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Fracture parameters of high strength concrete-an experimental study

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ACI 446.1R-91 (Re-approved 1999) strongly recommends the application of fracture mechanics principles to the quasi-brittle material like concrete. The behaviour of concrete is governed by the fracture parameters viz., fracture energy (G_F) and effective length of fracture process zone (C_f). Determination of these fracture parameters for normal strength as well as high strength concrete is essential to characterize the degree of brittleness of concrete. The present paper analyses the size dependency of the fracture energy (G_F) and the effective length of fracture process zone (C_F) of concrete determined as per the Bazant's Size effect method (SEM) and RILEM Work-of-fracture methods (WFM). The fracture parameters (G_F and C_f) are determined by measuring the maximum loads of geometrically similar notched high strength concrete (78MPa) specimens of different sizes in a size ratio of 1:4 with different notch depths (a_0/d = 0.10, 0.15 and 0.20) under three point bending through load-deflection curves. The variation of both the fracture energy and the effective length of fracture process zone as a function of the specimen size and notch depth were determined using Bazant's Size effect method and RILEM Work-of-fracture method. Fracture energy and Fracture process zone length determined by Size effect method are found to be decreasing with the increasing notch depth ratios. Fracture energy calculated using Work-of-fracture method is increasing with the increase in size of specimen and decreasing with the increasing notch depth ratios.

KEYWORDS: Brittleness number; crack length; effective length of fracture process zone; fracture energy; fracture parameters; size effect.

The size effect on structural strength is an important phenomenon. Unfortunately, despite the abundant experimental evidence, this phenomenon is still not taken into account in most specifications of the design codes for concrete structures, as well as the design practices.

Generally, concrete structures are designed based on the strength of a standard specimen size. The actual concrete strength of relatively larger structural members may be significantly lower than that of the standard size. In fact, with the increasing size of the specimens, the failure stress decreases. By neglecting size effect, predicted load capacity values are less conservative with the increase in the member size. The size effect can be quantified by comparing the stress at the maximum load of geometrically similar specimens of different sizes with geometrically similar notch ratios.

Investigations in this area of research are conducted by the authors using Servo Control Dynamic Testing Machine (1000kN capacity) under displacement control at Structures Division, Department of Civil Engineering, National Institute of Technology (N.I.T.) Warangal, to study the fracture parameters of High strength concrete. The fracture parameters are obtained by the Work-of-fracture method (WFM) according to RILEM Draft Recommendation 50-FMC and by the Size effect method (SEM) according to the RILEM Draft Recommendation TC89-FMT.

LITERATURE REVIEW

Guinea et al[1, 2], pointed that the application of the Size Effect Method (SEM) in place of the Work-of-fracture method has the main advantage of being not affected by this size dependence. If the fracture energy is to be considered as a material property, as intended by many researchers, its value must be independent of size effect, which justifies the use of the so-called size effect method.

Bazant[3], reported that the fracture energies, G_F obtained by the work-of-fracture method and G_f obtained by the SEM are two different material characteristics. The total fracture energy G_F represents the area under the complete load-deflection curve, and the initial fracture energy G_f represents the area under the initial tangent of the softening curve.

Bazant and Kazemi[4] concluded that fracture energy determined based on work-of-fracture method is size dependent, though the RILEM recommendations say that the work-of-fracture method is size independent. Further, it was mentioned in three point bent fracture specimens, the fracture energy according to the RILEM definition is dependent on the notch depth also.

Ravindra Gettu et al[5] tested geometrically similar three point bend specimens for fracture parameters and the brittleness of the material and quantified through Size effect

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(Discussion on this article must reach the editor before April 30, 2009)

method. They concluded that as the strength increases, the fracture energy and the fracture toughness of concrete also increase, although much less than the strength. The effective size of the fracture process zone diminishes resulting in decreased crack tip shielding and increase in the brittleness of specimen or structure.

Ravindra Gettu et al[6] stated that High strength concrete exhibits a higher value of B and a lower value of d_o than normal strength concrete indicating higher strength and higher brittleness and stated that the higher brittleness is also reflected in the lower fracture process zone, C_f and critical crack tip opening displacement, CTODc values of high strength concrete.

Einsfeld and Velasco[7] reported that the ratio of fracture energies obtained from the Hillerborg's RILEM Work-of-fracture and the Bazant Size effect method is approximately 2.88.

Zhao et al[8] performed three-point bend test on notched beams and a wedge splitting test on different size specimens for ten different concrete mixes and investigated the effect of specimen size and geometry on the fracture energy. From a comparison of the fracture energies, it was found that the fracture energy increases with an increase in specimen size in both the beam and wedge splitting tests.

RESEARCH SIGNIFICANCE

Determination of fracture parameters viz., fracture toughness and effective length of fracture process zone, is essential for design of concrete structures to have economical as well as more accurate detailing. In the process, the fracture parameters estimation is becoming tedious due to the inherent difficulties in capturing the post peak response. The size effect method provides a relatively easiness in arriving the fracture parameters as it involves the determination of peak load only. Thus, it is the concern of the researchers or designers to know the deviation in the estimation of fracture parameters determined by size effect method when compared to work-of-fracture method. The present research work focuses the variation in the estimation of fracture parameters by the mentioned two methods viz., work of fracture method and Size effect method. The SEM has the advantage of providing fracture parameters that are size and shape independent, with a lower scatter of results in comparison with the work-of-fracture. Therefore, for practical purposes, it would be of interest to establish a relation between the fracture energy obtained by the two processes.

The objective of present study is to characterize the brittle behaviour of the high strength concrete (HSC) to establish adequate safety criteria for the material utilization. The parameters obtained in the experiments can provide a database for calibrating of numerical models and the development of design criteria for HSC structures.

NON-LINEAR FRACTURE PARAMETERS

Fracture Energy

Bazant proposed the size dependency of nominal strength of geometrically similar concrete structures by the size effect law. Figure 1 shows a typical three point bend test set up for the determination of fracture parameters using Size effect law[9,10,11].

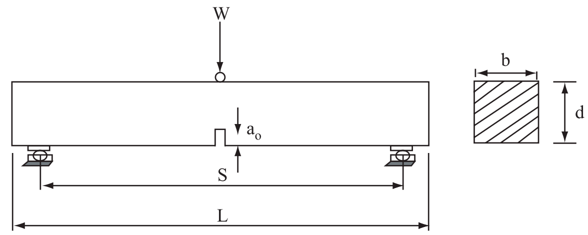


Fig. 1 Typical three point bending test set up

$$\sigma_N = \frac{Bf_t}{\sqrt{1+\beta}} \tag{1}$$

where $\beta = \dfrac{d}{d_o}$ where f_t is the material tensile strength, β is the brittleness number, and *B* and d_0 are empirical constants. The nominal strength of two-dimensional similar structures is defined as

$$\sigma_N = c_n \frac{P_u}{bd} \tag{2}$$

where c_n is a coefficient introduced for convenience, P_u is the ultimate load, *b* is the specimen thickness, and *d* is the characteristic specimen size (i.e., depth of the beam).

Fracture parameters were determined using size effect model by testing geometrically similar specimens under three point loading. A correction was made for the Peak loads of the specimens considering the influence of self-weight of the specimen.

$$P_1^o = P_j + \frac{1}{2} m_j g \tag{3}$$

$(j = 1, 2 \ldots n)$
where m_j is the mass of specimen j, g = acceleration due to gravity, n = number of tests conducted, P_1^o = corrected peak load and P_j = peak load.

Linear regression was carried out by taking the ordinates of Y_j on Y-axis and the ordinates of X_j on X-axis

where $\quad Y_j = \left(\dfrac{bd_j}{P_j^o}\right)^2; X_j = d_j$

To facilitate the evaluation of the constants in the size effect law, the above equation can be written as

$$\left(\frac{1}{\sigma_N}\right)^2 = \left[\frac{1}{(Bf_t)^2 d_o}\right] d + \left[\frac{1}{(Bf_t)}\right]^2 \tag{4}$$

Experimental data was arranged in a plot of $X = d$ and $Y = \left(\dfrac{1}{\sigma_N}\right)^2$; a linear regression equation may be found as $Y = AX + C$. Then regression constants Bf_t and d_o were evaluated from A (slope of regression line) and C (intercept on Y-axis) as

$$Bf_t = \frac{1}{\sqrt{C}} \tag{5}$$

$$d_o = \left(\frac{C}{A}\right) \tag{6}$$

For known values of relative crack length, $\alpha = \dfrac{a}{d}$, $S/d = 2.5$

$$F_{2.5}(\alpha) = \frac{1.0 - 2.5\alpha + 4.49\alpha^2 - 3.98\alpha^3 + 1.33\alpha^4}{(1-\alpha)\frac{3}{2}} \quad (7)$$

$S/d = 4.0$

$$F_4(\alpha) = \frac{1.99 - \alpha(1-\alpha)\left(2.15 - 3.93\alpha + 2.7\alpha^2\right)}{\pi\frac{1}{2}(1+2\alpha)(1-\alpha)\frac{3}{2}} \quad (8)$$

$S/d = 8.0$

$$F_8(\alpha) = 1.11 - 2.12\alpha + 7.71\alpha^2 - 13.55\alpha^3 + 14.25\alpha^4 \quad (9)$$

Linear interpolation can be used for other values of S/d, (where S, d = span and depth of beam respectively.)

For 4< S/d <10

$$F(\alpha) = F_4(\alpha) + \frac{[(S/d) - 4]}{4}\left[F_8(\alpha) - F_4(\alpha)\right] \quad (10)$$

where, $F(\alpha)$= function of relative crack length[10].

The non-dimensional energy release rate is

$$g(\alpha) = \left(\frac{S}{d}\right)^2 \pi\alpha\left[1.5F(\alpha)\right]^2 \quad (11)$$

where, $g(\alpha)$ = non-dimensional function which characterizes the geometry of the structure and can be determined using the Handbook[12].

For $\alpha_o = a_o/d$ = initial relative crack length, $g(\alpha = \alpha_o)$ was calculated.

The fracture energy G_f(mean prediction) was calculated using the following expression:

$$G_f = \frac{g(\alpha_o)}{E_c A} \quad (12)$$

where E_c =modulus of elasticity of concrete

Fracture Process Zone Length

The Size Effect method is based on energy considerations and introduces the fracture process zone[9] (C_f). This fracture parameter represents the length of the equivalent linear elastic crack that gives the same unloading compliance as the actual crack in an infinitely large specimen at the peak load.

$$C_f = \frac{g(\alpha_o)}{g'(\alpha_o)} d_o = \frac{g(\alpha_o)}{g'(\alpha_o)}\left(\frac{C}{A}\right) \quad (13)$$

where $g'(\alpha_o) = \frac{dg(\alpha_o)}{d\alpha_o}$

WORK-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 $W_f = \int P d\delta$

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

$$G_F(\alpha_o, d) = \frac{W_f}{B\left[(1-\alpha_o)d\right]} \quad (14)$$

where $\alpha_o = \left(\frac{a_o}{d}\right)$

EXPERIMENTAL PROGRAM

Material Details

Cement conforming to ASTM C150 Type I with specific gravity 3.15 is used for the concrete mix. Natural river sand with specific gravity 2.60 meeting the requirements of ASTM C-33 is used as fine aggregate. Crushed coarse aggregate passing through 20 mm sieve and retained on 10 mm sieve (60%) and retained on 4.75 mm (40%) with specific gravity 2.78 is used. The maximum aggregate size used in the study is 16 mm. The maximum size of the coarse aggregate is limited to 16 mm, as the smallest size of the beams tested was 60 mm (Crack free depth of a beam of height 75 mm with notch ratio of 0.20). Potable water is used for casting.

Ground granulated blast furnace slag, a mineral admixture is used as cement replacement by 10 percent (by weight) to increase the strength of concrete and also workability of concrete. Super plasticizer (CONPLAST 337, FOSROC company product) is used as a chemical admixture at a dosage of 35ml/kg of binder by weight (binder is cement plus GGBFS) to increase the workability of concrete.

Casting

Cubes of 100 mm size were used to determine the compressive strength of concrete. Cylinders with 150 mm diameter and 300 mm length were used to determine the Modulus of Elasticity of concrete. Prisms of 100 mm × 100 mm × 400 mm (B × D × L) size were adopted to determine the modulus of rupture. Moulds of different dimensions were used for beams of different sizes. A needle vibrator was used for compaction. Notches of required depth were made in specimens using Concrete cutter four hours before testing (Fig.2). The details of mix proportions are listed in Table 1.

All the specimens were cured for 28 days in the curing tank. The experimental program is designed to study the variation of fracture energy and the effective length of fracture process zone of High strength concrete beams under three-point bending. Geometrically similar concrete beams (78 MPa) of different sizes with varying notch depth ratios were cast.

Notch ratios of 0.10, 0.15 and 0.20 were adopted for the beams tested in this investigation. Beams were cast in three batches i.e., 09 beams in each batch (a_o/d = 0.10, 0.15 and 0.20). Three similar beams were cast in each beam size. Along with each batch of beams, 3 cubes, 3 cylinders and

Fig. 2 Notch making in a beam using concrete cutter

TABLE 1 DETAILS OF MIX PROPORTIONS AND BEAMS								
Beam Series	Compressive strength of Concrete	Notch depth ratio	Mix Proportions (Kgs per cubic meter of concrete)				Dimensions of beam Specimens (l × b × d)	Designation
		(a_o/d)	Cement	Fine Aggregate	Coarse Aggregate	water	mm × mm × mm	
Series A	76.30	0.10	665.07	581.94	1080.74	172.918	375 × 100 × 75	H/75/0.10
		0.10	665.07	581.94	1080.74	172.918	750 × 100 × 150	H/150/0.10
		0.10	665.07	581.94	1080.74	172.918	1500 × 100 × 300	H/300/0.10
Series B	79.97	0.15	665.07	581.94	1080.74	172.918	375 × 100 × 75	H/75/0.15
		0.15	665.07	581.94	1080.74	172.918	750 × 100 × 150	H/150/0.15
		0.15	665.07	581.94	1080.74	172.918	1500 × 100 × 300	H/300/0.15
Series C	78.29	0.20	665.07	581.94	1080.74	172.918	375 × 100 × 75	H/75/0.20
		0.20	665.07	581.94	1080.74	172.918	750 × 100 × 150	H/150/0.20
		0.20	665.07	581.94	1080.74	172.918	1500 × 100 × 300	H/300/0.20

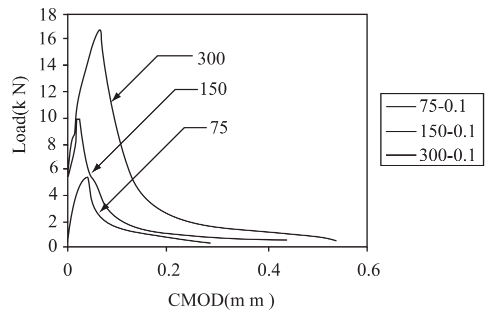
Fig. 3 Tested specimen using servo controlled dynamic testing machine

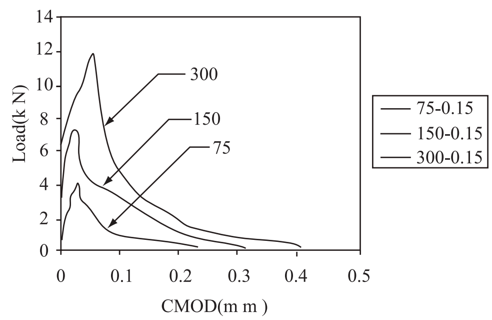
3 prisms were also cast for the determination of material properties such as compressive strength, Young's modulus and modulus of rupture respectively. The details of strength properties of concrete are summarized in Table 2.

TABLE 2 MECHANICAL PROPERTIES				
Beam Series	Wet density (kN/m^3)	Cube Compressive strength (f_{ck}) MPa	Modulus of rupture on Prisms (f_{bt}) MPa	Modulus of Elasticity (E) MPa
A	25.767	76.30	6.566	32000
B	25.832	79.97	6.986	32400
C	26.454	78.29	6.439	32250

Test Results

The specimens were tested on the 1000 kN Servo controlled dynamic testing Machine until failure. All the specimens were tested under displacement control at a rate of 0.15mm/min. A Bakelite based 120-Ohm Electrical Resistance Strain Gauge (ESRG) with gauge factor 2.1 was used to measure the Crack mouth opening displacement (CMOD) for all specimen sizes of all notch depth ratios. Three point bend tests were performed to determine the fracture parameters. All the tests were performed at National Institute of Technology (N.I.T.) Warangal, using Servo controlled dynamic testing machine equipped with 05 channels for data acquisition and a load cell of 1000 kN capacity. All the tests were conducted under vertical displacement control. A photograph of the test set-up is shown in Fig.3. The load-CMOD curves (Fig.4) and load-deflection curves (Fig.5) were continuously recorded for each beam of three different notch-depth ratios. For determining the fracture parameters with the help of size effect method, regression plots were prepared and presented





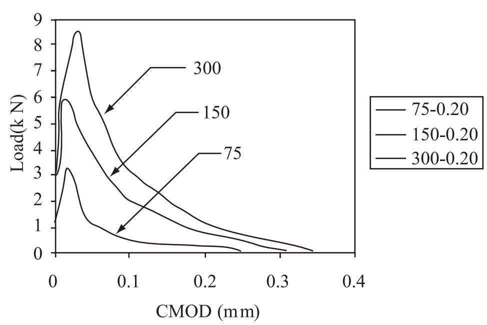


Fig. 4 Load-CMOD curves for different depth beams with same notch depth ratio

in Table 3 and Fig.6. The regression plots consisted $\frac{1}{\left(\frac{P^0}{bd}\right)^2}$ on Y-axis and size (d) on X-axis. The regression equation is presented in the form of $Y = AX + C$. The characteristic size of the tested beams is reported as $d_0 = \frac{C}{A}$ and the numerator in size effect law $Bf_t = \frac{1}{\sqrt{C}}$. Size effect plots were prepared on logarithmic scale and were presented in Fig.7 (for A, B and C series). Data pertaining to the size effect law variations is presented in Table 4 for all series of beams tested in this investigation. From the size effect method, the fracture parameters viz., fracture energy and effective length

TABLE 3 LINEAR REGRESSION DATA									
Beam Size (d) (mm)	SERIES A			SERIES B			SERIES C		
	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}	Y = $(bd/P^o)^2$ MPa^{-2}
75	1.875	3.159	5.179	1.864	3.206	5.204	1.875	2.707	5.143
150	2.223	4.0408	6.184	2.375	4.014	6.169	2.375	4.013	6.169
300	2.981	5.837	10.179	2.991	5.377	10.179	3.123	5.423	10.473

of fracture process zone were determined and reported in Table 5. From the load-deflection response of the tested specimens, fracture energy was calculated using work of fracture method. The test results are tabulated in Table 6.

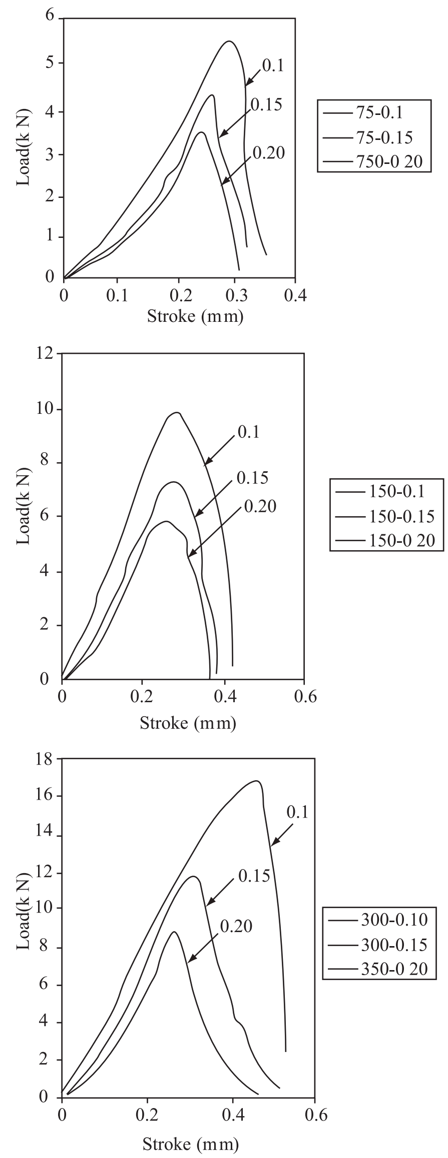


Fig. 5 Load-deflection curves for same depth beams with different notch depth ratio

DISCUSSION ON TEST RESULTS

The fracture energy determined by the size effect method is the mean prediction for a particular notch depth ratio. The fracture energy obtained by the Size effect method is computed as specified in RILEM TC89-FMT. From Eqn.(12), it can be observed that for a given notched beam ($\frac{g(\alpha_o)}{E_c}$ is a constant term) the fracture energy depends on the slope of the regression line (A). The fracture energy is inversely proportional to the slope of the regression line. In the present investigation, it is found that the slope of the regression line (A) is increased with the increase of the notch depth ratio. 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 (vide Fig.8). A decrease in fracture energy for crack extension indicates the brittleness of the structure. Thus, it can be concluded that a crack present in a structure pushes the structure to fail in a brittle manner when the crack length (may be referred as critical crack length) approaches a particular value. From Fig.9, it is clear that the effective length of fracture process zone C_f decreased with the notch depth ratio. A higher fracture process zone indicates a ductile failure in a structure allowing more dissipation of energy through FPZ. A small FPZ indicates a brittle failure. Thus with the increase in the notch depth ratio or increase in crack length reduces the FPZ, thereby pushing the structure into a brittle failure state.

TABLE 4 SIZE EFFECT LAW DATA						
Beam depth (mm)	SERIES A		SERIES B		SERIES C	
	Log (d/d_o)	Log (σ_N/Bf_t)	Log (d/d_o)	Log (σ_N/Bf_t)	Log (d/d_o)	Log (σ_N/Bf_t)
75	−0.598	−0.048	−0.434	−0.068	−0.252	−0.096
150	−0.297	−0.088	−0.133	−0.119	0.048	−0.163
300	0.003	−0.153	0.167	−0.196	0.349	−0.255

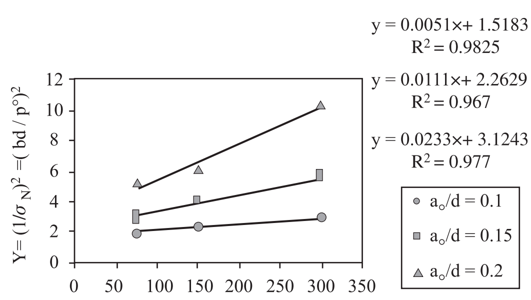


Fig. 6 Linear Regression Graphs for Series A, Series B, Series C beams

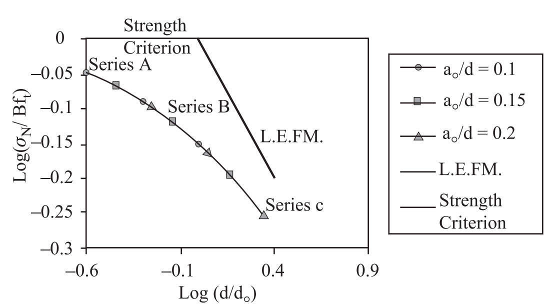


Fig. 7 Size effect law graphs for Series A, Series B, Series C beams

TABLE 5 FRACTURE PARAMETERS FROM SIZE EFFECT METHOD								
Beam series	a_o/d	A (mm^{-1} MPa^{-2})	C MPa^{-2}	d_o (mm)	Bf_t MPa	Brittleness Number $\beta = \frac{d}{d_o}$	Fracture energy, G_f (Mean Prediction) (G_f) N-m/m^2	Effective length of FPZ, C_f (Mean Prediction) (C_f) mm
A	0.10	0.0051	1.5183	297.71	0.812	0.252	67.347	32.852
B	0.15	0.0111	2.2629	203.86	0.665	0.736	44.722	30.913
C	0.20	0.0233	3.1243	134.09	0.566	2.237	28.956	23.807

TABLE 6 FRACTURE ENERGY FROM WORK-OF-FRACTURE METHOD			
Depth of beam (mm)	Average Fracture Energy (G_F) N-m/m^2		
	a_o/d = 0.10	a_o/d = 0.15	a_o/d = 0.20
75	128.47	86.369	67.026
150	167.277	110.292	92.066
300	210.016	132.005	97.502
Average G_F =	168.587	109.555	85.531

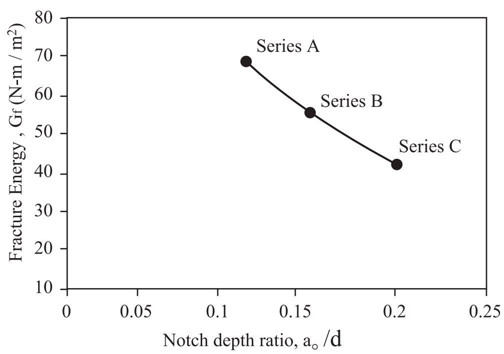


Fig. 8 Fracture energy (Mean prediction) variation with Notch depth ratio

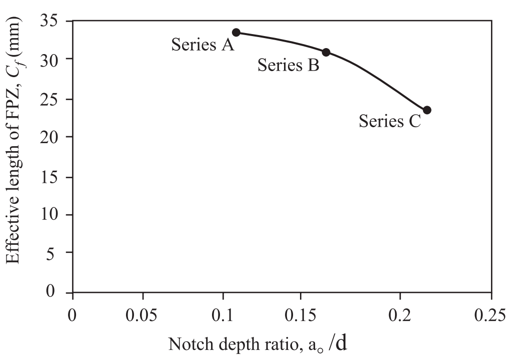


Fig. 9 Effective length of fracture process zone variation with notch depth ratio

Fig. 10 Tested beams-Series A, Series B, Series C

The size effect law (SEL) graphs represent a gradual transition from the strength criterion ($\sigma_N = Bf_t$ i.e., $\frac{d}{d_0} << 1$) to the energy criterion of LEFM ($\frac{d}{d_0} >> 1$). Size effect plots were prepared for the tested beams with varying notch depth ratio. From the size effect law plot, it can further be observed that the increase in the notch depth ratio increases the $\frac{d}{d_0}$, making the structure fail by brittle manner wherein energy criterion of failure can be applied. All the tested beams (Series A, Series B and Series C) are shown in Fig.10.

Brittleness Number

The Brittleness number as indicated by $\beta = \frac{d}{d_0}$ characterizes the brittleness of the member. For $0.1 < \beta < 10$, the nonlinear fracture mechanics should be used[9]. Quasi-brittle structures[13] are those for which $0.1 \leq \beta \leq 10$. If $\beta < 0.1$, then the failure may be analyzed on the basis of the strength criterion and if $\beta > 10$, then the failure may be analyzed according to the Linear Elastic Fracture Mechanics[14]. In the present study, increase in the notch ratio decreased the characteristic dimension d_o thereby increasing the brittleness of the member. In other words, it can be stated that an increase in the crack length (due to external forces) increases the brittle number of the element. Thus brittleness of concrete depends more on the crack size or crack length.

The fracture energy (G_F) varied with the size of the specimen and the notch ratio $\alpha = (a_o/d)$. Fracture energy, GF decreased with the increased notch depth a_o and increased with the increased size of the specimen (d) and hence this fracture energy is not size independent. However, it has been stated that the application of the boundary effect concept to the test results of (G_F) indeed gives a specific fracture energy value G_F that is independent of the size and shape of the test specimen[15]. The fracture energy (G_F) obtained by Work-of-fracture method and the size effect was found to be varying as confirmed by Bazant and Becq-Giraudon[16]. The ratio of fracture energy (G_F) calculated using RILEM Work-of-fracture method and that of fracture energy (G_f) calculated using Size effect method is found to be more than 2.40. The details of (G_F/G_f) ratios are given in Table 7. Size effect method (SEM) is simpler and needs less sophisticated equipment as it requires only the peak load value for fracture energy (G_f) determination, where as work-of-fracture method needs more sophisticated equipment as it requires post-peak load-deflection data to determine the fracture energy (G_F). It is observed that the fracture energy obtained from both these methods is size dependent. Thus Size effect method (SEM) is more suitable than work-of-fracture method for estimating the fracture energy, due to the simplicity of the test procedure. More tests are needed in this direction (comparing SEM and WFM) to verify the size dependency of fracture energy using highly brittle concrete (very high strength concrete) as well as highly ductile concrete (SIFCON). The total fracture energy G_F (based on WFM) represents the area under the complete load-deflection curve (including post peak response) and the fracture energy G_f based on Bazant SEM represents the area under the initial tangent of the softening curve. The difference in G_F and G_f is clearly shown in Fig.11. From this Fig.11, it is clear that sophisticated equipment is essential for the determination of G_F and only peak loads are enough for the determination of fracture energy G_f based on SEM. However, till today, there is a suspicion that the difference between the two methods in estimating the fracture energy might be due to some innate fault of one or other method[17]. In these circumstances, it is convenient to assess the fracture energy parameters through SEM and can be modified by a suitable factor, if work-of-fracture method is proved to be a correct one.

TABLE 7
FRACTURE ENERGY FROM SIZE EFFECT METHOD & RILEM WORK-OF-FRACTURE METHOD

Beam Series	Mean prediction of fracture energy(N-m/m^2)		Ratio of (G_F/G_f)
	Size Effect Method (G_f)	RILEM Work-of-fracture Method (G_F)	
A	67.347	168.587	2.503
B	44.722	109.555	2.449
C	28.956	85.531	2.953

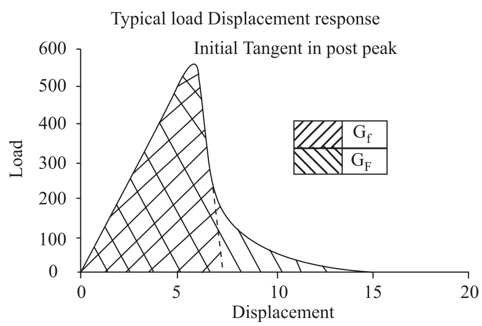


Fig. 11 Difference between fracture energy based on SEM and WFM

CONCLUSIONS

Based on the tests on notched concrete members of different sizes and notch ratios, the following conclusions were drawn.

1. 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.
2. The effective length of fracture process zone (C_f) decreases with the increase in size of the member resulting in decreased crack tip shielding and increase in the brittleness of the structure. A large fracture process zone indicates a ductile failure in a structure allowing more dissipation of energy through FPZ. A small FPZ indicates a brittle failure.
3. The fracture energy (G_F) obtained based on WFM is more than 2.40 times the fracture energy (G_f) obtained based on Size effect method (SEM).
4. The total fracture energy G_F based on WFM represents the area under the complete load-deflection curve (including post peak response) and the fracture energy G_f based on Bazant's SEM, represents the area under the initial tangent of the softening curve (portion of curve after peak load). This is bound to yield different results.

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