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Locating the site of diagonal tension crack initiation and path in reinforced concrete beams

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Abstract The most favorable site of diagonal tension crack initiation has been attempted to be located. Due to the numerous interacted parameters affecting both site and angle of diagonal tension crack initiation, twelve possible sites were investigated, at midheight of the shear span and at the bottom surface near the support of the beam with vertical and diagonal orientations. The first diagonal tension crack initiated from the bottom tip of the diagonal pre-crack at midheight of the beam as a result of constraint release. To verify the previous finding, a single diagonal pre-crack has been created at midheight of only one side of the shear spans in both normal and fiber reinforced concrete (FRC) beams. FRC beam showed different behavior, where couple of diagonal tension cracks initiated at both sides from the tip of flexural cracks regardless of the existence of pre-crack at one side of the beam.

1. Introduction

Even though the shear behavior of reinforced concrete has been studied for more than a century, the problem of determining the shear strength of reinforced concrete beams remains open to discussion. The shear strengths predicted by different current design codes [1–5] for a particular beam section can vary by more than the double. In contrast, the flexural strengths predicted by the same codes are unlikely to vary by more than 10%. For flexure, the plane sections hypothesis forms the basis of a universally accepted, simple, rational theory for predicting flexural strength. In addition, simple experiments can be performed on reinforced concrete beams subjected to pure flexure and the clear results from such tests have been used to improve the theory. In shear, there is no agreed basis for a rational theory, and experiments cannot be conducted on reinforced concrete beams subjected to pure shear [6]. Shear strength is still a controversial subject,

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specially when dealing with concrete. The main difficulty is that, concrete is a composite, non-homogeneous, and non-isotropic material that cracks at a low tension stress. Moreover, the shear-span-to-depth (a/d) ratio of a beam affects the load path, which in turn, has a significant influence on the beam shear capacity [7].

One of the most accepted traditional shear tests on a reinforced concrete beam is 4 PB. The region of the beam between the two point loads is subjected to pure flexure, whereas the shear spans of the beam are subjected to constant shear and linearly varying moment. Because the behavior of this member is changing from section to section along the shear span, it is difficult to use the results of such a test to develop a general theory for shear behavior. Thus, if a relationship is sought between the magnitude of the shear force and the developed strains in stirrups, it will be found that the strain magnitude is different for every stirrup and is also different over the height of each stirrup. Generally, the shear failure of a reinforced concrete beam is directly related to the diagonal tensile cracking that develops in the direction perpendicular to the principal tensile stress axis [6].

The shear behavior of concrete beams depends on the development of the two shear load transfer mechanisms namely: arch action and beam action. In brief, a load transferred in arch action goes directly from the loading point to the support while a load transferred in beam action goes through a truss before reaching to the support. The extent of arch and beam action depends highly on the shear-span-to-depth a/d ratio. Beam action is the dominant load transfer mechanism in slender and very slender beams (a/d ratios are between 2.5 and 6 or greater), while arch action develops in short and very short beams (a/d ratios are between 1 and 2.5 or smaller). For slender beams with no or a low level of web reinforcement, the typical failure mode is diagonal-tension failure. This type of failure is sudden and is due to the loss of equilibrium after the development of inclined flexure–shear cracks. If more web reinforcement is provided in slender beams, the mode of failure changes to shear–compression failure, which is a failure due to concrete crushing above the tip of a shear crack. Short beams fail in shear–compression failure, but they also commonly fail in shear–tension failure, which is bond failure due to secondary shear cracking along the tensile reinforcement. For very short beams, arch action dominates the shear transfer mechanism resulting in a near-uniform tensile force along the longitudinal tensile steel, which often leads to anchorage failure at the support. If adequate anchorage is provided for very short beams, web crushing failure is likely to occur [8]. To provide an accurate and consistent shear prediction for beams, a valley of diagonal tension failure could be achieved by adopting Kani Valley theory. The effect of tensile reinforcement of the beams, the relative flexural to ultimate moment of the beam M_u/M_{fl}, and the variation of shear-span-to-depth (a/d) ratio are considered [9,10].

2. Objective

The objective of the current work was to locate the most favorable site and path of diagonal tension crack initiation in both normal and fiber reinforced concrete beams. A parametric study concerning the inherent constraints surrounding the initiated crack was conducted to achieve that objective.

3. Experimental programme

The experimental study to accomplish the objective of this work was divided into three groups, pilot beam, virgin beams, and one sided precracked beams. All tested RC beams were large scale of $152 \times 254 \times 2000$ mm in dimension.

All groups were examined under four point bending, and designed to fail within shear span under the generated diagonal tension cracks (DT failure). Deficient shear reinforcement accompanied with well designed flexural reinforcement guaranteed such shear failure mechanism. Adopting Kani Valley theory a/d for current work was kept equal to 2.814. The critical $(a/d)_c$ for such configuration to force DT cracks equals (2.39), as will be detailed.

The concrete used in this test programme is high strength, self compacting, ready mix concrete (HSSCRMC) supplied from HOGG ready mix plant, Waterloo, Canada. The compressive strength of the concrete was 74 MPa and its tensile strength was 8 MPa. Steel fibers (hooked end RL-45/50-BN DRAMIX steel fiber) with mechanical properties shown in Table 1 were added on site at the conveying truck mixer when needed for fiber reinforced concrete beams fabrication.

Reinforcement steel with yield strength of 400 MPa caging was designed to achieve high flexural strength (bottom reinforcement 3 Dia 16), and deficient shear reinforcement (stirrups 2.5 Dia 8/m). The steel reinforcement was instrumented using three strain gages on the bottom reinforcement and one strain gage on each stirrup prior to concrete casting as shown in Fig. 1 .A full protocol of preparing reinforcement bars Prior to installing the strain gages was carried out. The strain gages were attached to the bars using special cement recommended by the manufacturer. The strain gages and the connecting terminals were covered with wax to protect the gages from damage during the concrete casting as shown in Fig. 1. Another group of strain gages was attached to the concrete surface at different positions. All beams were tested using a computer controlled actuator with a capacity of 440 kN and a data acquisition system recording the readings of load cell, strain gages, and LVDTs as shown in Fig. 2.

Table 1 DRAMIX data sheet.

Geometry	Length (L) 45/50.0 mm	Performance Class: 45	Aspect ratio $L/d = 48$	Diameter 1.05 mm
Specifications	Tensile strength 1000 N/mm^2	Coating None	Carbon content Low carbon	#/kg 2800 fibers/kg

DRAMIX **RL-45/50-BN** ($R_{\text{ound}} - L_{\text{oose}}$ class 45–50 mm $B_{\text{right-low carbo}}$N)