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Failure modes and serviceability of high strength self compacting concrete deep beams

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ABSTRACT

The behaviour of deep beams is significantly different from shallow beams. In deep beams, the plane section does not remain plane after deformation. The main purpose of this study is to facilitate the prediction of deep beam failure related to tensile bar and web reinforcement percentage variations. Six high strength self compacting concrete (HSSCC) deep beams were tested until failure. Strains were measured on concrete surface along mid span, tensile bar and compression strut trajectory. The load was incrementally applied and at each load increment new cracks, their widths and propagation were monitored. The results clearly show that, at ultimate limit condition, the strain distribution on concrete surface along mid-span is no longer parabolic. In deep beams several neutral axes were obtained before ultimate failure is reached. As the load increases, the number of neutral axis decreases and at failure load it reduces to one. The failure of deep beams with longitudinal tensile steel reinforcement less than that suggested by ACI codes is flexural and is accompanied by large deflections without any inclined cracks. As the longitudinal tensile steel reinforcement increases, the failure due to crushing of concrete at nodal zones was clearly observed. The first flexural crack at mid-span region was always vertical. It appeared at 25–42% of peak load. The crack length was in the range of 0.24–0.6 times the height of section. As the tensile bar percentage increases number of cracks increases with reduced crack length and crack width. The appearance of first inclined crack in compression strut trajectory is independent of tensile and web bar percentage variations.

1. Introduction

Deep beams are widely used as transfer girders in offshore structures and foundations. With the strong growth of construction work in many developing countries, deep beam design and its behaviour prediction are a subject of considerable relevance. Traditional design assumptions, especially regarding plane section remaining plane after bending for shallow beams, do not apply to deep beams. Even the definition of transition from shallow to deep beam is imprecise in most codes of practice. The ACI 318-99 [1] and CIRIA Guide 2 [2] use span/depth ratio to define RC deep beams while the Canadian code CSA 1994 [3] and CEB-FIP model code [4] employs the concept of shear span/depth ratio. The ACI code defines beams with clear span to effective depth ratios less than 5 as deep beams, whereas CEB-FIP 1993 [4] code treats simply supported and continuous beams having span/depth ratios less than 2 and 2.5 respectively, as deep beams. However, it should be noted that the design of these structural elements are not adequately covered by existing codes of practices. For example, the British code BS8110 [5], explicitly states that, for design of deep beams, reference should be made to special literature. The ACI code,

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draft of Eurocode EC/2 [6], Canadian code [4] and CIRIA Guide 2 [2] present some design guidelines based on empirical analysis or strut and-tie model. Failure behaviour of deep beams is significantly different from that of shallow beams because of geometry and load transfer mechanism. Thus serviceability and failure pattern of these structural elements is not reported extensively due to the lack of clear procedure for prediction of their behaviour.

Zhang and Tan [7] concluded that settlement of middle support significantly affects the serviceability load, crack pattern and failure mode. Yang et al. [8] proposed a numerical technique to assess the load capacity of continuous deep beams. The method was based on upper bound analysis of plasticity theory. Chemrouk and Kong [9,10] showed that the current codes and design manuals covering continuous deep beams could lead to severe cracking and may be unsafe for structural members. Ashour and Yang [11] stated that the strut and-tie model and mechanism analyses are more rational, adequately accurate and sufficiently simple for estimating the load capacity of reinforced concrete deep beams. Zekai Celep et al. [12] presented that the structural damage level is directly proportional to the amount of the insufficient quality in workmanship and usage of inadequate building materials.

The study carried out by Ray [13] and Mohammadhassani [14] confirmed that the strain and stress variations are nonlinear across the deep section depth. They also concluded that there are more than one neutral axis (N.A.D) before ultimate failure is reached. The use of HSSCC in deep beams has not been widely reported. In HSSCC, difference between the strength, elastic modulus of aggregate and matrix are much smaller compared with shallow strength concrete (NSC). Moreover, in NSC, the behaviour is linear up to 40% of the maximum stress while it is about 85% in HSSCC sections [15]. An experimental study by Mohammadhassani et al. [16] confirmed the need of evaluation of modulus of elasticity at higher stress value in stress–strain curve. Thus the behaviour of HSSCC is close to linear elastic with brittle failure, in comparison with the behaviour of same structure made of shallow concrete. Therefore the main objective of the present experimental study is to investigate different failure modes by varying different parameters such as concrete compressive strength, tensile bar and web reinforcement percentages. In addition, the present work also discusses serviceability of deep beams in terms of deflection.

2. Experimental programme

Six HSSCC deep beams were designed based on provisions given in ACI318-95 Code. HSSCC is a highly flowable, non-segregating concrete that can spread into mould and fill the formwork. It does not require vibrators for concrete consolidation. For deep beams the density of bars is high, making it difficult for vibration. Therefore the use of HSSCC in deep beams is highly desirable. The mix proportions for HSSCC is given in Table 1 and mix design details are presented by Mohammadhassani [14]. Local aggregate with maximum 20 mm diameter is used in producing concrete. Ordinary Portland cement, natural river sand, microsilica and super plasticizer are used. The concrete mix by weight with water cement ratio of 0.27 is kept constant for all the deep beams. Table 1 shows the specifications of HSSCC concrete mix design.

In mix design, flowability was kept in the range of 550–740 mm to prevent segregation. For each beam, nine cubes (100 mm × 100 mm × 100 mm) and three cylinders (150 mm diameter, 300 mm height) were casted as control specimens. Cubes were tested for crushing strength at 7 days, 28 days, and the age of loading. The cylinders were tested for splitting tensile strength at 28 days. The deep beams were casted in steel mould and were de-moulded after 3 days. Moreover, the test samples were covered with canvas and plastic for 2 weeks after casting. The canvas was watered twice a day for 11 days after the framework was removed. All cylinder and cube samples that have been used for strength control were demolded after 24 h and cured ms in humid conditions until the age of testing. The properties of hardened cementitious material and tensile bar percentage for each deep beam are listed in Table 2. The concrete strength mentioned in Table 2 is an average strength of three cube samples at the age of loading for each beam.

In this table ρ and f'_c are tensile bar percentage and concrete compressive strength of cube samples at loading age respectively. Table 3 shows the properties of steel bars used in the present study. Except 9 mm diameter bars all the other bars are high tensile strength deformed bars. Tensile test for number of samples were taken from each batch supplied. In this table f_y and f_u are yield and ultimate stresses of bars respectively.

Beam length, depth and thickness were kept constant while varying the percentage of tensile reinforcement. The geometrical parameters of deep beams are schematically presented in Fig. 1.

Table 1
HSSCC mix design.

Characteristic cube strength	75 MPa
Aggregate	Crushed granite and natural sand
Cement	Ordinary Portland cement
Slump of concrete	More than 650 mm
Coarse aggregate	553 kg/m^3
Fine aggregate	887 kg/m^3
Water-cement ratio	0.27
Water-binder ratio	0.25
Super plasticizer	46.0 kg/m^3
Silica fume–cement ratio	0.1