Experimental Investigation of Crack Propagation and Crack Branching In Lightly Reinforced Concrete Beams Using Digital Image Correlation

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Abstract— It is a recent advancement in the construction technology, since it is light in weight, therefore bringing economy in the construction. Steel is replaced by the glass fibre helps in avoiding structural deterioration and corrosion in reinforced concrete structures. Keeping in mind about the global environmental conditions, many alternatives are searched to increase the strength, durability, shrinkage characteristics and serviceability of concrete. Hence, here glass fibre is added and tests have been performed with varying percentage of 1%, 2% and 3% of cement by adding as an admixture.

Keywords: Glass Fibre, Light Weight, Economic, Eco Friendly, Compressive Strength

I. 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. 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 [1]. A realistic description of the FPZ is essential in order to understand damage mechanisms and to predict and optimize the behaviour of concrete structures.

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, thetype, 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 [3]. 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 [4]. 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 [5]. 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.

Understanding cracking in reinforced concrete is important for the strength assessment and renovation of existing structures. Relatively few fracture-oriented experimental studies have been conducted on concrete with internal steel reinforcement. Knowledge of concrete fracture processes can help identify suitable analytical approaches that capture the details of the crack process. This study presents an experimental investigation of RC beams subjected to three point bending. A particular focus is the localised zone around the crack and the crack branching phenomena. Crack branching is a toughening mechanism in quasi-brittle materials and can be a source of size effects. Yet it has received little or no attention when studying the fracture of RC beams. In reinforced concrete, the confinement provided by the reinforcement to the crack path increases the possibility of crack branching. The crack branching that takes places during the failure process makes the failure behaviour more ductile. The aim of this project is to experimentally determine the relationship between size, reinforcement ratio and ductility through investigation of crack branching in RC beams. Although more experiments are required to generalize the results, this project acts as a foundation to describe the flexural behaviour of lightly reinforced concrete beams and for further investigations of RC fracture processes.

II. Background and Scope

Over the past decades various studies were conducted to investigate concrete cracking and models were developed to simulate the cracking process in reinforced concrete beams. These models can broadly be classified as either plasticity-based models which are justified in the case of ductile behaviour e.g. beams with sufficient internal steel, or fracture mechanics-based models which do not treat fracture as a point phenomenon but use fracture mechanics principles to explain crack propagation. The cracking process in concrete is complicated because it is associated with thedevelopment of minor cracks and micro cracks as well as macro-cracks. Cracking is also connected with other phenomena such as strain localization and bridging. In a traditional strength criterion analysis, the behaviour is described using continuum variables of stress and strain. However, during fracture propagation the behaviour depends on what is happening in the fracture process zone (FPZ)ahead of the crack tip, which is a partially damaged zone with some residual ability to transfer stress. This zone is analytically challenging for model developers and structural engineers becauseit is a transition zone between the discontinuous open crack and the continuous intact material beyond the crack. So it cannot be modelled using the continuum variables. Since fracture mechanics provides rules and principles for crack propagation in materials, it can also provide atool for studying the cracking process in concrete. Interest in the application of fracture mechanics to concrete has been due to the realisation that strength criteria were not adequate to explain concrete cracking . Although fracture mechanics provides a rational approach for studying cracking and has been applied to concrete fracture for over forty years, it has typically not been widely adopted within design code equations and lacks a certain acceptance from the structural concrete community. One of the reasons is that fracture mechanics approaches are often modeled using finiteelement tools and this makes it difficult for inclusion in the development of guidelines. Furthermore, fracture mechanics has its own parameters and terms and civil engineers are less familiar with them. This means that conventional empirical stress-based approaches have been preferred for structural applications. In spite of the resistance of the structural concrete community to the application of fracture mechanics, fracture mechanics is important in order to better understand the behaviour of structures that are very sensitive to fracture such as structures in tension. Another example is where the tensile softening behaviour is important such as in lightly reinforced concrete beams. Reinforced concrete beams with low ratios of longitudinal reinforcement will be the subject of the current study. Although the fracture properties of reinforcedconcrete at the structural scale have been studied, there is a need for further detailed investigations of cracks in reinforced concrete to better understand the nature of the fracture process and improve existing models. Improving existing models does not necessary mean making them more complex. However, it does involve enhancing our understanding of the behaviour in a way that is translatedto new applications without missing the important features. The recent advances in image processing techniques as well as in high-resolution digital cameras can provide advanced tools to measure fracture properties and provide insight into the cracking process. Such real observationscan lead to the development of new models or the improvement of existing models.

III. OBJECTIVES

This project aims to carry out an in-depth investigation of the crack propagation RCC beams. This will be achieved through experimental work which is required to observe the true cracking behaviour in RC beams. More specifically, the objectives of this project are:

- To study the effect of reinforcement on the crack propagation in concrete beams.
- To observe the effect of beam depths on relative depth of crack branching.
- To study the effect of both beam depth and reinforcement on the ductility of RCC beams through investigation of crack branching.
- To see the relation between the relative depth of crack branching and ductility.

IV. TEST RESULTS AND DISCUSSION

The unreinforced beams D150,0% and D200,0% showed relatively lower flexural strength than thereinforced beams. The beams showed flexural strengths of 1.7 kN and 1.95 kN respectively. Both the unreinforced beams had a brittle failure and showed negligible deflections prior to failure. Due to brittle failure, the measurement of deflection was not possible during the test and the load deflection curves for unreinforced beams could not be obtained. The load deflection curves for reinforced beams are plotted as shown in figure 5.1.

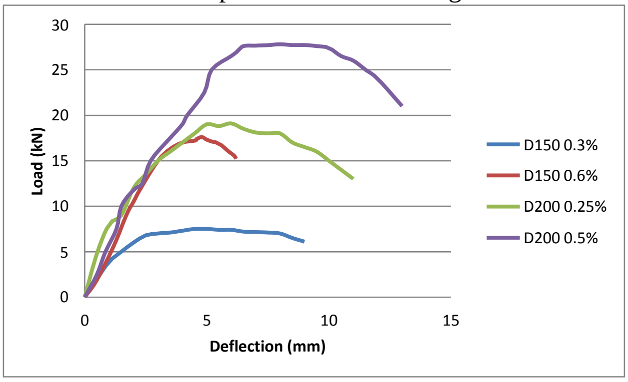

Fig. 5.1: Load vs Deflection curves of RCC beams

With the increase in percentage of steel from 0.25% to 0.5% in beams of depth 200 mm, peak load increases from 19.1 kN to 27.8 kN and maximum deflection increases from 11 mm to 13 mm. In case of beams of depth 150 mm, by increasing percentage of steel from 0.3 % to 0.6% the peak load increases from 7.5 kN to 17.6 kN whereas the maximum deflection decreased from 9 mm to 6.2 mm.

The crack formation in the unreinforced samples was instant and the failure was abrupt and hence the crack width measurement was not possible for unreinforced beam samples. However, the reinforced beams showed considerable deflections and the crack widths were measured after regular intervals of load. The plot of load versus crack width for beam samples of depth 150 mm and 200 mm of various percentages of steel reinforcement is shown in figure 5.2.

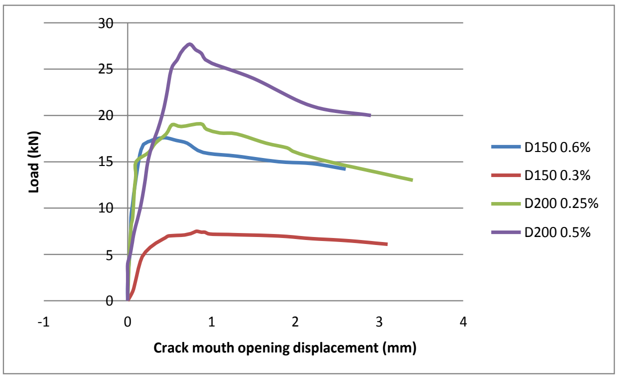

Fig.5.2: Load vs crack width curves for different beam samples

As the percentage of reinforcement is increased, the crack mouth opening displacement getsdecreased. This is due to increased stitching action of cracks by reinforcement and thus restricts the widening of cracks with increase in loads.

Load (kN)	Deflection (mm)	CMOD (mm)
0	0	0
2	0.5	0.09

5	1.5	0.19
7	3	0.49
7.5	5	0.82
6.5	8.5	2.6
6.1	9	3.1

Table 5.1: Readings for beam D150 0.3%

Load (kN)	Deflection (mm)	CMOD (mm)
0	0	0
5.7	1.2	0.03
9	1.7	0.04
12	2.3	0.08
15	3	0.13
17	4	0.2
17.6	4.8	0.44
16	5.9	0.9
15	6	2.2
14.2	6.2	3.1

Table 5.2: Readings for beam D150 0.6%

Load (kN)	Deflection (mm)	CMOD (mm)
0	0	0
4.8	0.5	0.02
8	1.4	0.04
12	2.2	0.08
15	3.6	0.1
18	4.5	0.46
19.1	6.2	0.87
17	8.5	1.65
15	10.3	2.4
13	11	3.4

Table 5. 3: Readings for beam D200 0.25%

Load (kN)	Deflection (mm)	CMOD (mm)
0	0	0
5	0.85	0.03
10	1.5	0.15
15	2.7	0.24
20	4.2	0.41
25	5.2	0.52
27	625	0.65
27.8	8	0.74
26	11	0.86
25	11.5	1.1
20	13	2.9

Table 5. 4: Readings for beam D200 0.5%

V. INTERPRETATION OF RESULT

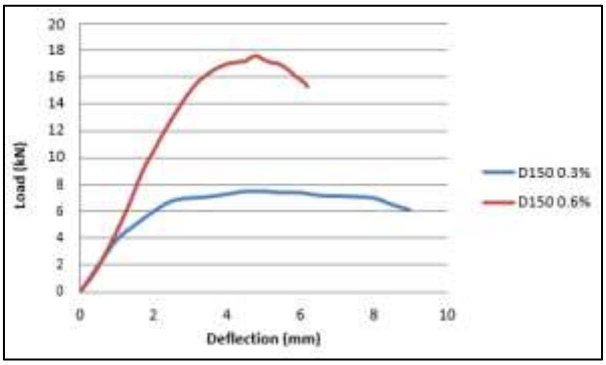

Fig.5.3: Load deflection curves for beams D150 0.3% and D150 0.6%

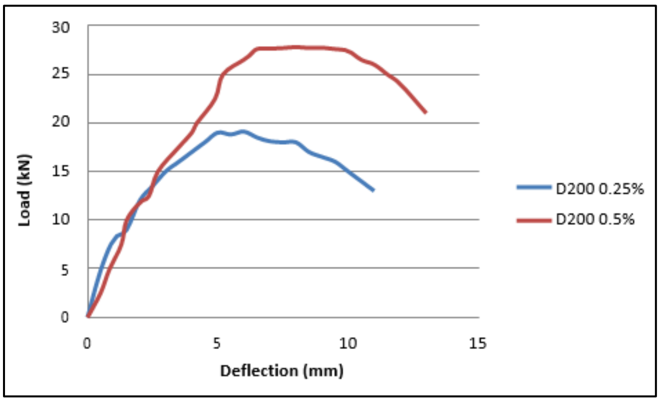

Fig.5.4: Load deflection curves for beams D200 0.25% and 0.5%

With the exception of beam M30,D150, 0.6%, which failed in shear, all the beams failed in flexure when a central crack propagated in the region of the highest applied moment. In case of beams of depth 150mm, the peak load increases from 7.5 kN to 17.6 kN but the deflection decreases from 9mm to 6mm.With increasing reinforcement ratio in beams of depth 200 mm, the peak load increases and the maximum deflection at the peak load Δmax also increases.

The ductility factor based on the deflection ratio Δmax/Δy was calculated. From the tabulated results, it can be seen that the ductility appears to increase with increasing reinforcement ratio and beam size. It is worth noting that these trends only apply for lightly reinforced concrete beams that exhibit flexural failure. The beam behaviour is expected to become brittle with increasing reinforcement ratio and the onset of shear failures in beam like M30,D150,0.6%.

Beam	Deflection at yielding Δy (mm)	Total deflection at failure load Δmax (mm)	Ductility factor μ = Δmax/Δy
D150 0.3%	3.3	8.9	2.61
D150 0.6%	2.9	6.2	2.13
D200 0.25%	3.8	10.6	2.78
D200 0.5%	4.4	13.25	3.01

Table 5.5: Ductility factor for different beam samples

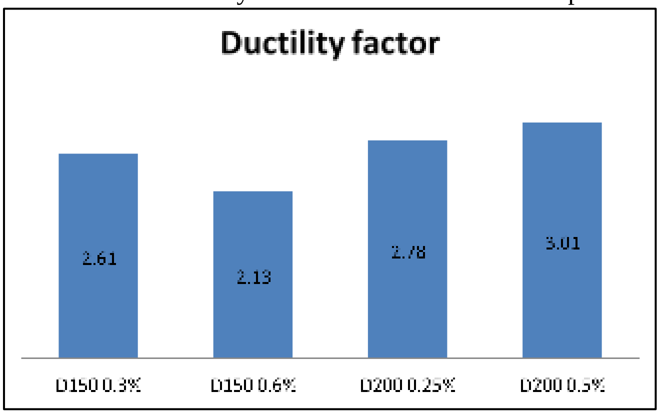

Fig. 5.5: Ductility factors for beam samples

VI. FRACTURE BEHAVIOUR

The reinforcement bridges the crack and exerts a force that opposes crack opening. In this section, crack profile observations are presented to investigate the fracture evolution in reinforced concrete. The unreinforced beams of depths (150mm and 200mm) were tested to establish the baseline concrete fracture properties. This helps to understand the effect of the reinforcement on the fracture behaviour of concrete. The unreinforced specimens failed due to a crack propagating from above the crack tip. In the reinforced specimens this crack starts as a single slightly curved shape but, with increasing load, the crack propagation continues along two branches. The localised zone advances in a single narrow band exhibiting some deviations from a straight line due to the heterogeneity of the concrete and aggregate interlock until it bifurcates into two branches. It was found that the branched localised zone was created in the beams at a load of around 7 kN in beam D150 0.3%, 17.5 kN in beam D200 0.25%, and 19 kN in beam D200 0.5%. The beam D150 0.6% failed in shear and did not show any branching and hence will not be discussed

Beam	CMOD at branching (mm)	Max. CMOD (mm)	% CMOD that occurs after branching
D150 0.3%	0.51	3.1	83.5%
D200 0.25%	0.61	3.4	82.1%
D200 0.5%	0.37	2.9	87.2%

Table 5. 6: Measurements associated with crack branching

Based on the results in Table 5.6 it can be seen that most of the CMOD in the tested beams happens after branching (or steel yielding as the two phenomena are connected) 80% to 90% of the CMOD was noticed in the tested beams after crack branching and thus indicating that the CMOD increases substantially close to the peak load. This indicates that before branching, the crack process is primarily about crack propagation whereas, after branching, crack opening dominates. The bifurcation leads to the failure in the compression zone in lightly RC beams.

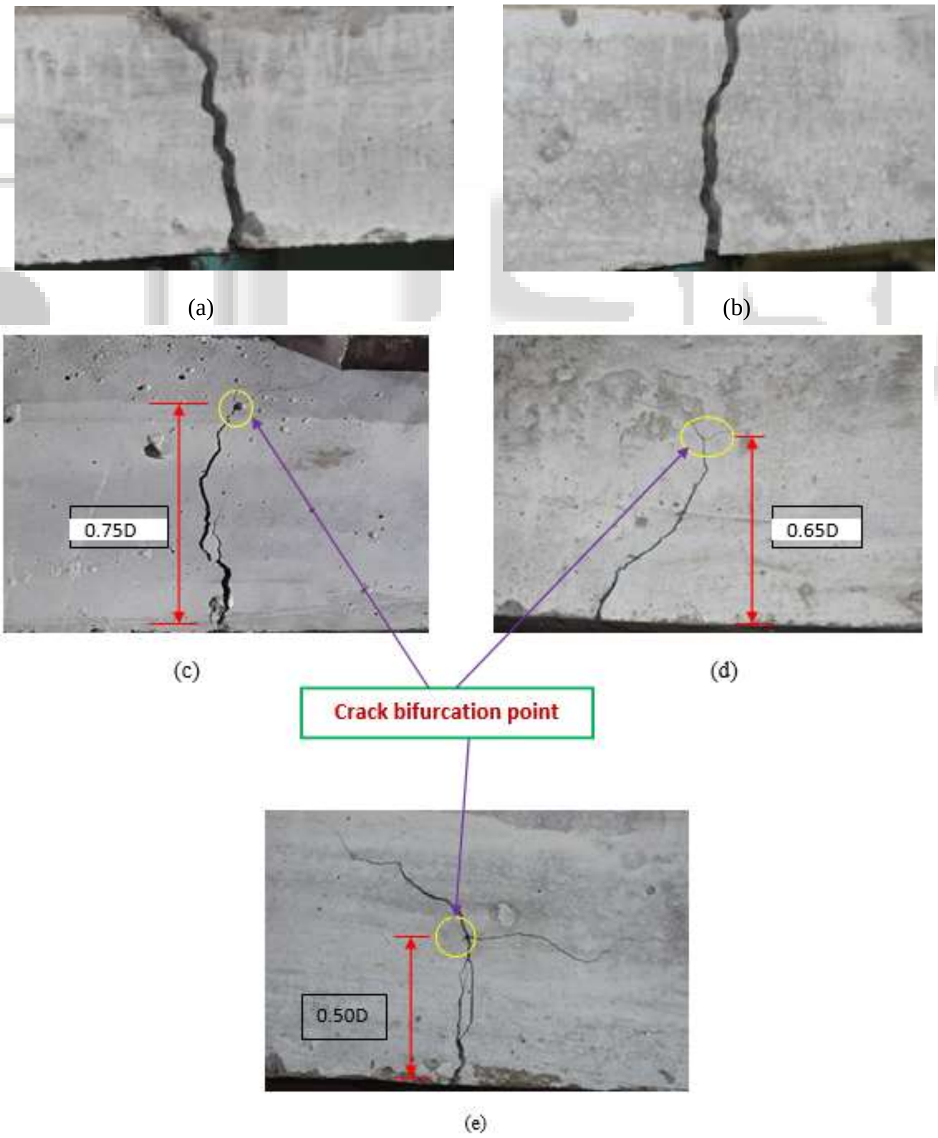

Fig. 5.6: Single flexural cracks without any branching in unreinforced beams (a) D150,0% (b)D200,0%. Crack branching at different depths in beams (c) D150,0.3% (d) D200,0.25% (e) D200,0.5%

With increasing load, the branched localised zone develops and its length increases. The bifurcationtook place at a depth of 0.75, 0.65 and 0.5 of the effective depth of beams D150 0.3%, D200 0.25% and D200 0.5% respectively.

Beam	Relative depth of branching
D150 0.3%	0.75
D200 0.25%	0.65
D200 0.5%	0.50

Table 5.7: Relative depth of crack branching

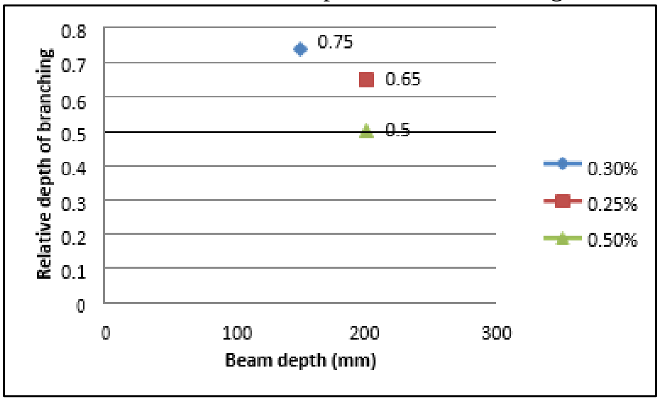

Fig. 5.7: Plot of relative depth of branching vs beam depth

The beam depth is plotted against the relative depth at which bifurcation took place. In the larger beams (of depth 200mm and length 1200mm) branching occurs at a lower relative height than inthe smaller beams(of depth 150mm and 1000mm). After the onset of branching, localisation continues to develop at the tips of the two branches until one of the branches dominates and leads tofinal failure. It was noted that the crack branching in beam D200 0.5% occurred at a relatively lower depth than that of D200 0.25 %.But there cannot be a clear trend in terms of the effect of the reinforcement ratio on the effective depth of branching. This is thought to be due to the different failure modes exhibited by the specimens. That is; the shear failure in beam D150, 0.6% andflexural failure in rest of the samples. This makes it difficult to make a clear conclusion about the effect of reinforcement on crack branching, and hence, on beam ductility. More specimens are required to be able to compare beams with similar failure modes. However, the reinforcement ratio does seem to have an effect on the branching angle. The different bifurcation angles for the beams are shown in Fig 5.6. It is of note that with increasing reinforcement ratio, the bifurcation angle seemed to become wider. For example, the bifurcation angle of beam D200,0.25% is relatively narrow when compared with the bifurcation angle of beam D200,0.5% which has higher reinforcement ratio.

Crack branching generates a larger surface area that absorbs energy and hence more energy is needed for fracture to propagate. In the larger beams, branching occurred at a lower relative height than in the smaller beams. This means that for lightly reinforced beams, by increasing the beam size, a more ductile behaviour can be obtained. Crack branching occurred in all the reinforced beams but was not noted in the unreinforced concrete beams and the beam D150, 0.6% which failed in shear. In reinforced concrete, the reinforcement provides an effective confinement to the crack path. The bifurcation occurs when the tip splits into two cracks.

The aim of the current work is to investigate experimentally the phenomenon of branching and provide evidence that it is associated with the presence of reinforcement (or confinement effects). The results of the experimental program showed this within the range of the tested properties and within the tested sizes. The load deflection behaviour of the experimental reinforced concrete beams show a capacity for post-peak deflection which is reflected in the ductility factors presented in Table 5.5. As the crack bifurcation is associated with ductility, it is postulated that a better understanding of crack branching and the incorporation of the experimental observations into theoretical models would give a better prediction of the cracking process and a better estimation of the ductility. This could lead to an improved evaluation of the minimum flexural reinforcement required for ductile behavior.

VII. Conclusion and Future Scope

An experimental investigation on the cracking process in RC beams was undertaken with a focus onthe localised zone and crack branching phenomena. The following conclusions can be drawn based on the experimental results:

- In unreinforced concrete beams the shape of the crack is in the form of a single curved band indicating the development of damage in the material. Softening behaviour ensues after the peak load where the load decreases with increasing vertical deflection. A considerable increase in the crack mouth opening occurs during the softening stage.
- In reinforced concrete, the crack initially propagates in the shape of a single narrow slightly curved band. However, the presence of the reinforcement prevents premature fracture and results in the development of crack branching where the single crack bifurcates. The combination of this bifurcation and cracking results in the failure of the compression zone.
- It has been found that the larger the beam size, the lower the relative depth at which branching takes place. The crack path is therefore influenced by depth of the compressive stresses.
- In reinforced concrete, the bifurcation angle was fairly narrow in beams with lower reinforcement ratios. With increasing reinforcement ratio, the bifurcation angle becomes wider.
- Crack branching generates a larger surface area that absorbs energy. Hence more energy is needed for the crack to propagate and this affects the ductility of RC beams. It was found that increasing the beam size or the reinforcement ratio increases the ductility of RC beams according to a conventional definition of ductility

VIII. Recommendations for Future Work

- In this project work, the considered parameters affecting crack propagation and ductilty are beam depth and reinforcement ratio. The other parameters like concrete grade can also be taken into consideration also to see the effect on crack propagation.

– Although the fracture properties of reinforced concrete at the structural scale have been studied, there is a need for further detailed investigations of cracks in reinforced concrete to better understand the nature of the fracture process and improve existing models. Improving existing models does not necessary mean making them more complex. However, it does involve enhancing our understanding of the behaviour in a way that is translated to new applications without missing the important features. The recent advances in image processing techniques as well as in high-resolution digital cameras can provide advanced tools to measure fracture properties and provide insight into the cracking process. Such real observations can lead to the development of new models or the improvement of existing models.

The experimental observations of the fracture process of RC beams need to be incorporated into analytical solutions for reinforced concrete cracking to develop better predictions for the cracking process of RC beams. This could lead to an improved estimation of theminimum reinforcement requirements for flexural members and associated ductility.

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