IJDI-ERET

INTERNATIONAL JOURNAL OF DARSHAN INSTITUTE ON ENGINEERING RESEARCH AND EMERGING TECHNOLOGIES
Vol. 10, No. 2, 2021
www.ijdieret.in

(Review Article)

Introduction to the Fracture Parameters and their Measurements Using Digital Image Correlation

Sajid Mannan[1*]

[1]Indian Institute of Technology Gandhinagar (IIT-Gn), Structural Engineering Department, Gujarat, India*

Abstract

In this study an attempt has been made to calculate various fracture parameters from experimental results for different size beams under three-point bending. Analyzing the full field of displacement, strain, crack propagation and formation of Fracture Process Zone (FPZ) in notched plain concrete beams using Digital Image correlation. In addition, analysis of fracture parameters obtained from the Rilem Method of Hillerborge, Jenq and Shah, and Bazant Size Effect Model has been carried out and further validated with existing literature and it has been found in good agreement.

Keywords: Fracture energy, Fracture process zone (FPZ), Non-linear elastic fracture mechanics (NLFM)

1. Introduction

Fracture Mechanics is another branch of mechanics in which we study about the nature of material and conditions in the vicinity of Cracks and at the Crack tip. While the idea of straight versatile Fracture Mechanics has been very much produced for more than recent years and effectively connected to metallic structures, a few structural designing materials, for example, cementitious materials, rocks, and fibre-strengthened composites generally known as quasi brittleness require an alternate fracture mechanics way to deal with demonstrate the fracture procedure. Cementitious materials can be demonstrated at different scales like the Nano-, small-scale, meso-, and macro levels. At meso level, they can be considered as a two-phase particulate composite, i.e., the network and the support. In the cement paste, mortar, and cement, the frameworks can be considered as the hydrated concrete gels, cement paste, and mortar, separately.

Concrete is composed of numerous materials, for example, cement, fine aggregate, coarse aggregate, water, and admixtures in complex courses of action. Apart from the two-stage particulate composite, huge numbers of inner voids running up to a few millimeters are available in the solidified concrete. These voids incorporating pores in cement, Cracks at matrix– total interface, and shrinkage breaking have critical effects on the mechanical behavior of cement. Going before an insecure or basic load, a sub-basic crack develops when a pre-Crack solid example is accumulated. The pre-basic crack development is commonly named as fracture process zone or damage process zone or moderate Crack development.

Despite of the fact that concrete is one of the most established development materials; there are still several crucial issues for researchers and designers to determine. The main task is to create concrete structures that are efficient and have a long service life making them more ecologically cordial. On the other hand, to discover a creative/technique system for governing the health of well-being of existing concrete structures cracks are unavoidable in a concrete structure, and fracture is a critical method of deformation in both types of concrete either plain or reinforced concrete (RCC). Fracture mechanics is a field concerned with the investigation of crack propagation using explanatory solid mechanics to describe a material's resistance to fracture. Even though the disfigurement reaction is an imperative part of the examination of a strengthened concrete structure under loading, prediction of crack development and their propagation is likewise required. Hence, the examining method that is picked must be able to find the area of another crack tip and crack width along the crack path during crack propagation. The primary goal of this exploration is to build up another system to distinguish fracture parameters, which are expected to demonstrate concrete structures subjected to unexpected loadings, for example, seismic shocks, flood, wind, and cyclone. The requirement for an exact non-contact and non-aggravating method that is equipped for checking the

[*]Corresponding Author: e-mail: sajidmannan98@gmail.com, Tel-+91-8350947428, +91-7982287385
ISSN 2320-7590

Fracture Process Zone (FPZ), too as the crack opening, is perceived by numerous scientists. The approach decided for this inquiry depends on the improvement of advanced camera resolutions that permit the following of a structure's deformation under loading on a noticeable scale and the extraction of exact material properties that can depict the crack behavior of the strained materials. A non-contact computerized picture connection (DIC) system utilizing the ARAMIS framework was performed for test estimation.

2. Digital Image Correlation Principle

Digital Image Correlation (DIC) is an advanced optical and non-contact system of determining the fracture parameter like displacement and strain on the surface of a beam in a concerned region/area. Here the image of the surface of the beam has been captured by a computerized camera before and after deformation. Which is further used to calculate the displacement and strain field at any point of time by trekking the pixel of the image at every point of time. DIC is broadly used to examine a wide scope of materials, in the generally unexpected scope of scales. Initially created in the 1980s, the DIC-based strategies and their fields of use have been becoming relentlessly because of the mechanical advance and reasonableness of computerized imaging frameworks. Initially, it was mainly used for steel and aluminum but nowadays it is widely used for glass and different types of cementitious material i.e., concrete either in plain or reinforced.

DIC depends on the following principle: the image of the body is portrayed by a discrete size speaking to the grey level of every pixel. The grey level is an incentive in the vicinity of 0 and 255 of its dim levels with the least esteem speaking to dark, most noteworthy esteem white, and qualities in the middle of speaking to various shades of dim. The relationship computations are completed for an arrangement of pixels, called a pattern. The uprooting field is thought to be homogeneous inside a pattern. The underlying image speaking to the body before deformation is a discrete function f (x y) and is changed into another discrete function. Because of its discreteness it is easier to measure the deformation pattern of each frame for different timesteps. However, the major challenge is to decide the parameters for examinations.

Although the user has control of a wide range of parameters that affect the examination. There are a few basic parameters for correlation. One is the subset estimate, h_{sub} (in pixels). As Bornert *et al.* have convincingly delineated, the spatial assurance of dislodging estimation is spoken to fantastically by the subset gauge; sinusoidal removal fields of a wavelength not actually h_{sub} can't be evaluated. The lower bound on subset measure is set by the essential that each subset contains wonderful information to remember it from neighboring. The dependable guideline contained in the DIC writing to fulfill this prerequisite is that $h_{sub} > 3\ h_{sp}$, where h_{sp} is the speckle size. Besides to avoid aliasing, each dot must contain a few pixels. The related general guideline is h_{sp} >3pixels. On the other hand, large spots require large subset sizes, along these lines decreasing spatial resolution. These come about are comprehensively reliable with the general guidelines for accomplishing ideal correlation's > 3pixels and $h_{sub} > 3\ h_{sp}$. The last delineates the abstract example of that greater spot sizes require greater subset sizes for full relationship. The least subset gauge foreseen by the reliable rule and the subset measure required for full relationship in like manner agree quantitatively.

3. Specimen Preparation

Concrete specimens were prepared with a standard Ordinary Portland Cement (OPC) of a 28-day curing. Crushed stones with a maximum diameter of 10 mm and river sand were used as coarse and fine aggregate, respectively. The mix proportions are listed in Table 1.

Table 1. Mix Proportion

Mix Proportion Components	Aggregate Quantity (12.5 mm) per m^3
Water	202kg
Cement	360 kg
CA	1055 kg

The measured compressive strength, specific gravity of FA, specific gravity of CA, and Poisson's ratio of concrete were 25 MPa, 2.71, 2.62 and 0.2, respectively.

3.1 Specimen Details:

Table 2. Specimen Details

Specimen Details	Small	Medium	Large
Overall Length(L)	300 mm	550 mm	1000 mm
Loading Span (S)	200 mm	400 mm	800 mm
Width(B)	50 mm	50 mm	50 mm
Depth (D)	50 mm	100 mm	200 mm

(a_0 /D)	0.2 mm	0.2 mm	0.2 mm
(S/D)	4 mm	4 mm	4 mm

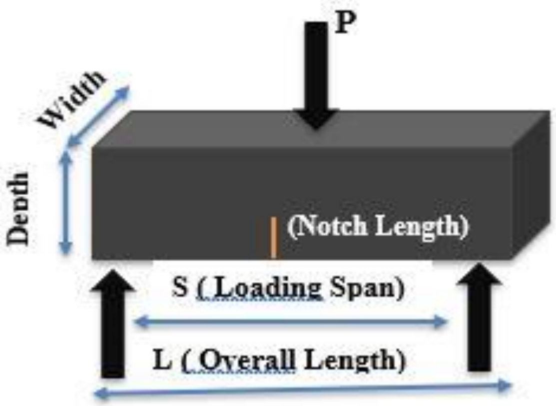

Figure 1. Notched Beam Under 3 Point Loading

Criterion for Selection of Specimen Size

Size of aggregate for mix (g_{max}) ≤ 25.4mm (1 inch)
Beam dimensions L, B, D ≥ 3(g_{max})

Range of (a_0 /D) = 0.15 to 4

Range of (S/D) ≥ 2.5

Depth of smallest specimen (D_1) ≤ 5(g_{max})

(Depth of largest size specimen/ Depth of smallest specimen) (D3/D1) Ratio ≥ 4

Once the paint was dried, speckles were marked using a spray paint gun. Special care was taken to ensure that the size of the speckles was maintained uniformly/isotopically and the speckles were random and contrast enough as clear from Fig.3. The DIC technique-based test setup beam using 300 kN capacity servo-hydraulic machine under Crack Mouth Opening Displacement (CMOD) control mode test. The notch to depth ratio, a/D is equal to 0.2 for this test. To quantify the fracture process zone of concrete, the visibility of clear speckles close to the notch is important.

3.2 Test Setup: The test setup included a universal testing machine (MTS), image-capturing equipment (camera), and a post-processing device. The camera was placed perpendicular to the specimen surface at a distance of its focal length in order to get clear magnification. The clip gauge installed at the centre of the notch was used to measure the displacement of Crack Mouth Opening Displacement (CMOD) and Linear Variable Transducer (LVDT) are placed near the clip gauge to measure the vertical deflection of the beam under the po load. The specimen was loaded at a rate of 0.005 mm/min, under controlled CMOD. The entire setup is shown below in Figure 2.

Figure 2. Test Setup

concrete is a three-phased material including matrix, aggregate and weak transition zone. The fine void between the matrix and aggregate after the hardening because of difference in the physical property of matrix and aggregate is known as weak transition zone. The mechanical behaviour of concrete under different loading condition is governed by initiation and propagation of these existing internal flaws and internal cracks. Different Cracking stage shown below in Figure 3.

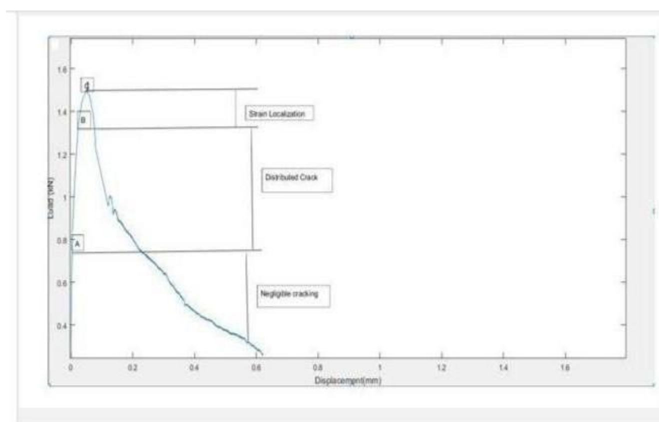

Figure 3. Cracking Stages

Initially before point A, which is nearly equal to 30% of peak load, there is negligible cracking or no cracking. But between the point A to B which is almost equal to 30% to 80% of the peak load, crack will start to propagate in distributed form and after that minor crack will start to localized which ultimately leads into a major crack, this process is known as strain localization. And the length of crack at the peak load is termed as critical crack length Although the crack length is continuously increasing even though load is decreased. Thus, the fracture behaviour of concrete is mainly governed by the phenomenon called strain localization.

3.3 Fracture Process Zone and Its Mechanisms: Fracture Process Zone (FPZ), the transitional space between a cracked and uncracked portion of the structure which surrounds by microcracks are known as fracture process zone. These are the crack propagate these microcracks merge to an individual major crack to give the direction to the already existing crack. In this manner, it goes about as spanning zone among cracked and uncracked portion.This inelastic zone is associated with various complicated mechanism like toughening mechanism such as aggregate bridging, crack branching, crack tip blunting and so on. The presence of these mechanisms limits the use of Linear Elastic Fracture Mechanics (LEFM) in case of quasi-brittle material like concrete. As here strain softening dominates over strain hardening. Although in case fracture study of ductile material we ignore the effect of inelastic zone since its size is too small and strain hardening is dominate over strain softening.

3.4 Static Test: The monotonic tests have been run up to the specimen's entire failure. The cracking design has been appeared in Fig. 4. It is observed that the crack path is tortuous but openly taken after the ligament centerline for all size. Other specimens moreover show comparable pattern. In this way the geometrical similarity of the failure mode is verified.

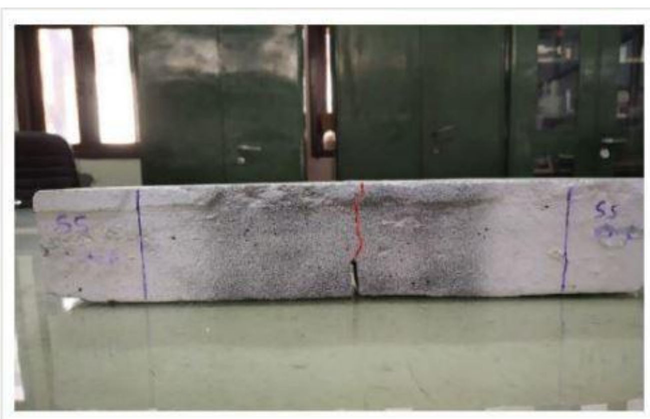

Figure 4. Cracking Pattern

The results obtained from three-point bending testing of the beam is Load-CMOD curve, Load-Displacement curve which is used for further calculations are shown below. For small, medium and large specimens, the peak load (P_u) is recorded as 2.23 kN, 3.89 kN and 6.32 kN, respectively.

Load as a function of Crack Mouth Opening Displacement (CMOD) for small, medium and large sizes are presented above respectively. A combined plot of load verses CMOD for all sizes are also shown. There is an increase in Critical CMOD opening as the size increase from small to large size specimen. Due to the fracture process zone, there were seen a softening curve and stress transfer in all size specimen's load versus CMOD curve after peak load. Crack initiation was seen at 95% of the peak load having a corresponding CMOD value is in the range of 0.002 mm to 0.071 mm and the final CMOD value was recorded as 0.72 mm, 0.94 mm and 1.63 mm for small, medium and large specimens respectively.

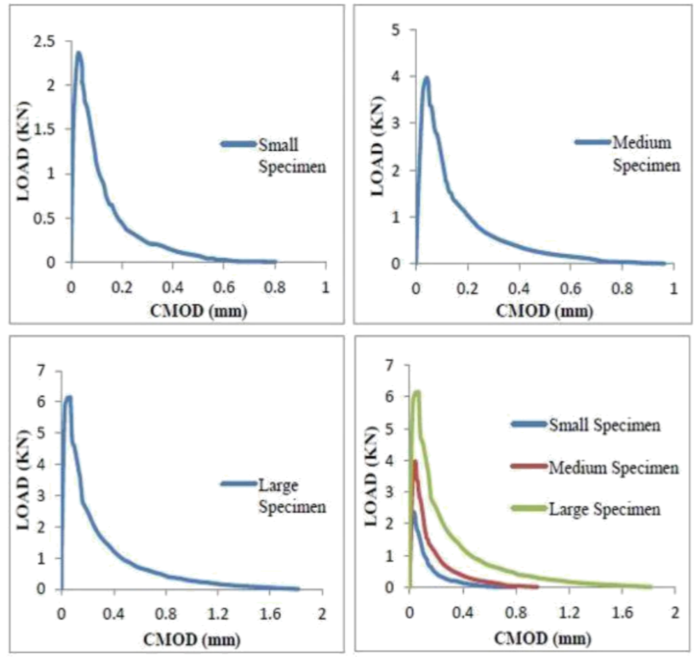

Figure 5. Load-CMOD Curve

3.5 Concept of Fracture Energy: Fracture energy is defined as amount of energy required to open unit area of crack surface. It is a material property and independent of size of structure. In other word it can be assumed as the summation of surface creation energy and summation of surface separation energy. curve for each size was generated numerically using the known elastic stiffness.

3.6 Fatigue Test: In repetitive loading test, the cracking design was analysed for each size specimen. During each repetitive loading test, the CMOD at different loading design was persistently observed to track the collective damage. For specimens of all size, the CMOD was seen to extend quickly within the to begin with little cycles, taken after by a considerable slowdown. After this, the development per cycle was slow and normal for numerous cycles (this behaviour is characteristic of a crack growth rate following a power law, i.e., Paris law). As the bar approached its lifetime, CMOD, additionally, its growth rate per cycle, was seen to extend quickly until catastrophic failure. It has seen that the crack path was complicated but clearly taken after the ligament centerline for each estimate. All the other examples moreover failed in the similar fashion. In this way, the geometrical similarity of the failure mode is confirmed. Table III shows the failure lifetime load cycles for each specimen and the loading pattern which has been followed. Typical load versus CMOD profile for small, medium and large size specimens is presented in figures respectively.

Table 3. Crack Length for Concrete

Sr. No.	Specimen	Loading Pattern	Cycle
1	Small	$0.2P_u$ to $1.1P_u$	2260
2	Medium	$0.2P_u$ to$1.6P_u$	4875
3	Large	$0.2P_u$ to $2.5P_u$	9017

4. Results and Discussion

Calculation of different fracture property by different methods mode 1 type of failure.

4.1 RILEM Method of Hillerborge: This method was based on a fictitious crack model which comprises three fracture parameters:

Fracture energy (G), the tensile strength of the material (f), and critical crack separation displacement (w).

Now G = (w)/ (b-a) *t = (W +2*P *delta)/ (b-a) *t where; W = energy due to applied load i: e (area under P, delta curve).

Table 4. Fracture Energy

S. No.	Parameter	Fracture Energy (G_F)
1	Small specimen	0.6181N.m
2	Medium specimen	0.6223N.m
3	Large specimen	0.6555N.m

It is observed from data that fracture energy increase with increase in size of specimen from small to large specimen. As sizes of beam increase, the values of brittleness number and characteristic length increases.

4.2 RILEM Method of Jenq and Shah: This method was based on two-parameter models by Jenq and Shah which include critical stress intensity factor (k_{ic}) and Critical Tip Opening Displacement ($CTOD_c$).

Table 5. Fracture Parameter

Parameter	Small specimen	Medium specimen	Medium specimen
Elasticity (E) (Mpa)	1.4888e+04	2.6668e+04	2.3428e+04
Kic (MPa.mm$^{0.5}$)	86.7201	99.931	87.4645
CTODc (mm)	0.0504	0.03615	0.03245
Ft (Mpa)	14.7506	15.24315	16.71535
ac (mm)	28.3726	42.5769	55.8523

Now it has observed that different fracture parameter has significant influence on fracture toughness of concrete. It plays a vital role in improving the existing flaws or cracks within the concrete.

4.3. RILEM Method of Bazant: This model was based on the size effect model by Bazant which includes material fracture energy (G_f) and critical crack length (C_f) using three-point bend beams. Now

G_f = g/(E*Ab);
C_f = (g*C_b)/(g'*A_b); where A_b and C_b are regression constant of the regression line.

Table 6. Crack Length & Energy

Parameter	Value
G_f (KN/mm)	0.120
C_f(mm)	20.4894

4.4 Static Test Results: For determination of fracture parameters related to size effect law, regression Analysis is carried out. The data input values are peak load values, specimen sizes, (a_0/D) ratio etc. The nominal strength is calculated for the different beam sizes for net cross-section of beam according to elastic beam theory. It is observed from the plot that it follows a horizontal line at the initial part, indicating no size effect. The curve approaches a straight line with slope of about (-1/2) towards the end. In the intermediate zone there is a smooth curved transitional part. Thus, it can be concluded that the plot shows presence of size effect in accordance with Bazant's size effect law.

Table 7. Brittleness Number (β)

Sr. No.	Specimen	Brittleness Number (β)
1	Small	0.487
2	Medium	0.982

a) Brittleness No. (β):

If (β) ≤ 0.1, then Plastic Limit Analysis.

(β) ≥ 10, then Linear Elastic Fracture Mechanics (LEFM).

0.1 < (β) < 10, then Non-linear Fracture Mechanics(NLFM)

It is observed from that data that (β) for all the specimen sizes falls in the category of Non-linear fracture mechanics (NLFM) analysis.

4.5 *Characteristic Length (lch):* If material is ductile, characteristic length or critical distance does not satisfy the concept of high-stress region and cannot be applied.

Table 8. Characteristic Length (l)

Sr.No.	Specimen	Characteristic Length (l)
1	Small	406.26
2	Medium	434.13
3	Large	519.67

However, to separate the effect of constraint on effective distance and local fracture stress remains an open question.

5. Conclusions

The above studies try to characterize the Fracture Process Zone in quasi-brittle material like concrete using both experimental and simulation frameworks. Experiments has done on different sizes of beams for both loading conditions, and Non-Destructive Technique (NDT) method like DIC were carried out throughout the experiment to validate the results and characterized the fracture process in concrete. Further, a more scientific approach has been used to understand the mechanism of FPZ in concrete. Results indicate that the length of FPZ increases as the size of specimen increases therefore it leads the phenomenon of size effect in concrete. Further, it has been seen that FPZ length comes out to be approximately same for both fatigue and static loading. Thus, the obtained FPZ results under static loading can be simply used for the modelling and analysis of crack growth problem under dynamic load. Additional work can be done to extend the methodology of characterizing FPZ by changing the value of input variables such as strain filter and subset size to minimize the noise and enhance the accuracy to a greater extent.

Acknowledgement

We owe our heartiest gratitude to respected Dr. Dharmendra Jha, Assistant Professor of Civil Engineering Department at National Institute of Technology Hamirpur, environmental engineering division for her critical supervision, inspiration and valuable advice, excellent guidance and constant encouragement, throughout the period of my project work.

References

1. S. Xu, and X. Zhang, “Determination of fracture param- eters for crack propagation in concrete using energy ap- proach,” *Engineering Fracture Mechanics*, vol. 75, no. 15, pp. 4292-4308, October 2008.
2. J. Guan, X. Hu, and Q. Li, “In-depth analysis of notched 3-p-b concrete fracture,” Engineering Fracture Mechanics, vol. 165, pp. 57-71, 2016.
3. Z. P. Bazant, “Determination of fracture energy from size effect and brittleness number,” *ACI Material Journal*, vol. 84, no. 6, pp.463-480, 1987.
4. Z. P. Bazant, and M. T. Kazemi, “Determination of frac- ture energy, fracture process zone length and brittleness number from size effect, with application to rock and concrete,” *International Journal of Fracture*, vol. 44, no. 2, pp. 111-131, 1990.
5. V. P. Rajan, M. N. Rossol, and F. W. Zok, “Optimization of digital image correlation for high-resolution strain mapping of ceramic composites,” *Experimental Mechanics*, vol. 52, no. 9, pp. 1407-1421, 2012. DOI 10.1007/ s11340-012-9617-1.
6. Z. Wu, H. Rong, J. Zheng, F. Xu, and W. Dong, “An experimental investigation on the FPZ properties in concrete using digital image correlation technique” *Engineering Fracture Mechanics*, vol. 78, no. 17, pp. 2978-2990, 2011.
7. N. Trivedi, R. K. Singh, and J. Chattopadhyay, “Investigation on fracture parameters of concrete through optical crack profile and size effect studies,” Engineering Fracture Mechanics, vol. 147, pp. 119-139, October 2015.
8. S Bhowmik, S Ray, “An experimental approach for characterization of fracture process zone in concrete”, Engineering Fracture Mechanics,211;(2019) :401-419, doi :10.1016/j.engfracmech.2019.02.026.
9. Pan B, Xie H, “Wang Z. Equivalence of digital image correlation criteria for pattern matching”, Applied Optics 2010;49(28):5501–9.

Biographical notes

S. Mannan has received his Bachelor of Technology, from National Institute of Technology Hamirpur (NIT-H) Himachal Pradesh in Civil Engineering. He is currently working as a PhD student at Indian Institute of Technology Gandhinagar (IIT-Gn) in Structural Engineering Department.