Engineering Failure Analysis 41 (2014) 73–80

Contents lists available at ScienceDirect

Engineering Failure Analysis

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

An experimental study on the failure modes of high strength concrete beams with particular references to variation of the tensile reinforcement ratio

Mohammad Mohammadhassani *,[1], Shatirah Akib, Mahdi Shariati, Meldi Suhatril, M.M. Arabnejad Khanouki

Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Available online 25 September 2013

Keywords:
Failure mode
High strength concrete
Tensile reinforcement ratio
Premature failure

ABSTRACT

For many years, high-strength concrete (HSC) has been used in high-rise buildings and bridges. The primary reasons for selecting HSC are to produce a more economical product, provide a feasible technical solution, or a combination of both. Despite a lot of advantages in the usage of HSC, it exhibits a brittle failure in comparison with normal strength concrete (NSC). For a comprehensive discussion on the failure of HSC beams, a total of six full scale reinforced HSC beams have been designed based on ACI code provisions and cast with compressive strength in the range of 65 MPa $\leqslant f'_c \leqslant$ 75 MPa and tested under two-point top loading. The general behaviour of tested beams has been investigated with observation on mid span deflection, failure mode and crack growth. Increase of the tensile reinforcement ratio results in more cracks but with lower height and width. The linear graphs between the applied load and corresponding deflection or curvature in reinforced HSC beams showed that the behaviour of these beams is elastic and any increase in the tensile reinforcement ratio results in an increase in the ultimate load too. The moment–curvature graph and load–deflection curve started with an initial elastic response followed by an inelastic behaviour that appears with a gradual decrease in stiffness till the ultimate moment is reached.

1. Introduction

Over the past three decades, the development of HSC has enabled builders to construct high rise concrete structures with compressive strength that exceeds 120 Mpa. With the expansion in material technology, it is possible to design HSC that has superior mechanical properties and structural behaviour. The use of HSC is reasonable where reduced weight is important or when architectural considerations call for small support sections. With the ability of carrying loads more efficiently than normal-strength concrete (NSC), HSC reduces the total amount of material used and the cost of the structure. Many researchers have studied the behaviour of structural elements constructed using HSC [1–7].

The codes of practice are still lacking a comprehensive provision in the design and failure prediction of HSC sections. In this study, attempts have been made to show the behaviour of HSC beams with regards to tensile reinforcement ratio variations. The purpose of this study is to present the probable failure modes of HSC beams with varying tensile

* Corresponding author. Tel.: +60 9133420110.
E-mail address: mmh356@yahoo.com (M. Mohammadhassani).
[1] Ph.D. at Structural Engineering.

1350-6307/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engfailanal.2013.08.014

reinforcement ratio. HSC exhibits a brittle behaviour and this study helps designer to be aware of limiting the amount of tensile reinforcement in the HSC beam section for preventing the brittle failure of concrete and predicting the failure modes. This is important for a designer to achieve the full potential of using steel reinforcement with a safe failure.

Various parameters affect the failure of RC beams which include shear span to effective depth ratio (a/d), tensile reinforcement ratio (ρ), aggregate type, concrete strength, loading type and support conditions, etc.

2. Shear span-to-effective depth ratio (a/d)

It has been shown that the failure mode is strongly dependent on the shear span to depth ratios (a/d). An increase in shear capacity with a decrease in a/d ratio has been reported [8], with this increased resistance to diagonal tension with small a/d, being described as a local loading effect due to direct transfer of load to supports through concrete compression [9]. An increase in diagonal cracking load with an increase in shear span of concrete compressive strength up to 27.59 MPa was discovered [10]. A decrease in relative flexural strength with an increase in a/d ratio up to about 2.5 for concrete compressive strength ranging from 17.24 MPa to 34.48 MPa was found [11]; afterwards the increase occurred at a slower rate. An increase in shear capacity due to a decrease in a/d ratio also was observed in another research [12].

It was concluded that the flexural strength and mode of failure are dependent on the a/d ratio [13]. At constant a/d ratio, the failure load increases with the increase in tensile reinforcement ratio 'ρ'. Fewer but wider cracks were observed in beams with lower tensile reinforcement ratio. In constant tensile reinforcement ratio, shear strength and failure load decrease and deflection of the beam increases with the increase in the a/d ratio.

In another research eighteen rectangular singly reinforced HSC beams without web reinforcement in combined shear and flexure have been tested [14]. The main variable in their tests involved shear span to effective depth ratio and tensile reinforcement ratio. In relation to shear span–depth ratio (a/d), with regard to Fig. 1, they conclude that the experimental shear strength decreases with an increase of a/d ratio. They find the a/d ratio of 2.5 as a transition zone. These results are corresponding to the classification of normal and deep beams in codes of design. In fact, for a given tensile reinforcement ratio and applied load on a beam, a larger ratio of a/d leads to flexural behaviour. In contrast, increasing the depth of penetration of load or a lower a/d ratio directs to shear behaviour of tested beams.Their findings show that an increase of the a/d ratio from 4.0 to 6.0 results in a shear strength reduction of 6.8% and 21.3% for beams of $\rho = 4.58\%$ and $\rho = 2.84\%$, respectively.

This significant reduction in strength shows the effect of yielding of the longitudinal steel close to failure which permitted the crack to increase in both length and width and adversely affected the dowel action in addition to a/d ratio.

Based on their results, they have concluded that the beams with a/d < 2.5 exhibited greater resistance to shear than other beams. They have found that the tensile reinforcement ratio has greater influence on the shear strength of beams whose a/d ratios are smaller than 2.5. The analyses of their results show that an increase of the tensile reinforcement ratio from 2.84% to 4.58% raised the shear strength by 38.9–44.7% for beams of a/d ratio of 2.0 and 1.0, respectively. They have categorized the failure modes of tested HSC beams into three groups based on the following experimental results.

3. Tensile reinforcement ratio

The shear strength of a beam increases with the increase in tensile reinforcement ratio. A strong relationship between cracking shear and reinforcement ratio in under-reinforced beams having steel ratio of <0.015 was confirmed [15] and a

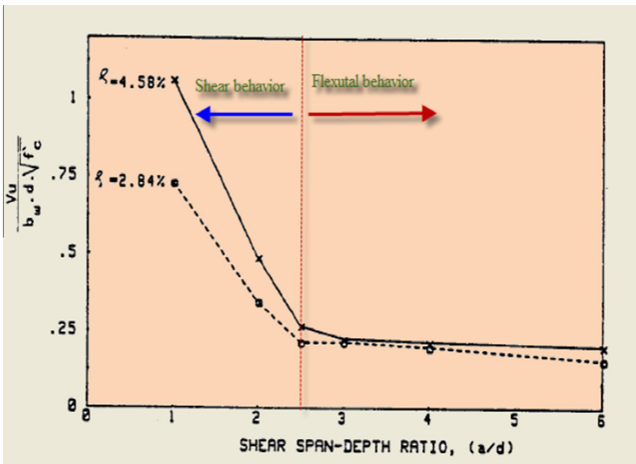

Fig. 1. Effect of shear span–depth ratio (a/d) on the experimental shear strength and behaviour of beams.