Investigation on crack propagation and crack branching in lightly reinforced concrete beams

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Abstract - In concrete structures the various cracks in the building occur during construction and/or after completion. A building member like beam or column develops cracks whenever the stress in the member exceeds its strength. The Stress in the building members are caused by externally applied loads. The cracks in Reinforced Concrete Beams are essentially characterised by the principle reason, cause or mechanism related with the function of cracks.The basic aim of the project is to investigate the cracking process in lightly reinforced concrete beams. Till now relatively few fracture oriented experimental studies have been conducted on concrete members that are reinforced. In this experimental investigation the cracking process in lightly reinforced concrete (RC) beams analysed and investigated and to observe the details at localised fracture process zone development during the pre and post loading process using digital image corelation. More specifically the aims were to investigate the relationships between beam height (120 mm, 220 mm and 320 mm), steel reinforcement ratio (0.1 to 0.5%) and the onset of crack branching in beams. In this work loads was applied to Reinforced concrete beams and experimental surface strains and crack openings were inferred using digital image correlation (DIC).

Keywords: Crack Propagation,Crack Branching,Deflection ,Digital Image Correlation, Flexural Failure ,Fracture Process

I. INTRODUCTION

Concrete has a weak tensile strength as compared to its strength in compression and being a quasi-brittle material. It is therefore susceptible to cracking. Many researches and investigations using different approaches such as finite element analyses, linear fracture mechanics (LFM) and non-linear fracture mechanics (NLFM) have been done over past decades, to develop models to simulate concrete 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). During cracking, no specific region is mentioned in between the area which is cracked and that which is not. But it is evident that in concrete, there is some intermediate space between cracked and uncracked portion. This region is defined as the *Fracture Process Zone (FPZ)*. FPZ consists of micro cracks which are minute individual cracks situated nearer to crack tip. As the crack propagates these micro cracks merge and becomes a single structure to give continuity to the already existing crack. So indeed, FPZ acts as a bridging zone between cracked region and uncracked region. Analysis of this zone deserves special notice because it is very helpful to predict the propagation of crack and ultimate failure in concrete. In steel (ductile) FPZ is very small and therefore strain hardening dominates over strain softening. Also due to small FPZ, crack tip can easily be distinguished from uncracked metal. And in

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ductile materials FPZ is a yielding zone.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. 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 effect. Theoretical studies have been conducted to understand the nature of the FPZ in concrete.

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 localized 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. 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

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 con-crete microstructure e.g. cement and aggregate. 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 interdependent. 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. 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.. However, in reinforced concrete the nature of the FPZ remains unclear. Most theoretical studies incorporate the reinforce-ment according to the principle of superposition by considering concrete fracture and adding the effect of the reinforcement as a closing force. Although the fracture properties of reinforced concrete at the structural scale have been stud-ied, there is a need for further detailed investigations to better understand the nature of the fracture process.

II. LITREATURE REVIEW

Literature pertaing to similar studies conducted from various sources are as follows

Tahreer M.Fayyad,Janet M.Lees(2017) An experimental investigation was undertaken to explore the cracking process in lightly reinforced concrete (RC) beams and to observe the details of the localized fracture process zone development. More specially, the aims were to investigate the relationships between beam height, steel reinforcement ratio, ductility and the onset of crack branching. It was found that the presence of the rein-forcemeat 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 branch-ing angle. These observations were associated with ductility measures for lightly reinforced concrete beams

Pooja Nama, Ankush Jain, Rajat Shrivastava and Yash Bhatia (2015) carried out certain investigations that how the cracks are classified such as in beams, columns and slabs. And various types of cracks such as structural cracks and non structural cracks and concluded that if proper consideration is taken then cracks can be controlled. And depending on the type of cracks visualized and accordingly the technique is taken so that it can be minimized.

Djamila Benarbia,Mohamed Benguediab (2017) It is aimed to simulate the phenomenon of propagations of cracks where beam is initially loaded to introduce damage then after bonding FRP plates. The Linear Elastic Fracture Mechanics (LEFM) is adopted to peruse the stress intensity factor’s evolution in 3-point bending before and after reparation of RC beams. Many parameters were taken into account, such as thickness of adhesive layer and reinforcing plate, the stiffness, young’s modlus. Results were identified and discussed.

Kishore Kunal, Namesh Killemsetty(2014) describes that there are various types of cracks which occur in the building and accordingly at proper time cracks can be minimized depending upon the cracks width . They described how epoxy resins is grouted into the cracks and how it is to be filled in it. They carried out investigation on cracks pattern and treatment measures to fill such cracks and techniques used accordingly.

Zhou Jing-Cheng,LI Xing-Fu(2015): He concluded that cracks is mainly due to structural defects of concrete itself. Various others factors can be such as internal and external stratification during the process of pouring of concrete, the existence of various transition zone and multiphase porous system of concrete.

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Suresh Chandra Patnaik (2016) focuses on fact that any nonstructural dormant crack of any cementious, or polymer modified cementious will be more suitable. The epoxy is the best material for injection into cracks in structural members. But for densifying and treatment of honeycombs, the cementious grouts will not only be suitable but also economical. The active cracks need to be treated with a Polyurethane sealant. But if the cracks are located in water retaining structures or in damp locations then polyurethane injection is the best option.

Ying Luo, Ziping Wang, Baiqiaing Xu(2012) conducted his findings in accordance with Stack Migration Imaging Technology which is an advanced imaging technique used in geophysical exploration. This technique was employed to detect the cracks inside the concrete structures. Ultrasonic transducers were utilized as both actuators and sensors to generate and receive stress waves in the concrete. In his findings the result showed that SMIT has advantage over ultrasonic machine. SMIT can detect not only the small cracks, but can also produce the imaging of the damage within the cross section of the specimen from one side. The migration technology has the potential for identifying the different types of failures such as matrics cracks and delamination in anisotropic structures.

Mayur Shantilal Vekariya (2013) In his findings he said that, Micro-cracks is the main cause to structural failure. One way to deal costly manual maintenance and repairs is to adopt method as self -healing mechanism in concrete. Another method can also be adopted as repair mechanism which is currently being investigated i.e.bio-mineralization of bacteria in the concrete. He emphases on the material i.e. Calcite mineral precipitating bacteria for repairing the concrete and plugging the pores and cracks in the concrete. Synthetic polymers such as epoxy treatment are also being used as repair material. He finally concluded that Microbial concrete technology have been proved to be the better technique than any other conventional method since it has eco- friendly nature and self-healing abilities.

D.G . Aggelis, T Shiotani(2007) Surface opening cracks are common defects in large civil structures like bridges. They allow penetration of water or other agents that result in loss of durability earlier than expected. Their repair can be conducted by injection of epoxy material that seals the crack sides keeping out any aggressive substances in addition to recovery of strength. In order to evaluate crack parameters before impregnation as well as to determine the final repair effectiveness, a combination of Rayleigh and longitudinal waves is applied. Rayleigh waves demonstrate the filling condition of material into the shallow layer near the surface while the tomography using longitudinal waves through the thickness yields information about area inside the structure. Wave propagation dispersion features are exploited by the proposed tomography at different frequencies, demonstrating that higher frequencies lead to more accurate characterization.

Rytis Skominas, Vincas Gurskis, Algimantas Patasius Cracks are one of the serious problems appearing in reinforced concrete. The reasons that cause the cracking of structures could be different: load impact, corrosion of reinforcement, unsteady settlement of framework, environmental effect etc. The cracks cause a decrease of the structure's durability and longevity. Therefore it is important to repair damaged structures.

To estimate the materials' suitability for crack repair a slant shear strength test and a water penetration test were used. The results show that polymer injection materials A and B can restore the strength of concrete. The repair carried out with modified cementitious material (for modification used expansive additive and polymer additive) has the same effect. Water penetration test shows, that all polymer injection materials are quite water resistant

III. EXPERIMENTAL WORK

The experimental work was undertaken to study the following parameters

- The cracking process & onset of cracking.
- To investigate the nature of fracture in RC beams.
- Load vs Deflecton Curves

The above mentioned parameters are closely inter related especially in case of lightly reinforced concrete beams. In beams the reinforcement provides a confinement to the crack path which can be a source of size effect and may lead to other toughening mechanisms such as crack branching. As the intention was for the RC beams to fail in Flexure, for each beam size and a given concrete strength, the reinforcement was provided such that flexural capacity was less than the shear capacity. Alternatively notches can be provided at midspan so that shear capacity gets subjugated over flexural capacity. Flexural failures are common in lightly reinforced concrete beams or beams with shear reinforcement. However, more heavily reinforced concrete beams without sufficient transverse steel will be predisposed to shear failures. Since the focus was to promote Flexural failures, both the ACI standard (ACI 318M-11) and the European Standard (EC2) were used to predict the minimum shear capacity of the designed specimens. The flexural capacity was calculated based on an ultimate limit state analysis using an equivalent rectangular stress block.

3.1 Experimental program

In this study total of nine unreinforced and reinforced concrete beams were tested in three point bending. The flexural crack propagation was tracked using DIC. Also for deflection and loading dial gauges were setup at midspan and point of loading respectively. All the beams tested were without shear reinforcement. The first series included six

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beams with different longitudinal reinforcement ratios (0%, 0.3%,0.5%) cast from a mix with a design concrete cube compressive strength of 30MPa. Two different beam sizes were considered but a constant clear span to effective height ratio was maintained (heights of 180 mm and 230 mm and lengths of 1000 mm and 1300 mm respectively). The second series included three unreinforced and reinforced concrete beams cast from a mix with a target compressive strength of M30 MPa. The beam sizes with a height of 230 mm and length of 1300 mm and different reinforcement ratios (0%, 0.3% and 0.5%) were used. All the test beams had a width of 120 mm and a concrete cover of 27 mm. In table below each beam has been identified using the following notation: a letter M followed by a number (showing the concrete mix strength), a letter D followed by a number (showing the effective depth), and then the reinforcement ratio as a%. The longitudinal steel consisted of deformed steel bars with average yield strength of 548 MPa for bars with a 6 mm nominal diameter.

Table 1.Details of test specimens.

Concrete cube compressive strength (Mpa)	Beam Dimensions			Reinforcement Ratio	Notation
	Width (mm)	Height (mm)	Length (mm)		
M1=30	120	180	1000	Unreinforced (0 %)	M25,D180,0
				0.3%	M25,D180,0.3
				0.5%	M25,D180,0.5
	120	230	1300	Unreinforced (0%)	M25,D230,0
				0.3%	M25,D230,0.3
				0.5%	M25,D230,0.5
M2=M30	120	230	1300	Unreinforced (0%)	MM30,D230,0
				0.3%	MM30,D230,0.3
				0.5%	MM30,D230,0.5

3.2 DIC experimental setup and specimen preparation

Digital Image Correlation (DIC) is a full-field image analysis method, that can be used to inspect the strain, fractures, contours and the displacements of an object under load in three dimensions.In a DIC analysis, a given image of the target area is split into small patches. These patches are tracked from one image to the next. It is then possible to measure the full field deformation of a selected area. To accurately track the patches, each patch should have characteristics that can be distinguished from other patches. Pan et al. found that the surface texture has a significant influence on the tracking results. During different stages of loading the lens was directed towards the area of interest and snapshots were being recorded simultaneously to track the strain characteristics with respect loading and to visualize the crack propagation.

A digital single lens reflex (NIKON D3400 DSLR) camera with a 24 megapixel CMOS sensor was used to record images of the test specimens under loading. The camera was mounted on a tripod with its axis perpendicular to the area of interest. The camera had a focal length of M30mm equivalent. The camera was directed toward the middle of the beam where textural cracks were expected to develop. The obtained spatial resolution differs according to the region of interest which in turn differs according to the beam dimensions.. For some beams, a second DSLR camera was used either to give a greater resolution in the FPZ or to record the crack propagation on the other side of the beam. External lighting was directed toward the region of interest to enhance the image quality. During the test, the images were shot continuously every 10 s.

3.3 Testing

In this setup each beam is being tested to failure under three-point loading. The beams with a height of 120 mm were tested in electro hydraulic servo-controlled Intron machine where the beams were supported on a wide flange steel beam to study loading rates on different parameters associated with this work. This meant that the beams could be positioned in the machine at an angle such that the side faces were visible. The end supports were two plates with a roller which allowed rotation and horizontal displacement. With the exception of the Intron loading plate that had a width of 20 mm, the widths of all the bearing pads were 75 mm. A C-clip was attached below the central notch of each beam to measure the crack mouth opening.

In order to obtain stable loading conditions, all the tests were performed under displacement control. Consequently, the load was applied as a function of the mid span deflection. This allowed a gradual increase in the mid span deflection and crack mouth opening, as well as a steady decrease of the load in the post-peak regime. In the large beam test rig, the loading jack was connected to a hydraulic servo controlled machine to achieve a constant deflection rate; however, there was a certain delay in the feedback to the jack due to the very small displacement rate. The loading rate was 0.1 mm/min for the first two specimens (beams M25,D180,0.3 and M25,D230,0.3). It was then increased to 0.15 mm/min for beams MM30,D230,0.15 and MM30,D230,0.3 and subsequently increased to 0.2 mm/min for the rest of the beams

IV. EXPERIMENTAL RESULTS & FRACTURE ANALYSIS

Under the given loading all the beams fail in flexure except M25,D230,0 which failed in shear. In most of the beams cracks propagated from the middle region vertically and after some time crack branching occurs horizontally and vertically.

M25,D180,0 : Shear failure

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M25,D180,0.3 : Sudden flexure failure
M25,D180,0.5 : Flexure failure then shear failure
M25,D230,0 : Flexure failure then branching
M25,D230,0.3 : Flexure failure then branching
M25,D230,0.5 : Bond failure between steel and concrete.
MM30,D230,0 : Flexure Failure
MM30,D230,0.5 : Flexure failure and simultaneous branching

In Beams M25,D180,0 & M25D180,0.3 Sudden flexure failure occurs due to reinforcement fracture when the load is applied. Beams M25D180,0.5 and M25,D230,0.3 fail due to shear capacity less than flexure capacity. However in beams M25,D230,0 ,MM30D230,0 and MM30D230,0.5 Flexure failure occurs. The Load-deflection curves of test beams are presented in fig. Each figure compares a set of beams that have either the same size, similar concrete or the same reinforcement ratios. For the medium and large beams the deflections were derived from the displacement of the loading jack. Corrections to account for any settlement of the testing system were made using the external LVDT readings at the beam supports It is of note that experimentally it was difficult to pinpoint the peak load due to the loading conditions so the maximum deflection was selected as the largest deflection associated with a load within ±5% of the peak load. With increasing reinforcement ratio, the maximum defection at the peak load D_{max} increases (Table 3). The ductility factor based on the deflection ratio D_{max}/D_y was calculated (Table 3). 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 textural failure. The beam behaviour is expected to become brittle with increasing reinforcement ratio and the onset of shear failures. The experimental results are in agreement with the findings in for lightly reinforced concrete beams that were based on a numerical analysis and an energy-based definition of ductility

The crack initiation in beams is resisted by the presence of reinforcement. The reinforcement bridges the crack and exerts a force that opposes crack opening. In this section crack profile observations vs loads are analysed to investigate the fracture evolution in reinforced concrete. One unreinforced beam was tested in each series 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. For beam M25,D180,0.5 flexure crack is followed by diagonal crack. For this beam flexure crack occurs below 10KN and diagonal crack occurs at 10KN.At 16.5 KN the width of the diagonal crack increases significantly. The failure occurs approximately at 21KN as load suddenly falls from 21KN to 20.5KN.

For beam M25,D230,0.3 the onset of cracking occurs at 5KN which propagates vertically at around mid span. For this flexure crack, width tends to increase until crack brancing takes place at approximately 15KN.The failure approximately occurs between 16KN and 17KN.If we compare beam M25,D180,0.5 and M25,D230,0.3 ,the reinforcement has predominant effect on the ultimate strength of beams. Although Beam 2 has higher effective depth the Beam 1 fails after beam 2 having higher reinforcement ratio.

For Beam 3 i.e MM30,D230,0.5 th crack starts to propagate at approximately 15KN.The branching starts at an load between 15 KN and 17KN.The crack width increases significantly after 20KN until 29KN at which Failure takes place. This type of failure may be attributed to shear bond failure or combined effect of shear and bond. For Beam M25,D180,0.3 the crack initiates at 10KN vertically upwards indicating pure flexure failure. The crack tends to propagate until 14KN and beam ultimately fails at 15KN.Comparing beam M25,D180,0.5 and M25,D180,0.3 we see that ultimate strength is increased by increasing reinforcement ratio keeping the effective depth same. It can also been seen that reinforcement prevents crack propagation upto certain limit after which sudden failure can occur without giving ample deflection For Beam MM30,D230,0 the beam starts to show cracks at 7KN after which crack tends to grow up vertically upto 10KN.At 5KN the beam fluctuates the vertical path and bends at small angle. The beam ultimately fails at 13KN.This deviation from path may be attributed to hetrogeniety of the material and aggregate interlock

BEAM 1

M25,D180,0.5

Load 10KN

Load 16.5 KN

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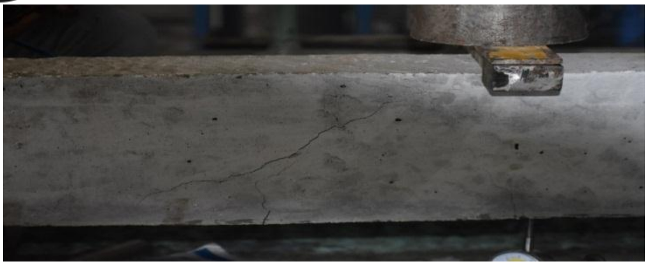
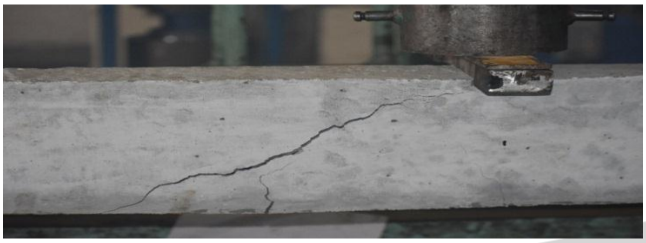


Load 18 KN

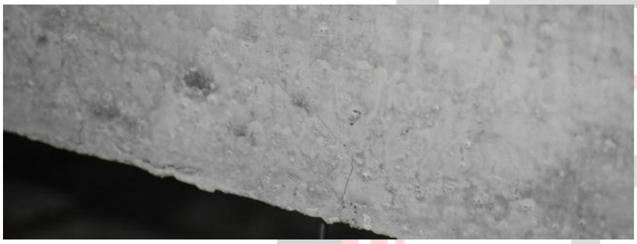


Load 15 kN

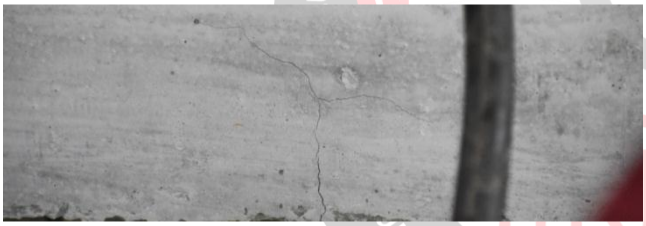
Fig 6.4 Crack Development of Beam M25,D180,0.5

BEAM 2

M25,D230,0.3

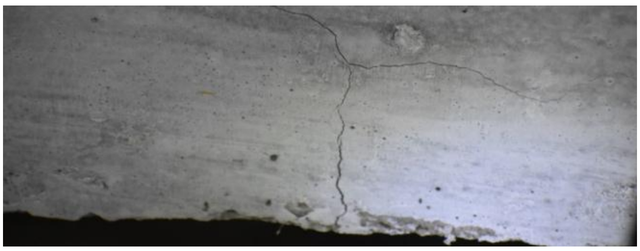


Load 5KN



Load 15kN

Load 19KN



Load 17KN

Fig 6.5 Crack Development of Beam M25,D230,0.3

BEAM 3

M30,230,0.5

Load 17KN

Load 20KN

Load 29KN

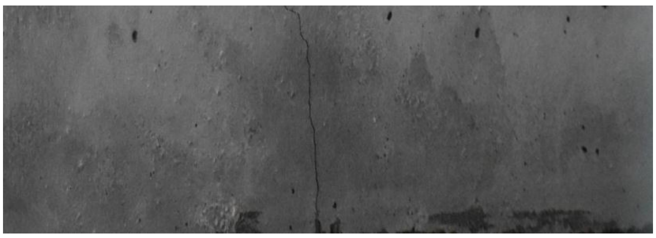
Load 25 KN

Fig 6.6 Crack Development of Beam M30,230,0.5

BEAM 4

M25,D180,0.3

Load 8KN



Load 12KN

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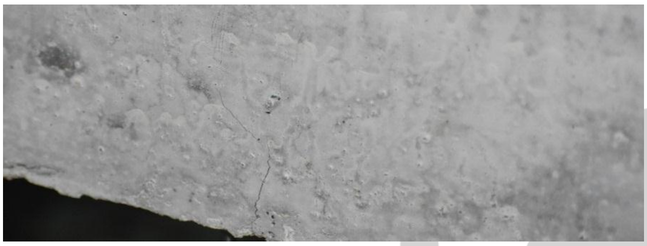
Load 15K

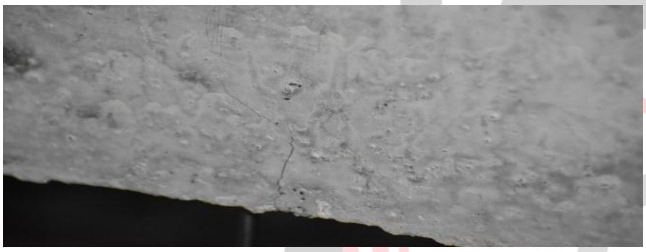
Fig 6.7 Crack Development of Beam M25,D180,0.3

BEAM 5

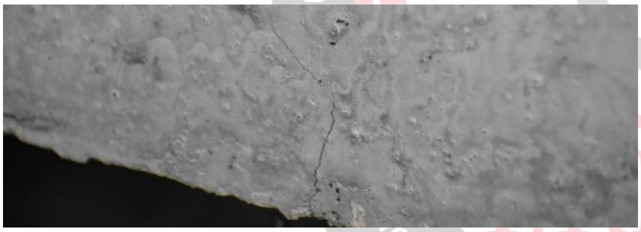
M30,D230,0



Load 3KN



Load 5KN



Load 6KN

Fig 6.8 Crack Development of Beam M30,D230,0

6.6 Load-Deflection Curves

The load deflection curves for various beams are obtained as shown below

Beam 1

M25,D180,0.5

Table 6.2 Load-Deflection Curve M25,D180,0.5

LOAD (KN)	0	5	10	12	14.1	16.5	18	15
DEFLECTION(MM)	0	0.5	1.1	1.5	1.7	2	3	3.5

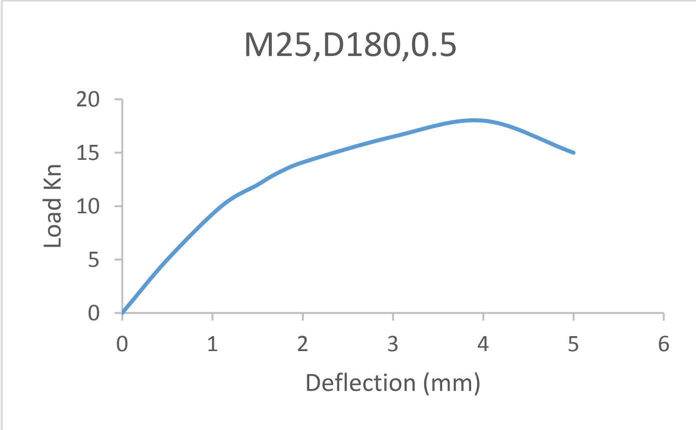


Fig 6.9 Load Deflection Curve of Beam M25,D180,0.

BEAM 2

M30,D230,0.3

Table 6.3 Load-Deflection Curve M30,D230,0.3

LOAD (KN)	0	7	12	15.3	16.3	17	16	15
DEFLECTION(MM)	0	0.5	0.9	1.5	1.75	2	2.3	2.5

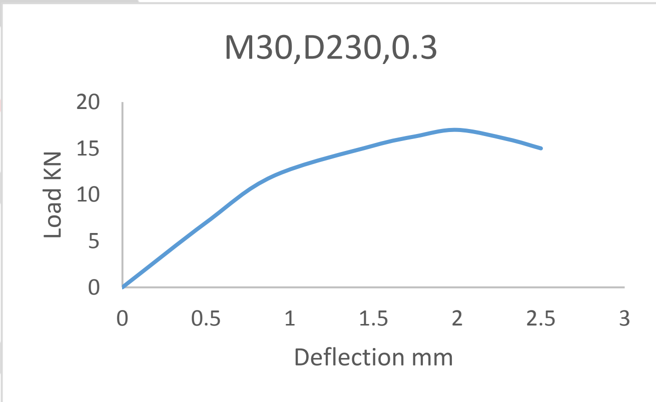


Fig 6.10 Load Deflection Curve of Beam M30,D230,0.3

BEAM 3

M30,D230,0.5

Table 6.4 Load-Deflection Curve M30,230,0.5

LOAD (KN)	0	5	10	15	20	25	30	25
DEFLECTION(MM)	0	0.22	0.5	0.8	1.1	1.5	2.2	3

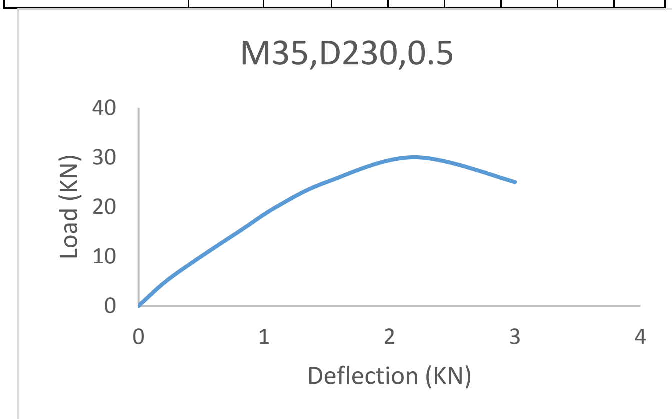


Fig 6.11 Load Deflection Curve of Beam

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M30,D230,0.5

BEAM 4

M25,D230,0

Table 6.5 Load-Deflection Curve M30,230,0

LOAD (KN)	0	2	4	6	8	10	12	14	12	10
DEFLECTION (MM)	0	0.07	0.16	0.25	0.4	0.58	0.8	1.3	1.6	1.8

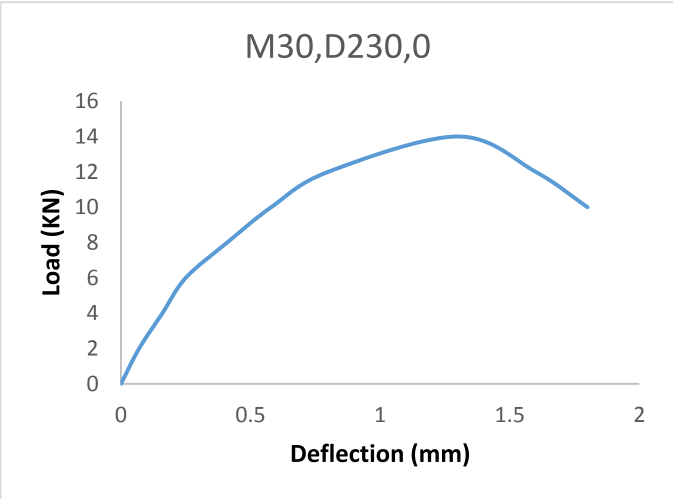

Fig 6.12 Load Deflection Curve of Beam M25,D230,0

BEAM 5

M30,D230,0

Table 6.6 Load-Deflection Curve M30,230,0

LOAD (KN)	0	2	4	6	8	10	12	14	16	18	16	14
DEFLECTION(MM)	0	0.04	0.09	0.13	0.2	0.3	0.5	0.8	1.2	1.7	2.2	2.5

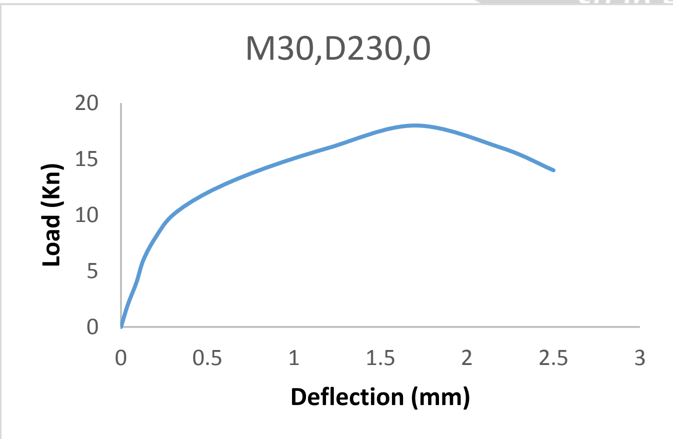

Fig 6.13 Load Deflection Curve of Beam M30,230,0

V. CONCLUSION

An experimental investigation on the cracking process in RC beams was undertaken with a focus on the cracking process, nature of fracture and load deflection curves & onset of cracking. The following conclusions can be drawn based on the experimental results:

The use of DIC method enabled the quantification and visualising of the fracture properties in reinforced concrete. The DIC technique was found to be very effective in monitoring the crack propagation process when a high resolution camera was used. The DIC method is capable of detecting and identifyimg early crack development, whereas the traditional method is incapable of doing so until the loading reaches the certain level that has already caused specimen cracking and rupturing The shape of the crack in unreinforced beam is in the form of a single curve thus indicating that damage occurs in the material .Crack deviates from vertical direction after it reaches in compression zone. Softening behaviour ensues after the peak load where the load decreases with increasing vertical detection. 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 curved band. However, premature fracture is prevented by the presence of reinforcement 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 shown that the beam size has no proper realtion with the depth at which branching takes place. Beams with a lower concrete strength showed less number to macro cracks. The crack path and number of cracks is therefore influenced by both the magnitude and depth of the compressive stresses. In reinforced concrete, the bifurcation angle was fairly steep in beams with lower reinforcement ratios. With increasing reinforcement ratio, the bifurcation angle becomes shallower.

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. 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 the minimum reinforcement requirements for flexural members and associated ductility.

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