300 mm cuboids that were cast and cured under the same laboratory conditions as the beams and tested at the time of beam testing. C27 and C40 indicated the compression strengths of concrete were 27 MPa and 40 MPa, respectively. The three variations of reinforcement provided within the beam specimens include Φ6, Φ8, and Φ10 steel bars, and the yield strengths were 235 MPa.

2.2. Specimens

The reinforcement distribution form of RC protection structures is dense and diverse under dynamic load, and the specimens take the well-distributed design of reinforcement. All beams had rectangular cross section of dimensions 120 mm wide and 120 mm deep and 1.2 m clear span length. The specimens had 300 mm anchorage length beyond the supports on each side of the beam. The layout of the reinforced beams is shown in Fig. 1. The main reinforcing bars were laid out three stories, and stirrups with 6 mm diameter were placed with spacing of 100 mm. It was worth noting that the beam was designed to fail in flexural mode, since enough stirrups were provided to prevent shear failure. Details of the beam type are given in Table 2. The first number of specimen denoted the diameter of the longitudinal bar, then the compressive strength of concrete was denoted by a hyphen.

2.3. Experimental methods

The experimental program was carried out on 6 type RC beams with shear reinforcement. The specimens were simply supported and were tested in a three-point bending configuration. The supports were able to make the beam rotate freely while restrain the perpendicular movement of the beam. Here, the time history of the impact load *P*, deflection *D* and strain ε were designed to be measured. 80 mm strain gauges were installed at the distance of 100 mm from the mid-span in the upper and lower surface of the beams to measure the concrete strains. The specific locations of the strain gauges are shown

Table 1
Mix proportion of concrete.

Concrete compression strength (MPa)	United weight (kg/m^3)					
	C	MP	S	G	AD	W
C27	335	84	885	932	9.6	154
C40	455	152	732	944	17.0	149

Note: C = cement; MP = mineral powder; S = sand; G = gravel; W = water; and AD = admixture.