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Response of high-strength reinforced concrete beams under shock-tube induced blast loading

Yang Li, Omar Algassem, Hassan Aoude *

Department of Civil Engineering, University of Ottawa, Ottawa, Canada

HIGHLIGHTS

- Ten high-strength concrete beams are tested under quasi-static & blast loads.
- Effects of concrete strength and steel reinforcement detailing are investigated.
- Failure mode and resistance under static and dynamic loading are compared.
- HSC beam response is predicted using dynamic inelastic SDOF analysis.

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ABSTRACT

This paper presents the results of study examining the blast performance of reinforced concrete beams constructed with high-strength concrete (HSC). As part of the experimental program, a series of five beams are tested under simulated blast loading using a high-capacity shock-tube at the University of Ottawa. Parameters investigated include the effect of concrete strength, shear reinforcement and longitudinal reinforcement ratio. The effect of loading rate is investigated by testing a companion set of five beams with identical properties under slowly applied (quasi-static) loading. The results show that increasing the reinforcement ratio improves the blast performance of HSC beams by increasing overall blast capacity and reducing maximum and residual displacements at equivalent blast loads. The effect of concrete strength on blast performance is found to be more limited, with companion normal-strength and high-strength concrete beams showing similar performance. The results also confirm the importance of providing transverse reinforcement to prevent blast-induced shear failures in HSC beams. As part of the analytical study, the blast response of the HSC beams is predicted using dynamic inelastic single-degree-of-freedom (SDOF) analysis.

1. Introduction

The need to design structures against blast hazards has become increasingly important. As demonstrated in recent events, blast loads caused by malicious attacks or accidental explosions can cause catastrophic and devastating failures in structures (e.g., Alfred P. Murrah Building, 1995; Khobar Towers, 1996; Lac-Mégantic Disaster, 2013). To better protect the public and provide guidance to engineers, blast design provisions have recently been developed worldwide, including in the United States, the UK & Canada [1].

The use of high-strength concrete (HSC) in structures has become widespread due to its enhanced strength, stiffness and durability properties. ACI Committee 363 defines HSC as "concrete that has a specified compressive strength of 55 MPa or greater", however concretes having strengths of 80–100 MPa are now commonly available and used in practice [2]. Over the years, extensive research has studied the behavior of HSC structures under quasi-static and earthquake loading [3,4]. Consequently, design requirements for the structural use of high-strength concrete are now well established in several codes worldwide [5]. In contrast, research on the blast behavior of HSC structural components is limited, especially in the case of flexural members subjected to far-field blasts. Moreover, current blast design provisions are intended for normal-strength concrete (NSC) structures and there is an important need for data to validate existing blast design procedures for HSC.

The work reported in this paper is aimed towards better understanding the behavior of high-strength concrete beams under blast loading. As part of the study, a series of large-scale beams are tested under simulated blast loads using a high-capacity shock-tube. Parameters investigated include the effects of concrete

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* Corresponding author.
E-mail address: haoude@uottawa.ca (H. Aoude).

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strength, steel reinforcement ratio and transverse steel detailing. The effect of loading rate is also investigated by testing a companion set of beams with identical properties under slowly applied loading. As part of the analytical study, the blast response of the HSC beams is predicted using dynamic inelastic single-degree-of-freedom (SDOF) analysis.

2. Background

It is well known that concrete becomes more brittle as its strength is increased, which can raise questions about the ductility of HSC structural members. In the case of beams, it can be shown through analysis that an increase in concrete strength (f'_c) enhances ductility when all other parameters are kept constant [6]. Experimental results reported by several researchers support this conclusion [7,8]. However, other studies report that the increase in ductility only occurs up to a strength of approximately 80 MPa, after which the trend reverses. For example, Ashour [9] observed that beam ductility increased as f'_c went up from 50 to 80 MPa, but then decreased as f'_c increased further to 100 MPa. Rashid & Mansur [6] and Shin et al. [10] have observed the same effect in doubly reinforced beams (see Fig. A1a). Many previous studies have also examined the effect of longitudinal steel ratio (ρ) on the flexural behavior of HSC beams [3]. Fig. A1b plots the displacement ductility of a large set of HSC beams from the literature as a function of the ratio ρ/ρ_b, where ρ_b is the balanced steel reinforcement ratio; it is evident that the ductility greatly reduces as this ratio is increased, particularly when ρ exceeds 0.4–0.5 ρ_b.

The behavior of reinforced concrete beams under impact loading has been studied by many researchers (see references [11,12] for an overview of previous studies). Among previous investigations, a few have focused on the effect of concrete strength [13–19] (see Table A1). Banthia [14] conducted one of the more comprehensive investigations in this area. As part of this study, a large set of plain and conventionally reinforced concrete beams ($f'_c = 40$ and 80 MPa) were tested using an instrumented drop-weight machine. In the case of the plain specimens, HSC was found to have higher bending strength but reduced fracture energy when compared to NSC, an indicator of increased brittleness. Moreover, steel-reinforced HSC specimens showed reduced fracture energy and more brittle behavior under impact versus static loads, and as the stress-rate (drop-height) was increased. Adding fibers was found to be effective in increasing the ductility and energy-absorption capacity of HSC. Conclusions from other studies are summarized in Table A1.

Despite this important research, a survey of the literature reveals limited data on the dynamic performance of HSC beams having concrete strengths greater than 85 MPa, although a few previous studies have focused on beams built with ultra-high performance concrete (UHPC) [20–22] (see Fig. A2). Several studies have reported that the dynamic properties of HSC change as its static compressive strength is increased. For example, Guo et al. [23] examined the strain-rate dependence of three high-strength concretes with compressive strengths of 60, 80 and 110 MPa (C60, C80, C110) using a Split Hopkinson Pressure Bar (SHPB) device and reported much lower dynamic increase factors (DIF) for the C110 concrete when compared to the C60 and C80 mixes. Similar observations have been made by Ngo et al. [24] and others. Hence, there is a need for further research on the dynamic performance of beams built with higher-strength HSC ($f'_c > 85$ MPa).

Compared to impact, very few experimental investigations have focused on the blast behaviour of beams [25–29], although a few studies have examined this problem numerically [30–32] (see Table A2). Research on the performance of beams subjected to far-field blasts is particularly limited. Data on the blast behavior of HSC beams is also scarce, however Magnusson et al. [27] conducted one of the few studies in this area. In this study, the blast behavior of beams having varying concrete strengths, fiber contents and reinforcement ratios was assessed by detonating a spherical plastic explosive placed at 10 m from the specimens. The study found that beams of all concrete grades experienced increased load capacities under dynamic loading, with dynamic-to-static load ratios ranging from 1.04 to 1.81. However, in some cases, the failure mode changed from ductile flexure to brittle shear under blast. Plain HSC beams with larger steel ratios were particularly susceptible to suffering such shear failures, while the provision of fibers was effective in solving this problem. It is noted that the beams in this study had relatively small depth-to-width ratio (h/b = 0.5). It is well known that shear and flexural failures in RC beams are size dependent. Consequently, there is a need for further research on the blast behavior of HSC beams with larger depth-to-width ratios [27].

In summary, several researchers report that beam ductility under quasi-static loads improves as concrete strength is increased, however other data indicates this only occurs up to a strength of about 80 MPa. Research shows that higher-strength HSC shows reduced strain-rate dependence, and there is limited data on the impact performance of HSC beams built with concrete strengths exceeding 85 MPa. Experimental research on the behavior of beams subjected to far-field blasts is scarce and there is also a need for data on the blast performance of HSC beams with larger depth-to-width ratios.

This paper presents the results of well-instrumented experiments examining the behavior of high-strength concrete beams under far-field blast loading. The tests provide important insights into the effects of various design parameters affecting HSC beam blast performance, including: concrete strength, longitudinal reinforcement ratio and transverse steel detailing. The tests also provide much needed data on the dynamic performance of beams built with higher-strength HSC and larger depth-to-width ratios. Finally, the study includes specimens tested under both static and blast loads providing important data on the effects of loading-rate on the behavior, resistance and failure mode of HSC beams.

3. Experimental program

3.1. Description of test specimens

A total of ten reinforced concrete beams were built and tested in this research program. Five of the beams were tested under simulated blast loads using the University of Ottawa shock-tube, while a companion set of five beams were tested under static loading. As shown in Fig. 1a, all specimens had dimensions of 125 mm × 250 × 2440 mm and were tested under four-point bending over a simply-supported span of 2232 mm. In all cases, the beams had a constant moment region of 750 mm and shear spans of 741 mm, resulting in a shear-span-to-depth ratio, a/d = 3.7. The beam dimensions were chosen based on the limitations of the shock-tube (size of the end-frame, configuration of the load-transfer device and limitations on possible reflected pressure and impulse). Table 1 summarizes the design details of the specimens. The majority of the beams were cast using high-strength concrete having a specified strength of 100 MPa (C100), with two beams cast using a lower-strength concrete having a specified strength of 50 MPa (C50). Longitudinal reinforcement consisted of either 2 – No.4, 2–15M or 2–20M bars (steel areas, $A_s = 258$ mm^2, 400 mm^2 and 600 mm^2), resulting in reinforcement ratios of $\rho = 1\%$, 1.6% and 2.4%. The steel ratios were chosen based on the limits prescribed in the CSA S850 blast standard [1] which