Fracture Parameters of Plain Concrete Beams Using ANSYS

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Abstract: **The present paper analyses the size dependency of the fracture energy and the fracture toughness of concrete determined as per the RILEM Work-of-fracture method (WFM). Normal and high strength concrete notched beams have been modeled using the finite element software, ANSYS 12.1 to study the variation of the fracture parameters. The fracture parameters (G_F , K_I and SIF) are determined using Work of fracture method by testing geometrically similar notched Plain normal and high strength concrete (20,30,40,50,60,70MPa) specimens of different sizes in a size ratio of 1:4 with different notch depths (a_0/d = 0.15, 0.30 and 0.45) under three point bending through load-deflection curves. The variation of both the fracture energy, fracture toughness and the stress intensity factor as a function of the specimen size and notch depth was determined using RILEM Work-of-fracture method. Fracture energy, fracture toughness and stress intensity factor calculated using Work-of-fracture method are increasing with the increase in size of specimen and decreasing with the increasing notch depth ratios.**

Index Terms—**Crack length, Fracture energy, Fracture toughness, Stress Intensity factor, Brittleness, Peak load, Finite element analysis, ANSYS.**

I. Introduction

Concrete, the highest consumed material in the construction field endowed with the inherent qualities of easy mouldability to the desired architectural shape and finish, high resistance to fire, easy and economically available raw ingredients with high compressive strength. Cracking in any material occurs when the principal tensile stress reaches the tensile strength of the material at that location. The study of the conditions around the crack tip is called fracture mechanics. None of the conventional strength theories like elastic or plastic theory describes how the cracks propagate in a structure. The safety and durability of concrete structures is significantly influenced by the cracking behavior of concrete. Therefore, concrete structures are mainly designed to satisfy two criteria namely, safety and serviceability. The evaluation of adequate margin of safety of concrete structures against failure is assured by the accurate prediction of ultimate load and the complete load-deformation behavior or moment-curvature response .Based on the tensile stress-deformation response, most engineering materials can be categorized into three main classes:

Brittle: stress suddenly drops to zero when a brittle material fractures.

Ductile: stress remains constant when a ductile material yields.

Quasi-brittle: It is characterized by a gradually decreasing stress after the peak stress.

A. Modes of Fracture

According to the mode of failure, fracture behaviour is classified into three categories. The three basic modes of failure are presented in Fig1.1. Mode I failure is known as the Opening mode failure. In this mode, the displacement of the crack surfaces is perpendicular to the plane of the crack. Mode II failure is known as the Sliding mode or Planar Shear mode failure. In this mode, the displacement of the crack surfaces is in the plane of the crack and perpendicular to the leading edge of the crack. The third basic mode is known as the Tearing mode or Anti-Plane Shear mode failure. In this mode, the displacement is in the plane of the crack and parallel to the leading edge of the crack. In practice, it is difficult to develop pure mode II or mode III fractures in concrete structures. Thus, besides pure mode I, mode of failure is often a combination of basic modes which is called mixed mode.

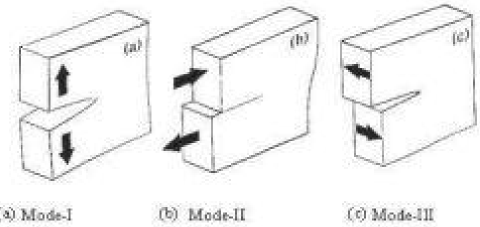

Figure 1. Modes of Fracture

B. Stress Intensity Factor K_i

The stress intensity factor is utilized as a part of fracture mechanics to predict the stress state ("stress intensity") close to the tip of a notch brought about by a remote load or residual stresses. It is a hypothetical construct normally applied to a homogeneous, linear elastic material and is helpful for giving a failure criterion for brittle materials, and is a basic technique and is a critical technique in the discipline of damage tolerance.. The idea can likewise be connected to materials that display little scale yielding at a notch tip.

C. Fracture Energy G_f

The strain energy discharge rate (or essentially energy discharge rate) is the energy dispersed during fracture per unit of newly created crack surface region. The energy discharge rate failure criterion expresses that a notch will grow when the accessible energy discharge rate G is greater

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than or equivalent to a basic worth Gc. The amount Gc is the fracture energy.

D. Non-Linear Fracture Parameters

Fracture Energy usingWork-Of-Fracture Method. Based on a measured load-deflection curve of a fracture specimen, typically a three point bend beam (including the effect of its own weight), the work of load P on the load-point displacement δ in RILEM method is calculated as $W_f = \int P d\delta$.

Figure 1.shows a typical three point bend test set up for the determination of fracture parameters using RILEM Work-of-Fracture method.

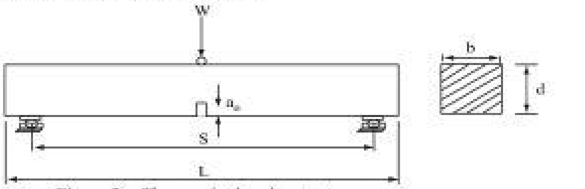

Figure 2 . Three point bend test set up

The fracture energy according to the RILEM[3] definition, W_f

$$G_F(\alpha_o, d) = \frac{Wf}{B\left[(1-\alpha_0)d\right]} \qquad \text{Where } \alpha_0 = \left(\frac{a_0}{d}\right)$$

E. Fracture Toughness K_{IC}

Fracture toughness is the property which portrays the capacity of the material containing a crack to resist fracture. If a material has high fracture toughness it will presumably undergo ductile fracture. For two dimensional issues (plane stress, plane strain, anti-plane shear) including crack that move in a straight path, the Mode I fracture toughness is identified with the energy release rate, G_f by

$$K_{IC} = \sqrt{GfXE}$$

II. Sample Load Calculation

The most extreme load and Fracture Load are observed to appear as something else and an exceptional quality for the fracture load is obtained.

The peck load carried by M20 grade concrete having beam size of 100mm x 150mm & a/D: 0.15

BendingEquation: $\frac{M}{I} = \frac{\sigma cbc}{y} = \frac{E}{R}$

$$\sigma cbc = \frac{fck}{3} \frac{20}{3} = 6.67\text{N/mm}^2$$

For simply supported beams, the maximum bending moment is

$$M = \frac{w\ell}{4} = \frac{w X 1050}{4}$$

M = 262.5w

Where width of beam is = 100mm

Effective depth, d = 150 – 22.5 = 127.5mm

Moment of inertia

$$I = \frac{100 X (127.5)3}{12} = 17.272 \times 10^6 \text{mm}4$$

Depth of Neutral axis $y = \frac{127.5}{2} = 63.75$mm

$$\sigma cbc = \frac{M}{\ell} xy = \frac{262.5w}{17.272 \times 10\hat{\ }6} \times 63.75 = 6.67 \text{ MPa}$$

Live Load, w = 6884.28 N

Self weight of Beam:

0.1X 0.15 X 25 = 0.36kN/m = 360N/m

Dead Load w_D = 378 N

Total Load = w+ w_D= 7262.28N

The Peak load values of various grades of concrete (M20 – M70) with different a/D ratiosand different beam sizes are calculated and tabulated in the Table I.

TABLE I.

PEAK LOAD VALUES FOR BEAMS OF DIFFERENT SIZES, GRADES AND NOTCH-DEPTH RATIOS

Grade of concrete	Size of Beam (mm x mm)	a/D	Peak Load N
M20	100 X 75	0.15	3536.643
		0.3	2428.88
		0.45	454.79
	100 X 150	0.15	7262.28
		0.3	5046.57
		0.45	3260.209
	100 X 300	0.15	15280.77
		0.3	10850.1
		0.45	5764.11
M30	100 X 75	0.15	5255.13
		0.3	3594.327
		0.45	634.6788
	100 X 150	0.15	10699.27
		0.3	7377.365
		0.45	4699.154
	100 X 300	0.15	22154.84
		0.3	15512
		0.45	10154.77
M40	100 X 75	0.15	6975.346
		0.3	4760.936
		0.45	814.7379
	100 X 150	0.15	14139.69
		0.3	9710.487
		0.45	6139.539
	100 X 300	0.15	29035.78
		0.3	20178.67
		0.45	13034.46
M50	100 X 75	0.15	8695.558
		0.3	5927.546
		0.45	994.79
	100 X 150	0.15	17580.52
		0.3	12043.61
		0.45	7579.92
	100 X 300	0.15	35916.73
		0.3	24845.33
		0.45	15915.08
M60	100 X 75	0.15	10415.77
		0.3	7094.155
		0.45	1174.856
	100 X 150	0.15	21020.54
		0.3	14376.73
		0.45	9020.309
	100 X 300	0.15	42797.68
		0.3	29512
		0.45	1879.69
M70	100 X 75	0.15	12135.98
		0.3	8260.765
		0.45	1354.916
	100 X 150	0.15	24460.96
		0.3	16426.35
		0.45	10460.69
	100 X 300	0.15	49678.62
		0.3	34178.67
		0.45	21676.31

III. Finite Element Modelling

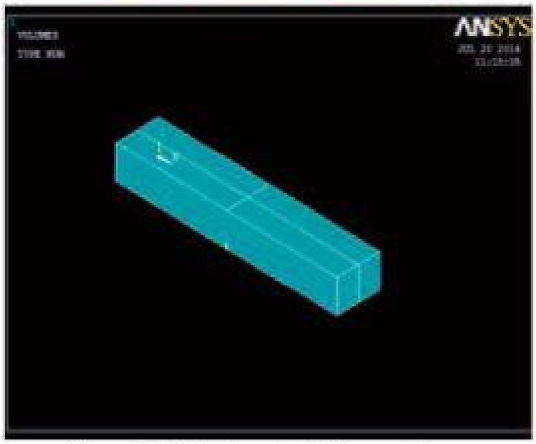

Figure 3. 3D Modeling of notched concrete beam

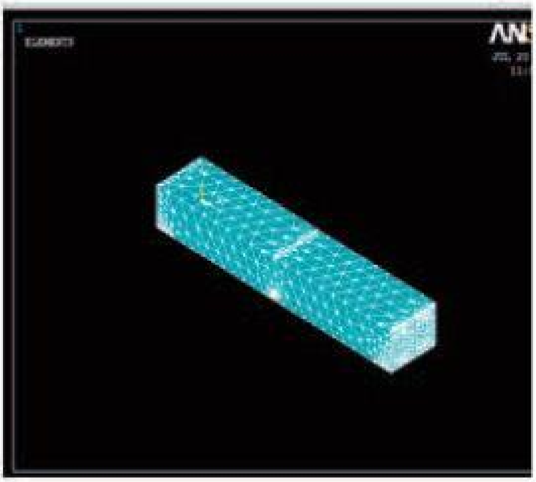

Figure 4. 3D Meshing of notched concrete beam

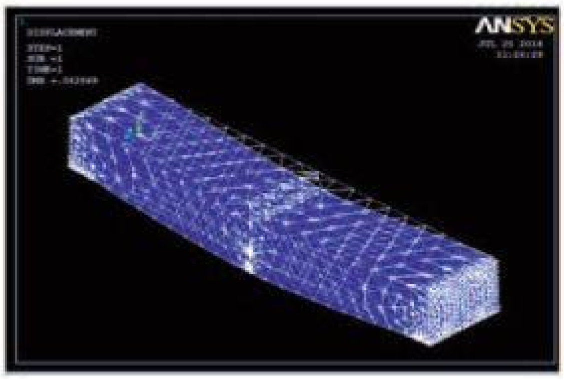

Figure 5. Deformed shape of notched concrete beam

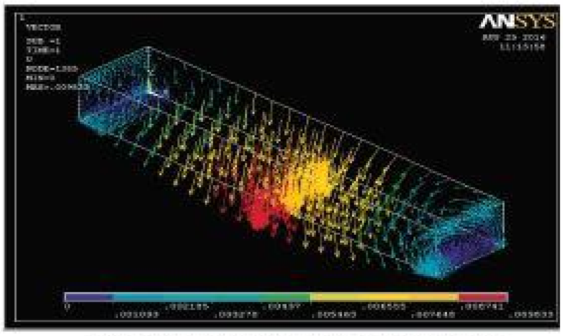

Figure .6. Vectorload Plot of notched concrete beam

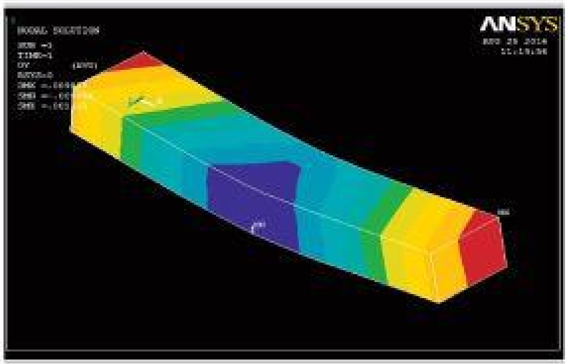

Figure 7. Stress variation over the notched concrete beam

IV. Analysis Of Notched Concrete Beams

The load-deflection figure shows a different deformation and behavior under the loads for beams, thus beam specimens had been made with two variables (notch depth/beam depth ratio, and Concrete grade) were tested to the ultimate load capacity so as to research deflection behavior in this study.

For particular depth, notch depth-beam depth ratio, The Stress intensity factor is observed to be increasing with the increase in the load and this stress intensity factor determined at crack tip. The following table shows the test results of the beams.

Grade of concrete	Size of Beam (mm x mm)	a/D	Deflection mm	Stress intensity factor N/mm²
M20	100 X 75	0.15	0.062869	4.77808
		0.3	0.047178	3.00501
		0.45	0.009912	0.581767
	100 X 150	0.15	0.10838	5.06743
		0.3	0.083037	3.70101
		0.45	0.083037	1.89274
	100 X 300	0.15	0.205183	6.42495
		0.3	0.160362	4.57469
		0.45	0.118737	2.22868
M30	100 X 75	0.15	0.076864	7.14012
		0.3	0.057006	4.47298
		0.45	0.011293	0.678518
	100 X 150	0.15	0.130372	6.57468
		0.3	0.099113	5.41035
		0.45	0.070993	3.05666
	100 X 300	0.15	0.242896	6.09492
		0.3	0.188195	5.328

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Grade of concrete	Size of Beam (mm x mm)	a/D	Deflection mm	Stress intensity factor N/mm²
		0.45	0.115158	3.404411
M40	100 X 75	0.15	0.088355	9.42384
		0.3	0.065392	5.65244
		0.45	0.012554	0.871014
	100 X 150	0.15	0.149211	10.536
		0.3	0.11298	8.22713
		0.45	0.080327	3.99358
	100 X 300	0.15	0.275686	11.3609
		0.3	0.210886	8.95672
		0.45	0.150406	4.36984
M50	100 X 75	0.15	0.096178	12.736
		0.3	0.072495	7.37656
		0.45	0.013675	3.1247
	100 X 150	0.15	0.183628	12.2141
		0.3	0.125368	7.94811
		0.45	0.087948	4.40057
	100 X 300	0.15	0.30523	13.6341
		0.3	0.231193	9.36027
		0.45	0.164004	5.16299
M60	100 X 75	0.15	0.1069	13.2991
		0.3	0.079203	8.82835
		0.45	0.014744	5.12879
	100 X 150	0.15	0.180488	12.9171
		0.3	0.136615	9.48784
		0.45	0.10416	5.2368
	100 X 300	0.15	0.33284	16.1583
		0.3	0.250691	11.1184
		0.45	0.177231	5.75713
M70	100 X 75	0.15	0.115315	15.4955
		0.3	0.092228	10.2801
		0.45	0.015742	4.1456
	100 X 150	0.15	0.194449	16.0312
		0.3	0.144513	10.8405
		0.45	0.102579	6.07302
	100 X 300	0.15	0.357694	18.7562
		0.3	0.288795	12.8765
		0.45	0.189231	6.63946

TABLE II

DEFLECTION, STRESS INTENSITY FACTOR FOR BEAMS OF DIFFERENT SIZES, GRADES AND NOTCH-DEPTH RATIOS

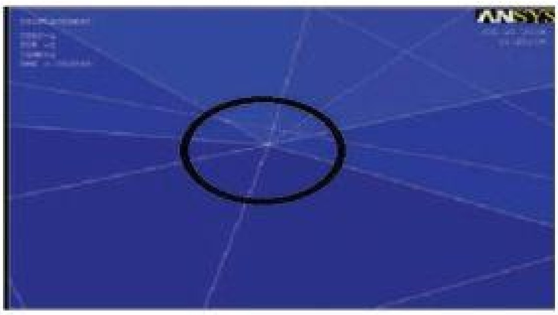

Figure 8. Deflection at point of application of load

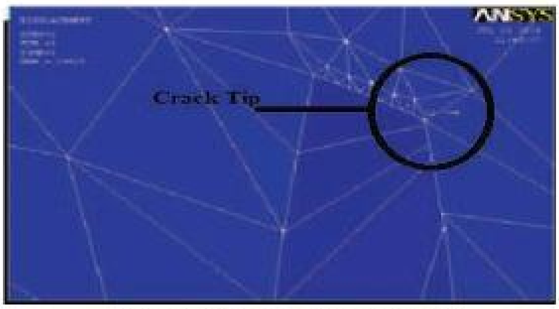

Figure 9. Stress intensity factor at crack tip

V. Results Analysis

A. Peak Load Vs Notch-depth Ratio

When the grade of concrete and the size of the beam is constant, then the peak load and the deflection were found to be decreasing with the increase in the notch depth ratios. This is due to the increase in the brittleness of the member, in other words, the increase in the crack length in a member makes it to behave in a brittle manner. The following graphs shows relation between peak load and notch – depth ratio.

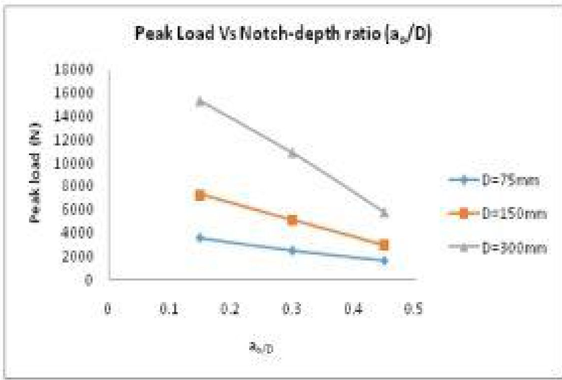

Figure10. Peak Load vs Notch-depth ratio (M20 Concrete)

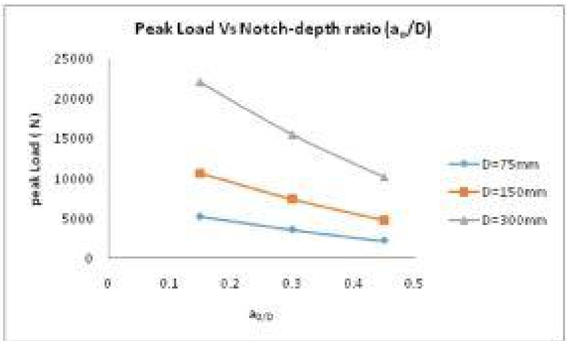

Figure 11. Peak Load vs Notch-depth ratio (M30 Concrete)

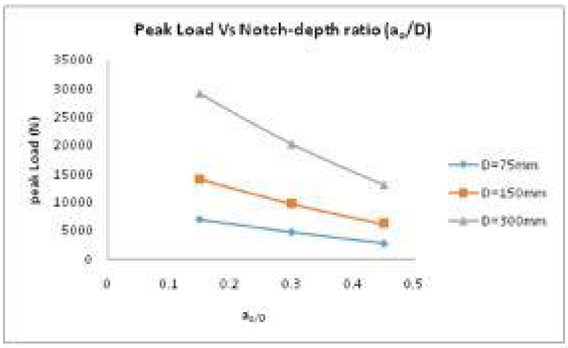

Figure 12. Peak Load vsNotch-depth ratio (M40 Concrete)

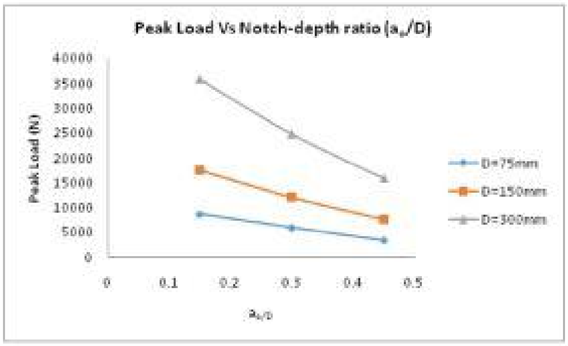

Figure 13. Peak Load vsNotch-depth ratio (M50 Concrete)

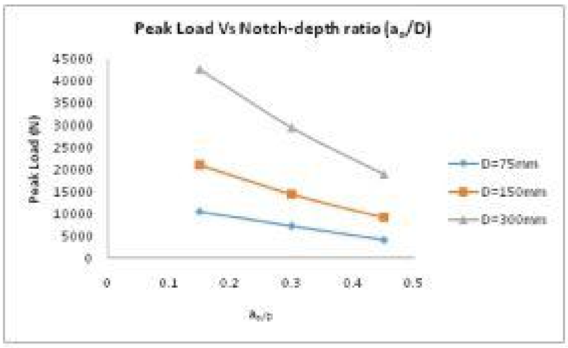

Figure 14. Peak Load vsNotch-depth ratio (M60 Concrete)

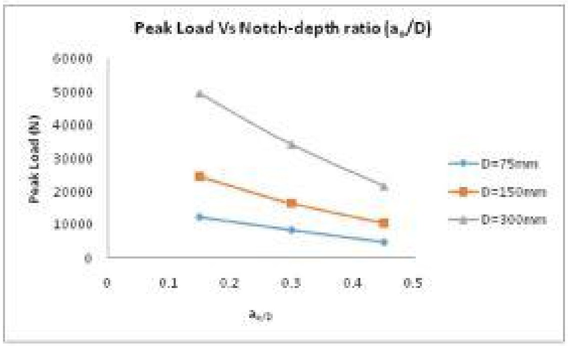

Figure 15. Peak Load vsNotch-depth ratio (M70 Concrete)

B. *Depth Vs Fracture Energy (G_f)*

From the following graphs it is clear that in a particular notch depth-beam depth ratio, the fracture energy is observed to be increasing with the increase in the beam depth. This is due to the increase in the depth of uncracked ligament which has enhanced the load resisting capacity and hence the fracture energy of the larger depth beams. Same trend was observed with the increase in the notch depth to beam depth ratio. Similar trend was observed in all the higher grades of concrete (M30, M40, M50, M60, M70)

TABLE III

FRACTURE ENERGY FOR BEAMS OF DIFFERENT SIZES, GRADES AND NOTCH-DEPTH RATIOS

Grade of concrete	Size of Beam (mm x mm)	a/D	Fracture Energy (G_f) N-mm
M20	100 X 75	0.15	118.9005
		0.3	61.4389
		0.45	2.253866
	100 X 150	0.15	413.7122
		0.3	179.7514
		0.45	118.641
	100 X 300	0.15	1590.953
		0.3	874.1657
		0.45	378.2803
M30	100 X 75	0.15	174.8352
		0.3	107.4548
		0.45	3.457815
	100 X 150	0.15	720.9258
		0.3	382.877
		0.45	169.2044
	100 X 300	0.15	2698.787
		0.3	1278.975
		0.45	599.3161
M40	100 X 75	0.15	283.4675
		0.3	160.6794
		0.45	5.153569
	100 X 150	0.15	1153.086
		0.3	587.6143
		0.45	242.7794
	100 X 300	0.15	3609.718
		0.3	1858.153
		0.45	1149.008
Grade of concrete	Size of Beam (mm x mm)	a/D	Fracture Energy (G_f) N-mm
M50	100 X 75	0.15	430.9933
		0.3	214.858
		0.45	7.299549
	100 X 150	0.15	1712.186
		0.3	754.939
		0.45	333.6196
	100 X 300	0.15	5481.438
		0.3	2894.537
		0.45	1304.962
M60	100 X 75	0.15	556.7235
		0.3	280.9394
		0.45	8.660802
	100 X 150	0.15	1896.978
		0.3	982.0472
		0.45	500.306
	100 X 300	0.15	7122.385
		0.3	3699.201
		0.45	1665.591

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M70	100 X 75	0.15	699.7285
		0.3	380.9375
		0.45	10.66446
	100 X 150	0.15	2378.209
		0.3	1186.913
		0.45	536.5238
	100 X 300	0.15	8880.893
		0.3	5235.318
		0.45	2070.237

C. Fracture Energy Vs Notch Depth

Increase in the notch ratio (a/D) increases the brittleness of the member. In other words, increase in crack length in a structure pushes the structure to behave in a brittle manner. It indicates that the increase in notch depth ratio decreases the fracture energy. In other words, increase in crack length of a structure requires less fracture energy for extending the crack. A decrease in fracture energy for crack extension indicates the brittleness of the structure.

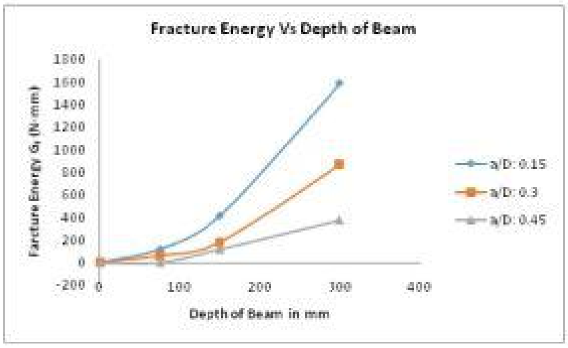

Figure 16. Fracture Energy Vs Depth of Beam (M20 concrete)

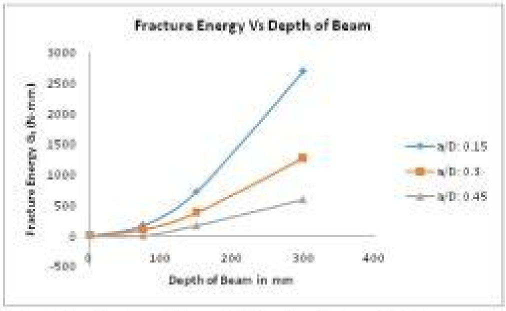

Figure 17. Fracture Energy Vs Depth of Beam (M30 concrete)

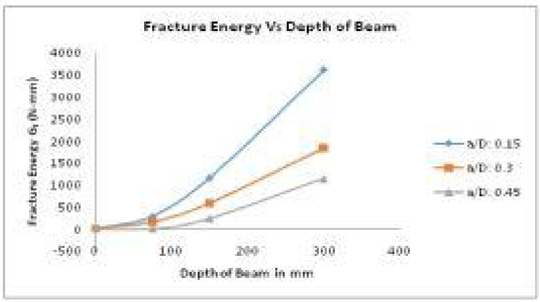

Figure 18. Fracture Energy Vs Depth of Beam (M40 concrete)

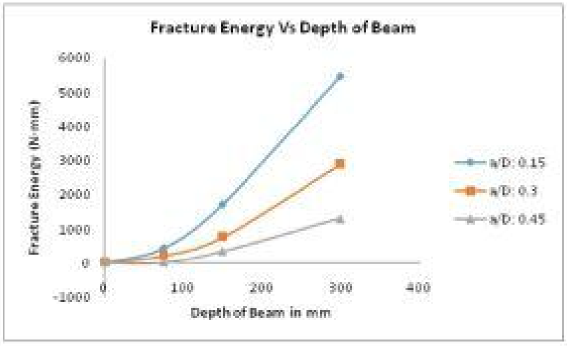

Figure 19. Fracture Energy Vs Depth of Beam (M50 concrete)

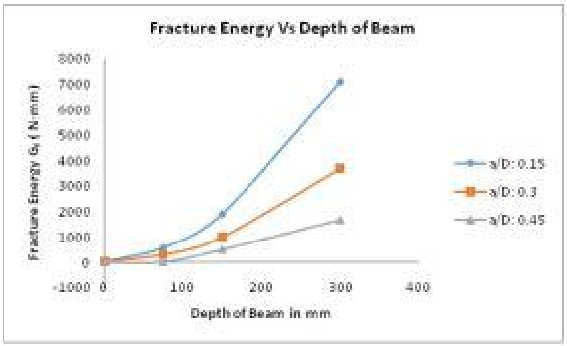

Figure 20. Fracture Energy Vs Depth of Beam (M60 concrete)

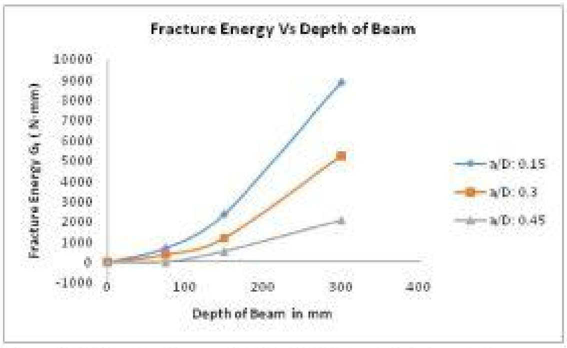

Figure 21. Fracture Energy Vs Depth of Beam (M70 concrete)

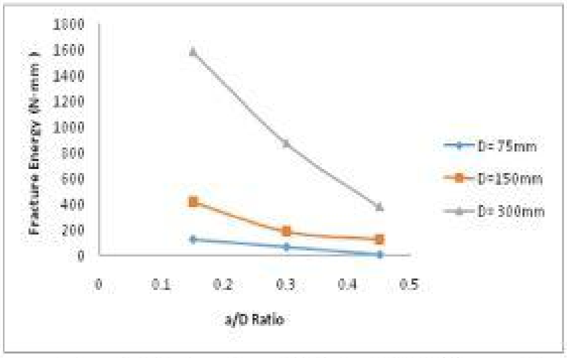

Figure 22. Fracture Energy Vs Notch depth (M20 concrete)

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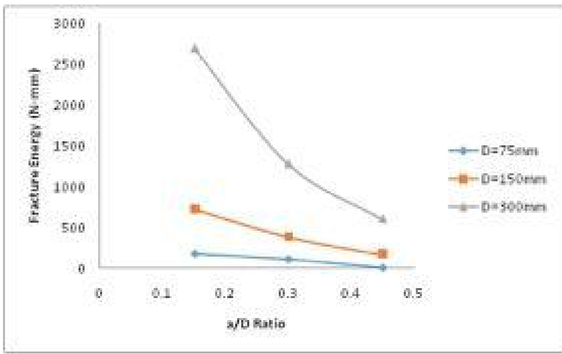

Figure 23. Fracture Energy Vs Notch depth (M30 concrete)

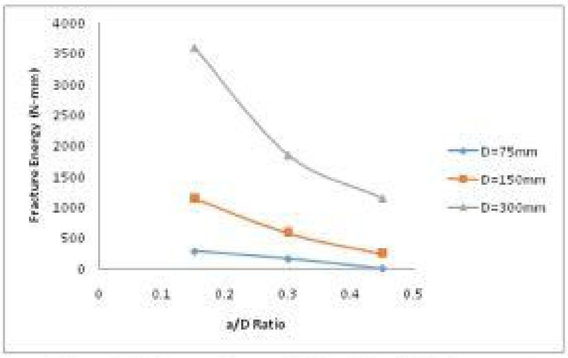

Figure 24. Fracture Energy Vs Notch depth (M40 concrete)

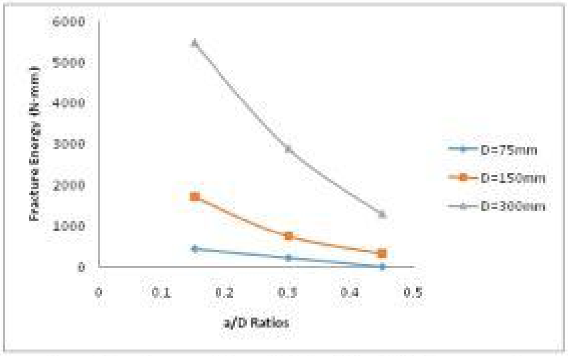

Figure 25. Fracture Energy Vs Notch depth (M50 concrete)

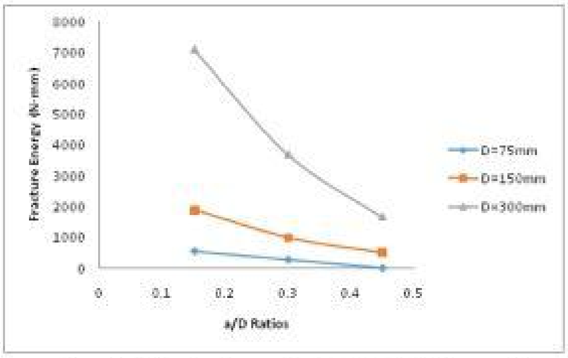

Figure 26. Fracture Energy Vs Notch depth (M60 concrete)

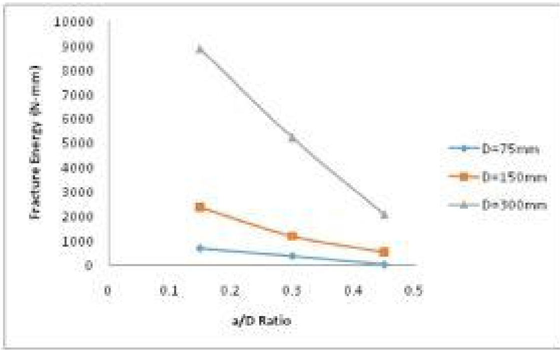

Figure 27. Fracture Energy Vs Notch depth (M70 concrete)

D. Peak Load Vs Depth of Beam

From the following graphs it is clear that in a particular notch depth to beam depth ratio, the Load carrying capacity is observed to be decreasing with the increase in the notch depth to beam depth ratio. If notch depth to beam depth increased the depth of uncracked ligament portion will be decreased so stiffness of member will be reduced. So load carrying capacity will gradually decrease. Same trend was observed with the increase in the notch depth to beam depth ratio. Similar trend was observed in all the higher grades of concrete (M30, M40, M50, M60, M70)

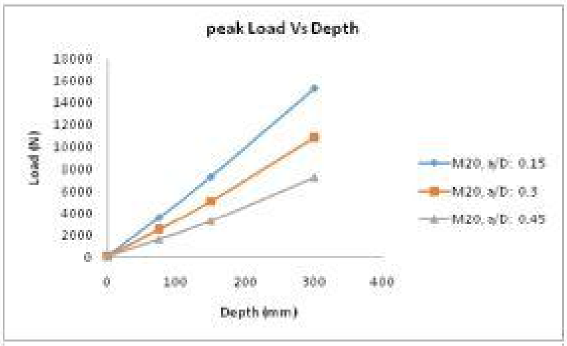

Figure 28. Peak Load Vs Depth (M20 Concrete)

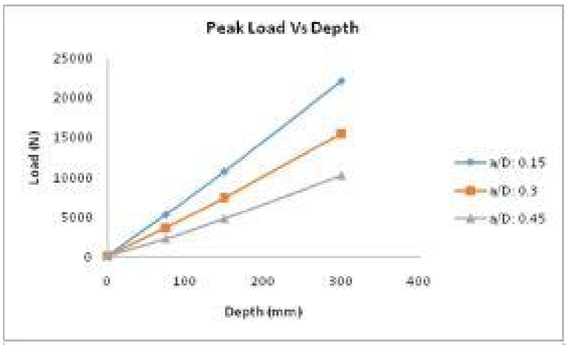

Figure 29. Peak Load Vs Depth (M30 Concrete)

doi:10.32377/cvrjst1104

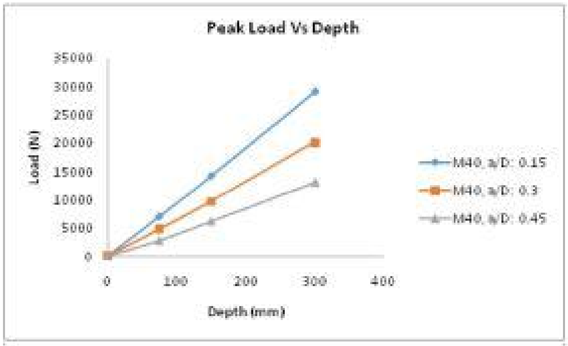

Figure 30. Peak Load Vs Depth (M40 Concrete)

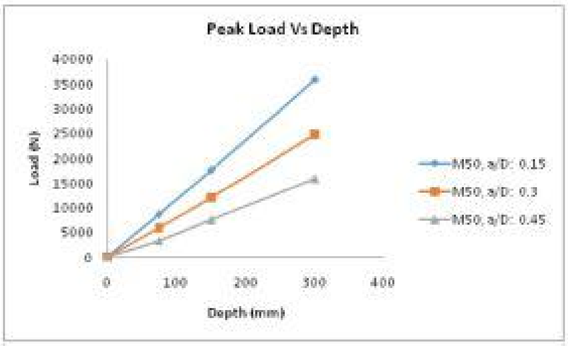

Figure 31. Peak Load Vs Depth (M50 Concrete)

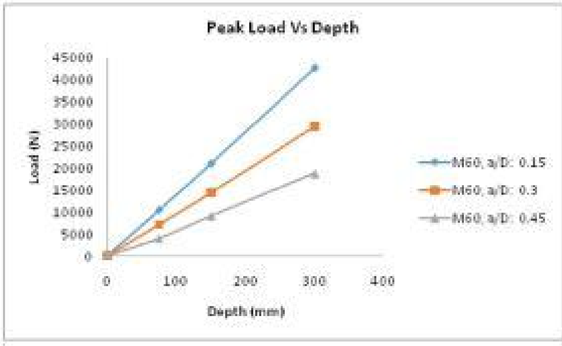

Figure 32. Peak Load Vs Depth (M60 Concrete)

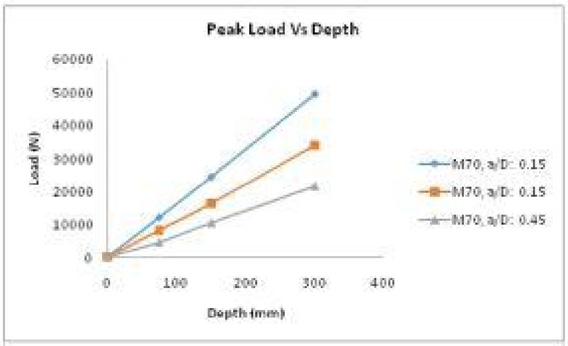

Figure 33. Peak Load Vs Depth (M70 Concrete)

E. Peak Load Vs SINT (Grade Wise)

In a particular size of the beam and for a particular notch depth ratio, the stress intensity factor is observed to be increasing with the increase in the grade of the concrete. This is due to the increased load resisting capacity of the beam with the increase in the grade of concrete.

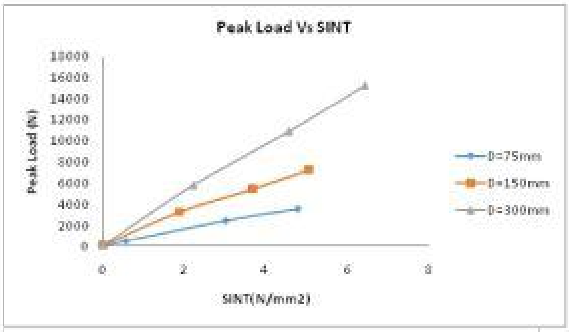

Figure 34. Peak Load vs SINT (M20 Concrete, a/D: 0.15, 0.3, and 0.45)

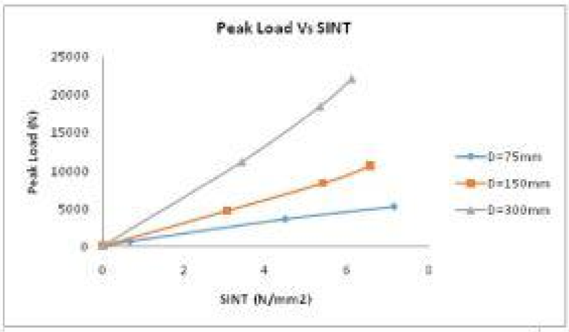

Figure 35. Peak Load vs SINT (M30 Concrete, a/D: 0.15, 0.3, and 0.45)

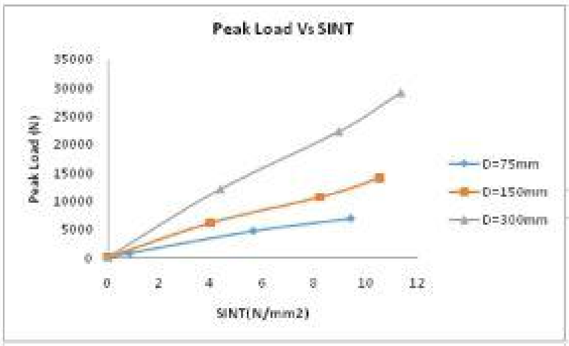

Figure 36. Peak Load vs SINT (M40 Concrete,a/D: 0.15, 0.3, and 0.45)

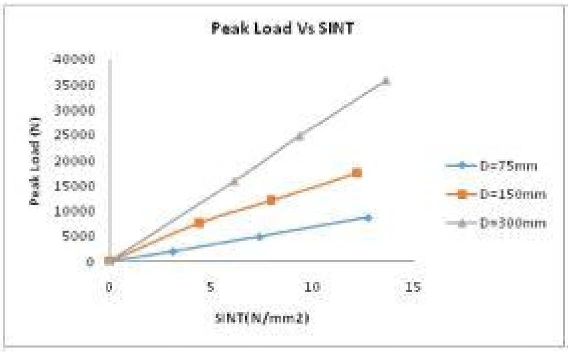

Figure 37. Peak Load vs SINT (M50 Concrete, a/D: 0.15, 0.3, and 0.45)

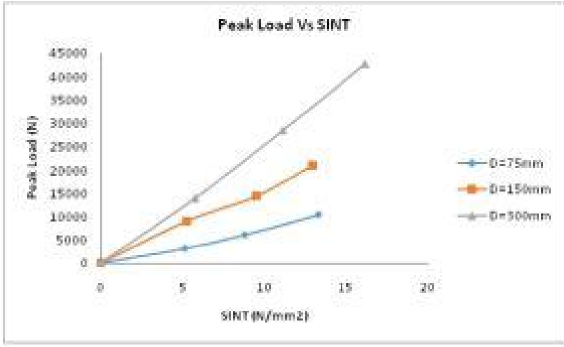

Figure 38. Peak Load vs SINT (M60 Concrete, a/D: 0.15, 0.3, and 0.45)

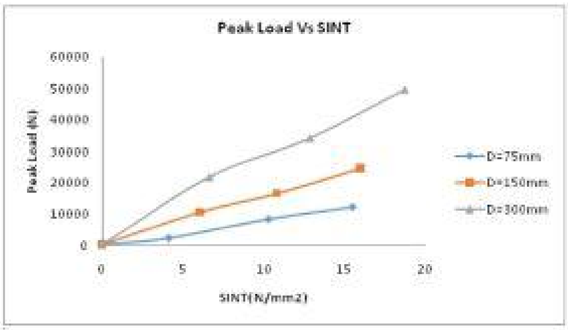

Figure 39. Peak Load vs SINT (M70 Concrete, a/D: 0.15, 0.3, and 0.45)

F. *Fracture Toughness Vs a_0*

Fracture Toughness is found to be decreasing with an increasing the notch depth ratio. Increase in the notch depth ratio (a/D) increases the brittleness of the member. In other words, increase crack length in a beam it behaves in a brittle manner.

TABLE IV

FRACTURE TOUGHNESS FOR BEAMS OF DIFFERENT SIZES, GRADES AND NOTCH DEPTH RATIOS

Grade of concrete	Size of Beam (mm x mm)	a/D	Fracture Toughness (K_I)
M20	100 X 75	0.15	1630.551
		0.3	1172.099
		0.45	224.4949
	100 X 150	0.15	3041.527
		0.3	2004.835
		0.45	1628.77
	100 X 300	0.15	5964.461
		0.3	4421.192
		0.45	2908.368
M30	100 X 75	0.15	2188.163
		0.3	1715.451
		0.45	307.7274
	100 X 150	0.15	4443.351
		0.3	3238.135
		0.45	2152.639
	100 X 300	0.15	8597.053
		0.3	5918.291
		0.45	4051.29
M40	100 X 75	0.15	2993.999
		0.3	2254.136
		0.45	403.6956
	100 X 150	0.15	6038.525
		0.3	4310.684
		0.45	2770.805
	100 X 300	0.15	10684.07
		0.3	7665.504
		0.45	6027.837

Grade of concrete	Size of Beam (mm x mm)	a/D	Fracture Energy (G_f) N-mm
M50	100 X 75	0.15	3903.577
		0.3	2756.153
		0.45	508.0138
	100 X 150	0.15	7780.419
		0.3	5166.345
		0.45	3434.419
	100 X 300	0.15	13921.14
		0.3	10116.19
		0.45	6792.45
M60	100 X 75	0.15	4643.469
		0.3	3298.596
		0.45	579.1644
	100 X 150	0.15	8571.443
		0.3	6167.214
		0.45	4401.905
	100 X 300	0.15	16608.7
		0.3	11969.52
		0.45	8031.691
M70	100 X 75	0.15	5410.337
		0.3	3991.962
		0.45	667.9269
	100 X 150	0.15	9974.348
		0.3	7046.427
		0.45	4737.552
	100 X 300	0.15	19274.71
		0.3	14798.95
		0.45	9306.139

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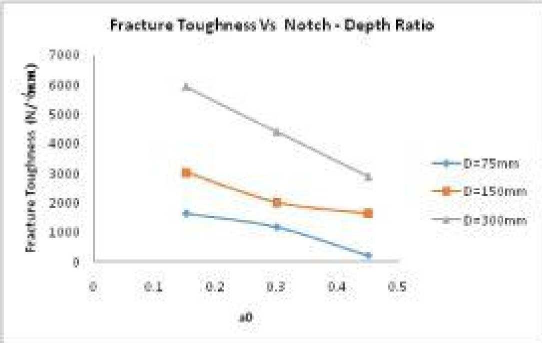

Figure 40. Fracture Toughness Vs notch-depth ratio (M20 Concrete)

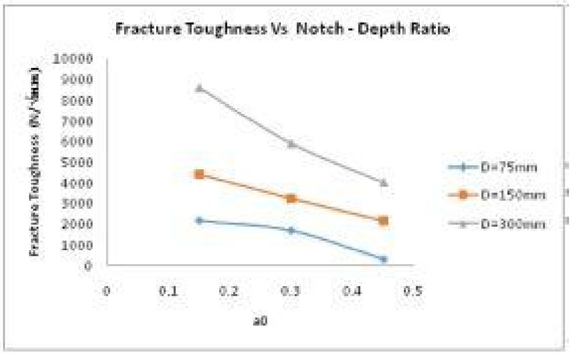

Figure 41. Fracture Toughness Vs notch-depth ratio (M30 Concrete)

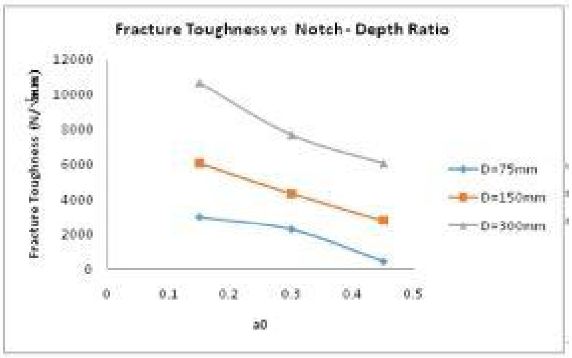

Figure 42. Fracture Toughness Vs notch-depth ratio (M40 Concrete)

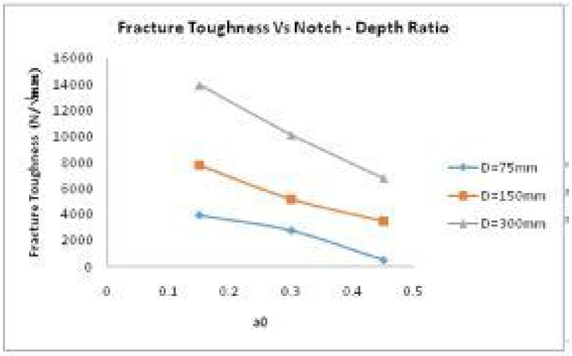

Figure 43. Fracture Toughness Vs notch-depth ratio (M50 Concrete)

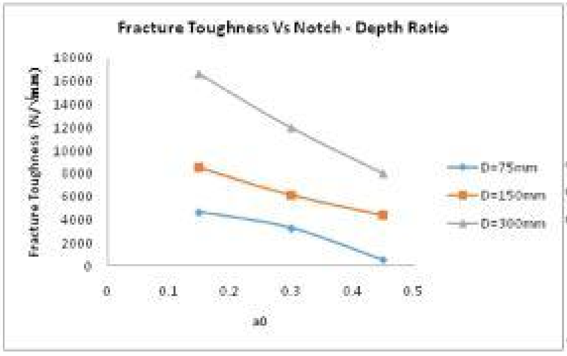

Figure 44. Fracture Toughness Vs notch-depth ratio (M60 Concrete)

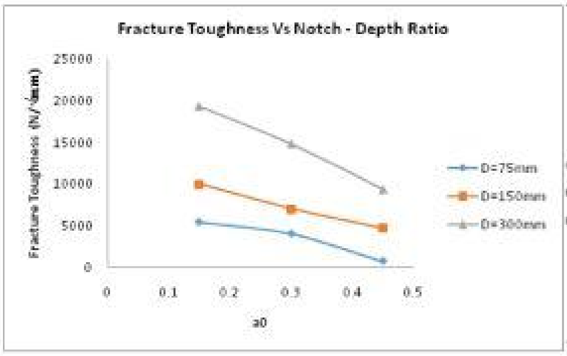

Figure 45. Fracture Toughness Vs notch-depth ratio (M70 Concrete)

VI. Conclusions

The fracture behavior of the notched plain concrete beams of different sizes and notch depth ratios for different grades of concrete has been analyzed based on the modelling of beams in ANSYS. The variation of fracture parameters has been studied and presented below.

1. In a particular size of the beam and for a particular notch depth ratio, the fracture energy and fracture toughness are observed to be increasing with the increase in the grade of the concrete. This is due to the increase in the depth of uncracked ligament which has enhanced the load resisting capacity. Hence, the fracture energy of the larger depth beams. Same trend was observed with the increase in the notch depth ratios.

2. In a particular grade of concrete and for a particular size of the beam, the fracture energy and fracture toughness are observed to be decreasing with increase in the notch depth ratios. This is due to the decrease in the depth of uncracked ligament. Same trend was observed with the increase in the size of the beams.

3. When the grade of concrete and the size of the beam is constant, then the peak load and the deflection were found to be decreasing with the increase in the notch depth ratios. This is due to the increase in the brittleness of the member. In other words, the increase in the crack length in a member makes it to behave in a brittle manner.

4. In a particular size of the beam and for a particular notch depth ratio, the stress intensity factor is observed to be increasing with the increase in the grade of the concrete.

This is due to the increased load resisting capacity of the beam with the increase in the grade of concrete.

5. In a particular size of the beam and for a particular notch depth ratio, the peak deflection value is observed to be increasing with the increase in the grade of the concrete. This is due to the increased load resisting capacity of the beam with the increase in the grade of concrete.

6. Increase in the notch ratio (a/D) increases the brittleness of the member. In other words, increase in crack length in a structure pushes the structure to behave in a brittle manner.

7. It indicates that the increase in notch depth ratio decreases the fracture energy. In other words, increase in crack length of a structure requires less fracture energy for extending the crack. A decrease in fracture energy for crack extension indicates the brittleness of the structure.

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