International Journal of Impact Engineering 67 (2014) 39–51

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Resistance of double-layer reinforced HPC barriers to projectile impact

Avraham N. Dancygier*, Amnon Katz, David Benamou, David Z. Yankelevsky

National Building Research Institute, Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel

ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form
31 December 2013
Accepted 6 January 2014
Available online 21 January 2014

Keywords:
High performance concrete
Perforation resistance
Protective structures
Steel fibers
Layered barriers

ABSTRACT

The resistance of double-layer reinforced high performance concrete (HPC) barriers to impact by a non-deforming projectile was studied experimentally. The methodology of this study consisted of comparative tests of various 800 × 800 × 200 mm^3 reinforced concrete plate specimens that were subjected to impact by “reference projectiles” that were accelerated to different velocities using a gas gun system. The effects of aggregate size, use of steel fibers, and casting in layers were evaluated. Results include the perforation limit and performance under impact as determined from damage records of the different specimens. Analysis of the results also revealed the effects of mix ingredients of the front and rear layers on the barriers’ performance. Specifically, it was found that steel fibers and appropriate use of large aggregates in different layers can enhance the overall impact resistance. Analysis of the results also included an assessment of the thickness reduction that can be obtained by applying these findings.

1. Introduction

Reinforced concrete (RC) is commonly used in structural elements that are designated to act as barriers that are required to withstand impact, whether they be civilian structures (e.g., rock sheds) or defence structures (e.g. shelters). Such structures may be subjected to impact by projectiles that result in local response characterized by penetration and local damage. Damage to the front (impacted) side of the barrier includes the formation of a crater, cracking, and penetration. Rear (inner, protected) side damage includes perforation by the striking projectile with residual velocity and cratering associated with the formation of a shear plug. Rear face scabbing may, however, develop even when the barrier is not perforated (e.g. [17]). Thus, the parameters that characterize the resistance of an RC barrier and its performance under impact load are the perforation limit, the penetration depth, and the amount of damage that develops at the front and rear faces.

Until about two decades ago, concrete resistance to impact was represented by the concrete’s compressive strength, f_c, where the resistance is inversely proportional to f_c raised to a power of about 0.5 (e.g. [11–15]). Thus, the increased strength of High Strength Concrete (HSC) called for its use in barriers required to resist impact. Indeed, it was shown in the mid 1990’s that HSC has an improved resistance to impact [1]. Further research has shown that other concrete mix ingredients should also be considered, in addition to the single strength parameter that used to represent the barriers’ impact resistance [2–4,16]. These ingredients include the use of fibers, the size and type of aggregates, and the detailing of the steel rebars. Moreover, these studies showed that each of these ingredients plays a different role in contributing to the barrier’s overall resistance to impact.

These findings lead to the understanding that prudent design of protective barriers should consist of different layers with mechanical properties that vary according to the position of each layer in the path of a penetrating projectile. Although very little experimental evidence has been published, it is likely that the performance under impact of a barrier made of different layers that consist of different concrete mixes will potentially be enhanced. This potential was partially indicated in tests of double-layered RC plates conducted by Shirai et al. [5]. Their specimens were double-layer composite plates with and without absorbers between layers of limited thickness (about 1:1 ratio between projectile diameter and target thickness). In addition to recognizing the advantage of using HSC, Shirai et al. concluded that resistance to impact is increased when double layers are applied and that a thicker rear layer reduces local damage even without absorbers between the layers.

The current study was inspired by the authors’ earlier studies (e.g. [4]) that indicated that a single layered specimen may exhibit

* Corresponding author.
E-mail address: avidan@technion.ac.il (A.N. Dancygier).

0734-743X/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2014.01.001

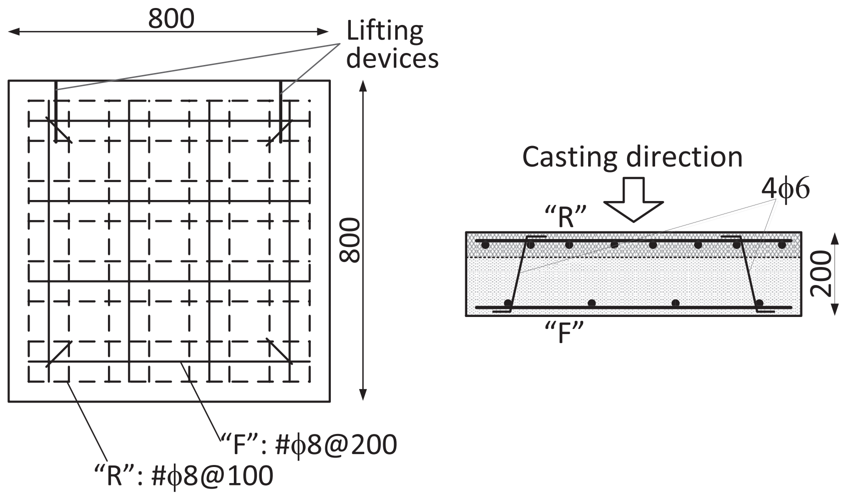

Fig. 1. Schematic description of a typical specimen (“F” and “R” denote front and rear faces, respectively).

different efficiency with regard to different modes of damage such as its resistance to perforation, size of front and rear face craters, etc. This finding led the authors to study the behavior of targets made of layers that may enhance the targets' overall behavior compared to single-layered targets. The present study focuses on the resistance to impact of layered barriers made of high performance concrete (HPC). Specimens consisting of two layers, which were cast continuously, one on top of the other, were tested under impact of reference projectiles. Their resistance and performance were compared with each other as well as with single-layer control specimens.

2. Experimental program

The study was based on laboratory experiments using 800×800 mm^2 concrete specimens that were composed of two different layers, Fig. 1. Single-layer control specimens were also tested for comparison. All specimens were 200-mm thick and included meshes of 8-mm deformed bars (nominal yield strength of 400 MPa) at spacing of 200 and 100 mm near the front and rear faces, respectively. The concrete cover was 15 mm thick. Casting of the layers was continuous, rear layer on top of front layer (horizontal forms).

The specimens were subjected to impact by a “reference projectile”, 50-mm in diameter, with a conical nose made of hardened steel and a nominal weight of 1750 gr, Fig. 2. The projectiles were accelerated by a gas gun to various striking velocities of up to ~300 m/s.

All mixes were of high strength concrete (HSC) with uniaxial compressive strengths ranging from 90 to 117 MPa (measured at 28 days on 150-mm cubes). Mixes differed in two of their ingredients: dolomite aggregate, whose maximum size was either 19 or 37 mm, and type and amount of fibers. Additionally, some of the specimens had uneven layers in terms of thicknesses. Table 1 presents the specifications of the different specimens, whereby notation of the specimens includes the following terms: “SL” denotes single-layered specimens, “19” and “37” indicate the maximum aggregate size (mm), “F” and “R” stand for front and rear layers, “100” and “140” indicate the thickness of the front layer in mm. The corresponding thickness of the rear layer is 100 and 60 mm, respectively, summing to a total thickness of 200 mm. The terms “−0”, “−1” and “−11” indicate specimens without fibers, with fibers at 60 kg/m^3, and with fibers at 80 kg/m^3, respectively. For example, the specimen denoted 140F37-1/R19-0 had a 140-mm front layer with maximum aggregate size of 37 mm and 60 kg/m^3 fibers and a 60-mm rear layer with regular aggregates (maximum size of 19 mm) without fibers. Three to six plates were cast from each of the specimens that are detailed in Table 1 and 61 plates were tested in total.

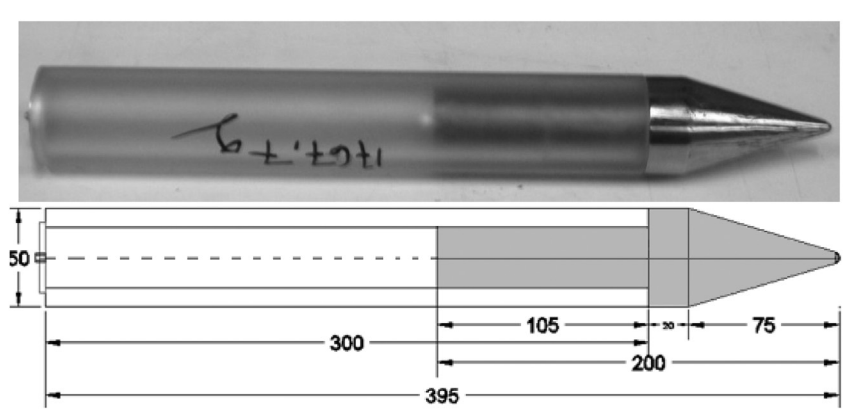

Fig. 2. Photo and sketch of the reference projectile.