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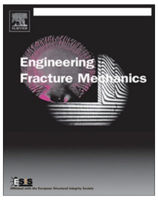

Experimental investigation of crack propagation and crack branching in lightly reinforced concrete beams using digital image correlation

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ABSTRACT

Relatively few fracture-oriented experimental studies have been conducted on concrete that is reinforced. An experimental investigation was therefore undertaken to explore the cracking process in lightly reinforced concrete (RC) beams and to observe the details of the localised fracture process zone development. More specifically, the aims were to investigate the relationships between beam height (120 mm, 220 mm and 320 mm), steel reinforcement ratio (0.1–0.5%), ductility and the onset of crack branching. RC beams were tested in three-point bending and experimental surface strains and crack openings were inferred using digital image correlation (DIC). It was found that the presence of the reinforcement prevented premature fracture and led to crack branching where a single crack bifurcated in the region of the compression zone. In the larger beams the branching developed at a lower relative height and a greater reinforcement ratio led to a shallower branching angle. These observations were associated with ductility measures for lightly reinforced concrete beams.

1. Introduction

Concrete is a quasi-brittle material that has a relatively weak tensile strength when compared with its compressive strength. It is therefore susceptible to cracking. Over the past decades the mechanics of concrete cracking have been investigated using different approaches such as finite element analyses, linear fracture mechanics (LFM) and non-linear fracture mechanics (NLFM), to develop models to simulate concrete cracking [1–8]. The cracking process in concrete is complex because the crack itself is a partially damaged zone with some capability for stress-transfer in the fracture process zone (FPZ). The FPZ acts as a transition zone between the discontinuous open crack and the continuous intact material beyond the crack. Although there is some debate about what constitutes a FPZ, and the size of the FPZ, there is a general agreement that it exists in concrete [9]. A realistic description of the FPZ is essential in order to understand damage mechanisms and to predict and optimize the behaviour of concrete structures. The FPZ is also important in determining a characteristic length of the microstructure that reflects size effects [10,11]. Theoretical studies have been conducted to understand the nature of the FPZ in concrete. Wecharatana and Shah [12] developed a theoretical model to predict the FPZ length where it was found that the length of the FPZ remains constant during slow crack growth. However, theoretical calculations of the length of the FPZ are very sensitive to the value of the critical crack mouth opening displacement (CMOD) [12].

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Nomenclature

μ	ductility factor
ϕ_{max}	maximum curvature of the critical section of the beam
ϕ_y	curvature at yielding
θ_{max}	maximum rotation at the plastic hinge
θ_y	rotation at yielding
Δ_{max}	maximum displacement
Δ_y	displacement at yielding

Various experimental techniques such as optical interferometry and imaging analysis techniques have also been adapted to investigate the extent of the FPZ. This is a challenging undertaking due to the existence of high localised stresses and strains in the FPZ which cannot be measured using standard gauges. An early attempt to investigate the strain field around the FPZ was undertaken by Cedolin et al. [13] who used optical interferometry to map the FPZ with contour lines of equal deformation. A more recent development is the use of digital image correlation (DIC) to measure the width of the FPZ in unreinforced concrete [10].

In reinforced concrete, the fracture process is further complicated by the presence of the reinforcement that affects the crack development and propagation. The cracking process is associated with diverse phenomena such as the formation of cracks, crack propagation, the existence of micro-cracks, interactions between the reinforcement and concrete, and the concrete microstructure e.g. cement and aggregate [2]. In addition, numerous factors can influence the cracking process and reinforcement crack bridging including the concrete compressive strength, the type, the properties and the ratio of the longitudinal reinforcement, the bond between the reinforcement and the concrete, and the geometrical properties and the size of the beam. These factors can be inter-related and inter-dependant. Furthermore, the cracking process in reinforced concrete (RC) may involve several macro-cracks propagating at the same time leading to different failure modes. Internal reinforcement bridges a crack and improves the fracture toughness by providing a stitching action that prevents the crack faces from opening and controls the crack growth by increasing the energy demand for crack advancement [14]. The fracture energy is closely related to the FPZ size and this implies that the existence of a FPZ may be the intrinsic cause for size effects. In concrete the FPZ covers a narrow crack band and only the region along the crack path is affected by cracking [15–17]. However, in reinforced concrete the nature of the FPZ remains unclear. Most theoretical studies incorporate the reinforcement according to the principle of superposition by considering concrete fracture and adding the effect of the reinforcement as a closing force [4,7,18–20]. Although the fracture properties of reinforced concrete at the structural scale have been studied, there is a need for further detailed investigations to better understand the nature of the fracture process.

A survey of literature in this field shows that relatively few experimental studies have investigated the fracture process in reinforced concrete as opposed to unreinforced concrete. Digital image correlation (DIC) has been used to evaluate the displacement and strain fields in bending tests on RC beams [21] where the focus was to test the performance of DIC and demonstrate its potential for investigating fracture properties. Skarzynski and Tejchman [16] tested small RC beams with a height of 80 mm and length 320 mm (effective length 240 mm) with a reinforcement ratio of 1.5%. It was found that the localised zones are always created prior to the attainment of the peak load and the lengths of the fracture zones in RC beams (0.8 of the beam height) are higher than those in unreinforced concrete beams (0.6 of the beam height). Alam et al. [22] used Acoustic Emission (AE) to study microcracking in RC beams. It was found that as the beam size increases, the fracture process changes from tensile-microcracking-macrocracking to shear-compression macrocracking. Digital image correlation has also been used to study the cracking in reinforced concrete beams failing in shear [23] and it was found that the observed size effect was in agreement with Bazant's size effect [24].

Ductility is implicitly linked to the energy dissipation. Ductility in RC structures can be defined as the ability of a material to provide sufficient inelastic deformation beyond yielding and prior to failure. The importance of ductility in steel RC is that the steel consumes applied energy in irreversible inelastic displacement after yielding. This means that what happens during crack growth (or arrest) would affect the ductility and the structural behaviour. There is debate about how best to quantify ductility because deformation can be translated into different measures such as curvature, rotation and displacement [25,26]. A displacement-based ductility factor can be defined as $\mu = \frac{\Delta_{max}}{\Delta_y}$, where Δ_{max} is the maximum displacement and Δ_y is the displacement at yielding based on the load-deflection behaviour. However, the maximum displacement can be open to different interpretations especially when measured in a displacement-controlled test. One option is to define the maximum displacement as the maximum displacement at the maximum attained load, although a small reduction in the load after the peak load can be taken into account [27]. In a cracked beam, ductility can also be defined using fracture mechanics formulations as being associated with the propagation of a crack in a stable manner [28]. Stable behaviour is associated with

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