# The experimental determination of double-K fracture parameters of concrete under water pressure

J.M. Wang ,X.F.Zhang & S.L.Xu
*State Key Laboratory of Coastal and Offshore Engineering, Institute Dalian University of technical, China*

ABSTRACT: The main purpose of this paper is to experimentally determine the fracture parameter of concrete under water pressure. Wedge splitting fracture geometry is used. Similar to the work by Brhuwiler and Saouma, in order to obtain the true load-crack mouth opening displacement curve (*P-CMOD*), cycle loading-unloading of water pressure is carried out. At the stage of loading and unloading of water pressure, two different loading modes are used. One is constant crack mouth opening displacement (*CMOD*)-controlling loading mode. Another is constant load *P*-controlling loading mode. For the former 11 specimens are tested while for the latter 7 specimens are tested. In the tests, to monitor the initial cracking load and measure crack length, electric-resistance strain gauges are used and strategically arranged on surface of specimens. Then, from the measured data, the double- K fracture parameters proposed by Xu and Reinhardt, i.e., the initial fracture toughness $K_{Ic}^{ini}$ and unstable fracture toughness $K_{Ic}^{un}$ are experimentally determined. The results indicate that, compared to constant *CMOD* loading mode, for constant *P* loading mode the operation is easy. Therefore, it is more applicable for common lab. The results also show that the cycle loading of water pressure accelerates the development of crack and hence results in a sharp decrease in the maximum load. However, water pressure has little effect of on the initial cracking load.

## 1 INTRODUCTION

As well known, in the whole world, there exist plenty of constructed concrete dams and constructing concrete dams. The presence of cracks during either the construction period or the running period of concrete dam are generally regarded to be unavoidable and moreover will seriously influence the safety, integrality and durability of dam.[1.] Traditional design method for dam takes into account the action of water pressure, self-weight as well as other loads such as ice pressure, earthquake load and wind load. However, the impact of water pressure distributed over the crack face on the mechanical behavior of concrete dam seldom is involved. Recent researches on this issue [2,3]show that water pressure inside cracks accelerates the extension of crack and eventually greatly reduces the ultimate failure load sustained by structure. Hence, it can be said that the estimated load response of concrete dam based on the traditional design method is not safe. As a result, in order to improve the existing design codes, especially code in China, and for having better and enough understanding of the effect of water pressure inside crack on the fracture behavior of concrete, it is quite necessary and important to carry out the related work.

In 1995, Brhuwiler and Saouma experimentally investigated the fracture behavior of concrete under water pressure. In their report, the distributed shape of water pressure along crack face with the development of crack is main care. In order to describe it, wedge splitting fracture geometry is used and crack mouth opening displacement controlling-loading mode is designed. Later, using the same experimental arrangements and loading pattern, Slowik and Saouma further studied the effect of loading rate on the change of water pressure along crack face with the development of crack. However, besides these, the associated experimental work is rather few. Especially in China, the study on it can be accurately said to be in vacancy.

Therefore, in this paper, as a first attempt, the Brhuwiler and Saouma's work is firstly followed, in which crack mouth opening displacement (*CMOD*)-controlling loading mode is adopted. Then, a different loading mode, i.e., load-controlling loading mode is adjusted according to the available test condition. Also, in our tests, to experimentally monitor the initial cracking load and measure crack length, electric-resistance strain gauges are strategically arranged on the surface of specimen. Finally, two fracture governing parameters propose by Xu and Reinhardt[4], i.e.,the initiation fracture toughness $K_{Ic}^{ini}$ and unstable fracture toughness $K_{Ic}^{un}$ are experimentally determined, based on the double-K fracture model which was recommended and had been accepted as a theoretical base of “fracture test specification for hydro-engineering concrete” in China.

## 2 EXPERIMENTS AND RESULTS

### 2.1 *Test setup*

Wedge splitting fracture geometry is used. The dimensions of specimens are present in table.1. In this test, a total of 18 specimens are cast. The mix proportion of used concrete is 1:2.17:3.29:0.52 (cement: sand: aggregate: water by wt.). The maximum size of coarse aggregate is 30mm. Fine aggregate is river sand, with the maximum size of 5mm.

In the tests, besides water pressure, specimens are subjected to applied external mechanical load. The experimental setup is shown in Figure.1. During the testing, all specimens are loaded on the oil-pressure controlling testing machine with the maximum capability of 5000KN.Water is injected by a dynamo-electric pressure pump.

Figure 1. Experimental setup

In order to exert water pressure, during the whole fracture process, a close system must be made. Therefore, the rubber thin membrane is glued around the direction of the development of crack. Furthermore, for preventing leakage caused due to poor seal, the steel plate is used outside the rubber membrane and clamped using tightening bolts. In order to control the input and output of water pressure, two manometers are mounted on the water-injecting pipe and drainpipe, respectively, as shown in Figure.1.

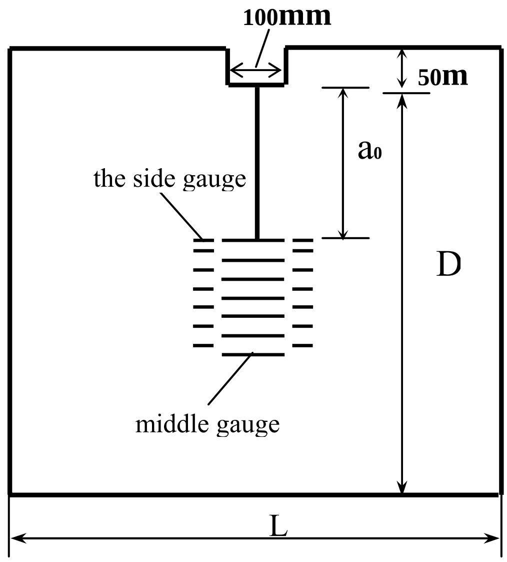


Figure 2. The arrangement of electric resistance strain gauge

In this test, two different length electric resistance strain gauges are used. Figure.2 shows the arrangement of electric resistance strain gauges. For side gauges (amount of 12), the short are used and connected by full bridge circuit method in order for arresting the initial cracking load and measuring development length of crack, while for the mid gauges (amount of 7), the long are adopted and connected by means of half bridge circuit method in order to measure the opening of crack. To avoid the damage of mid strain gauges caused because of the use of rubber member and steel plate, epoxy glue is brushed on the surface of them. MTS clip extensometer is mounted in the groove to measure the value of the crack mouth opening displacement *CMOD*. Finally, all readings are continuously picked by data collecting system.

Table1. The dimension of specimen

| length (mm) | height (mm) | thickness (mm) | $a_0$ (mm) | wedge angle( θ ) | wedge weight(Kg) |
|---|---|---|---|---|---|
| 400 | 400 | 200 | 180 | 15° | 0.168 |

### 2.2 *Load mode*

To eliminate the effect of action of water pressure, rubber membrane and steel plate on the true load-crack mouth opening displacement curve, during exerting external mechanical load, water pressure is cyclically firstly loaded, then held and finally unloaded. In every cycle, two different loading controlling modes are used. Firstly, following the studies carried out by Brhuwiler and Saouma, during loading- unloading of water pressure the value of *CMOD* keeps constant, called constant *CMOD* loading mode. Then, after considering our existing experimental conditions, another loading mode, named as constant mechanical load *P* loading controlling method is used, in which mechanical load still holds constant during the whole cycle of loading-holding-unloading of water pressure. The below will show the difference of the two loading modes.

### 2.2.1 *"constant CMOD" loading mode and experimental result*

For good comparison, in Figure.3, the principle of constant *CMOD* loading mode used in the work of Brhwiler and Saouma (1995a) is again present.

In Firgure.3, from O point to A point, only mechanical load P is applied. At this stage, with the increase in mechanical load, the displacement *CMOD* linearly increases. Then, water pressure is loaded up to the designed value of test. During this process, the displacement is controlled to keep constant. Because of this, the mechanical load must drop, as demonstrated from A point to B point in the picture. At next stage from B point to C point, holding water pressure, we again increase the mechanical load. Thus, the displacement will correspondingly increase. After these, the water pressure is gradually unloaded by the drainpipe. At this stage, due to which displacement is again kept unchangeable, mechanical load will increase. The part from C point to D point in the picture shows features of this stage. Up to now, a loading-holding-unloading cycle of water pressure is finished. Continuing to repeat this cycle, a true load-crack mouth opening displacement curve can be obtained.

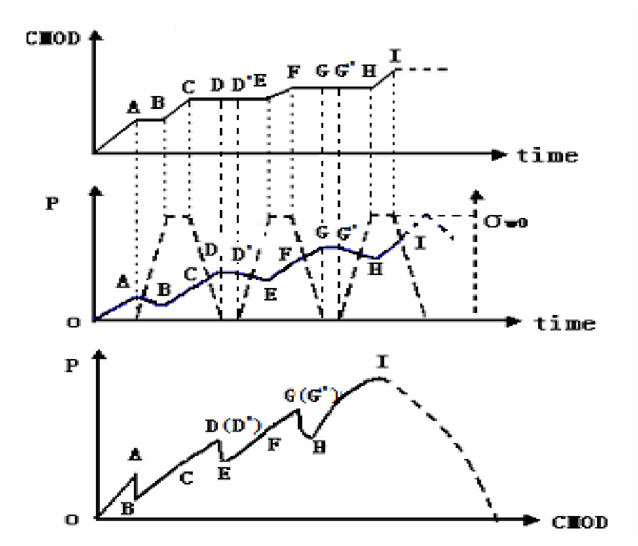


Figure 3. the principle of constant CMOD loading mode

Using this loading mode, we carry out four sets of tests of which values of water pressure are different, i.e., 0 MPa, 0.1 MPa, 0.2MPa and 0.3 MPa. Eleven specimens are cast. However, because of the difficulty in seal especially in the case of high water pressure, only three different water pressure, i.e., 0 MPa, 0.1 MPa and 0.2MPa are carried out successfully. Figure 4 shows the obtained *P-CMOD* curve by this loading mode. From this figure, it can be seen that the maximum load of specimen and the initial slope of P-CMOD curve under water pressure are sharply smaller than those under dry condition. Also, it can be seen that with the increase in water pressure, the reduction in maximum load is remarkable, too. This shows that the cycle loading of water pressure before the maximum load heavily damages concrete and hence accelerates the development of crack.

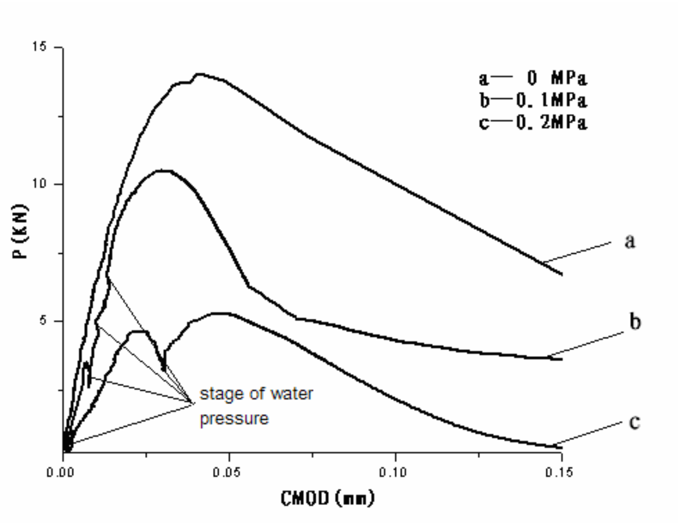


Figure.4. The curve of P-CMOD

### 2.2.2 *"constant mechanical load" loading mode and experimental result*

However, due to lack of closed-controlling operation system, control of *CMOD* is rather difficult, hence limiting the number of cycle as shown in Figure4. Considering this, a different loading mode was adopted in the following experiment.

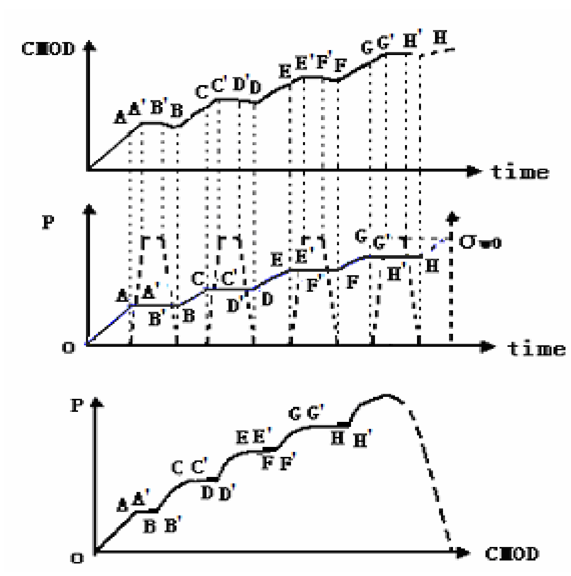


Figure.5 Load mode and curve of constant mechanical load

Figure 5 shows that detailed procedures of this loading method. It can be seen that the mechanical load still keeps constant during the whole cycle of loading-holding-unloading of water pressure. However, during every cycle, for example AA′B′B, crack mouth opening displacement firstly increases from A point to A′ point, then keeps a constant value and finally withdraws from B′ point to B point. Thus, based on this method, in order to plot the P-CMOD curve, one only need delete the segments of AA′B′B, CC′D′D, EE′F′F… and so on.

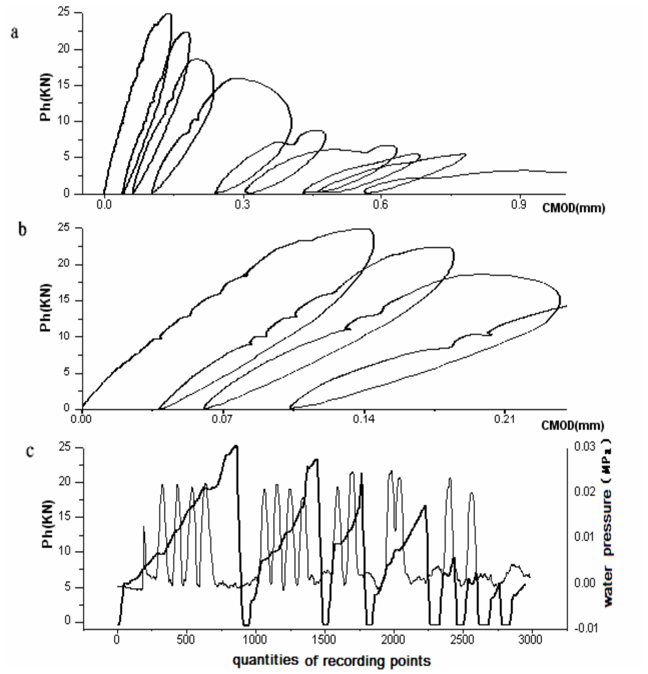


Figure.6. (a) P-CMOD curve (b) Enlarge drawing
(c) Comparision between mechanical load and water pressure

In this batch of tests, water pressure is 0.02MPa. Seven specimens are tested. The experimental results are plotted in Figure.6. From this figure, it can be seen that using this loading method many cycles of water pressure before maximum load are achieved. Every fluctuant part on the curve means a cycle of water pressure.

## 2.3 *Determination of Double-K fracture parameters*

### 2.3.1 *Double-K criterion*

A large number of experimental observations had verified that in concrete crack development undergoes three different stages, i.e., crack initiation, stable crack propagation and unstable crack propagation. In order to describe such observation, double-*K* fracture model was proposed by Xu and Reinhardt [4]. Then, they further developed the corresponding analytical calculation equations for the determination of double-*K* fracture parameters introduced in their model. Using the two parameters, i.e., the initiation fracture toughness $K_{Ic}^{ini}$ and unstable fracture toughness $K_{Ic}^{un}$, they constructed double-*K* fracture criterion [4],

(1) when $K = K_{Ic}^{ini}$, the crack begins to develop;
(2)when $K_{Ic}^{ini} < K < K_{Ic}^{un}$, the crack develops in stable state;
(3) when $K \geq K_{Ic}^{un}$, the crack propagates in unstable state;

### 2.3.2 *Determination of double-K fracture parameter*

#### 2.3.2.1 *The determination of Young's module*

Because of the use of the rubber membrane and steel plate in the test, we consider that concrete is locally strengthened. Therefore, the measurement value of Young's module by the standard testing procedure can be not true. Therefore, instead of direct experimental measurement, the Young's modules of all specimens are determined using equation (1)[5].

$$E = V(\alpha)/Bc_i$$
$$V(\alpha) = \left(\frac{1+\alpha}{1-\alpha}\right)^2 (2.163 + 12.219\alpha - 20.065\alpha^2 - 0.9925\alpha^3 + 20.609\alpha^4 - 9.9314\alpha^5) \quad (1)$$

where $\alpha = a_0/D$; *B*=specimen thickness; *D*= specimen height; $a_0$=initial crack length and $c_i$=initial compliance which is equal to the reciprocal of the initial slope of *P-CMOD* curve.

#### 2.3.2.2 *the determination of the critical effective crack length* $a_c$

Now, it had been generally accepted that the presence of fracture process zone ahead of initial crack tip is associated with the nonlinear fracture behavior of concrete. Therefore, to determine the unstable fracture toughness, the influence of fracture process zone must be taken into account. Often, elastic-equivalent method is used in many fracture models. Among these models, double-*K* fracture model considers that the nonlinear fracture process zone can be equated in terms of a linear asymptotic superposition. Thus, every point on the nonlinear segment of load-crack mouth opening displacement curve can be viewed as a representation of linear cases.[4, 6] According to this assumption, for wedge splitting geometry, critical effective crack can be determined by substituting maximum load and corresponding critical crack mouth opening displacement into equation[6] (1):

$$E = V(\alpha)/Bc_{max} \quad (2)$$

in which $c_{max} = CMOD_c/P_{max}$.

2.3.2.3 *the determination of the unstable fracture toughness* $K_{Ic}^{un}$

Based on linear asymptotic superposition, substituting the calculated the critical effective crack length $a_c$ and the maximum load $P_{hmax}$ into the equation (3)[7], the unstable fracture toughness $K_{Ic}^{un}$ can be determined.

$$K_{Ic}^{un} = \frac{P_{h\max}}{B\sqrt{D}} F(\alpha)$$

$$F(\alpha) = [(2+\alpha)(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)]/[(1-\alpha)^{3/2}] \quad (3)$$

Where $\alpha = a_c/D$; $P_{hmax}=(P_{max}+mg)/2tan\theta$; $m$= the weight of wedge loading equipment; θ= wedge angle , $P_{max}$= the maximum of vertical load.

2.3.2.4 *the determination of initial fracture toughness* $K_{Ic}^{ini}$

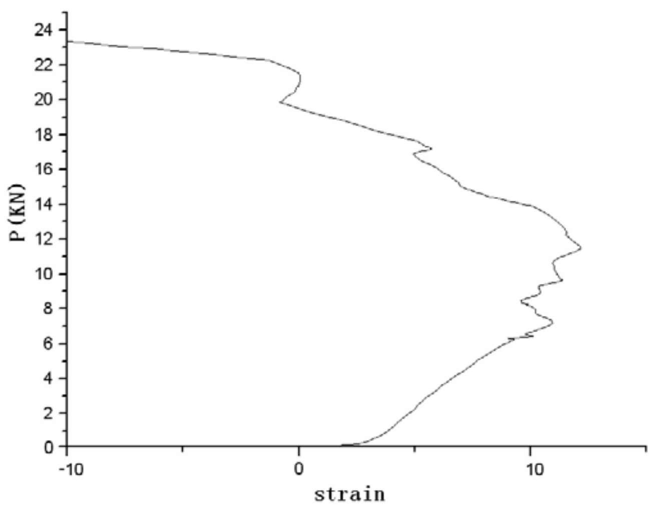


Figure.7. The change of load with the strain

Double-K fracture model considers that when the initial crack does not develop, the specimen remains in elastic state. Therefore, if one can measure the initial cracking load, replacing the initial crack length $a_0$ and the cracking load $P_{ini}$ into the equation (4), the initial fracture toughness $K_{Ic}^{ini}$ can be determined. To determine it, in this paper, we use electric-resistance strain measurement technique. Figure.7 shows the change of strain measured by side strain gauge near to crack tip with the increase of load. From this figure, it can be seen that when water pressure is unloaded the strain at crack tip also takes on withdraw, but when water pressure is reloaded again strain then begins to increase. However, once initial crack develops, namely crack passes by the strain gauge near to the initial crack tip, stress will be released and hence strain starts to gradually decrease. According to this, from the figure7, the cracking load can be determined. Thus, one can have initial fracture toughness.

$$K_{Ic}^{ini^t} = \frac{P_{ini}}{B\sqrt{D}} F(\alpha_0)$$

$$F(\alpha_0) = [(2+\alpha_0)(0.886 + 4.64\alpha_0 - 13.32\alpha_0^2 + 14.72\alpha_0^3 - 5.6\alpha_0^4)]/[(1-\alpha_0)^{3/2}] \quad (4)$$

Where $\alpha_0 = a_0/D$.

The results of the second batch of tests are summarized in the table2. In this test, concrete compression strength is 39MPa. In this table, the calculated Young's modulus also is listed. According to the above steps, the unstable fracture toughness and initial fracture toughness are calculated and placed in the table2.

Table 2 The results of E, $P_{hmax}$,CMOD, $K_{Ic}^{un}$, $K_{Ic}^{ini}$

| Specs. | E (GPa) | $P_{hmax}$ (KN) | $CMOD_c$ (mm) | $K_{Ic}^{un}$ ($MPam^{1/2}$) | $K_{Ic}^{ini}$ ($MPam^{1/2}$) |
|---|---|---|---|---|---|
| ws-1 | 49.12 | 25.06 | 0.154 | 2.621 | 0.552 |
| ws-2 | 48.30 | 20.32 | 0.132 | 2.183 | 0.495 |
| ws-3 | 46.28 | 22.40 | 0.164 | 2.500 | 0.429 |
| ws-4 | 48.42 | 24.12 | 0.183 | 2.795 | 0.352 |
| ws-5 | 47.36 | 25.01 | 0.139 | 2.422 | 0.411 |
| ws-6 | 46.75 | 25.65 | 0.121 | 2.191 | 0.532 |
| ws-7 | 47.26 | 23.02 | 0.145 | 2.364 | 0.463 |
| Aver. | 47.64 | 23.65 | 0.148 | 2.439 | 0.462 |

From table 2, we can easily see that unstable fracture toughness and initial fracture toughness are about 2.44MPam$^{1/2}$, 0.46MPam$^{1/2}$, respectively. For the initial fracture toughness, this value is close to that obtained in previous work where fracture tests under dry condition were performed on specimens with the similar compression strength[8]. Therefore, it can be concluded that the action of water pressure does not alter the value of initial fracture toughness.

## 3 CONCLUSIONS

In this paper, the impact of water pressure distributed along crack face on the fracture behavior of concrete under nature dry condition is experimentally investigated. Following the researches carried out by Brhuwiler and Saouma, using the constant CMOD loading mode, the first batch of tests are performed on 11 specimens. The results show that the action of water pressure reduces the maximum load of structure, and that as water pressure goes up the maximum load will drops sharply.

However, the difficulty in controlling constant CMOD using common testing machine limits the use of this approach. Therefore, another loading pattern where the mechanical load is kept to be constant during the whole cycle of loading-holding-unloading of water pressure, called constant P loading mode is proposed. According to this loading mode, the facture tests of seven specimens under water pressure of 0.02MPa are carried out. From the obtained load-crack mouth opening displacement and the change of strain near to crack tip, double-K fracture parameters are calculated. The results indicate that the action of water pressure has little influence on the initial fracture toughness.

## REFERENCE


Huang,Y.Y. & Hu,Q.G.2002. Stabilization analysis of cracks in one concrete dam. *Journal of Zhejiang Water Conservancy and Hydropower College*: 1-3

Brühwiler.E. & Saouma.V.1995. Water Fracture Interaction in Concrete－PartⅠ: Facture Properties. *ACI Materials Journal* V. 92. No. 3, May-June: 296-303

Brühwiler.E. & Saouma.V.1995. Water Fracture Interaction in Concrete－PartⅡ: Hydrostatic Pressure in Cracks. *ACI Materials Journal* V. 92. No. 3, July-August: 383-390

Xu,S.L. & Reinhardt,H.W.1999. Determination of double-K criterion for crack propagation in quasi-brittle fracture, PartⅠ：Experimental investigation of crack propagation. *International Journal of Fracture 98*: 111-149

Xu S & Reihardt HW. Determination of double-k criterion for crack propagation on quasi-brittle fracture, Part Ⅲ: Compact tension specimens and wedge splitting specimens, International Journal of Fracture 1998,98: 179-193.

Xu S & Reihardt HW. Determination of double-k criterion for crack propagation on quasi-brittle fracture, Part II: Analytical evaluating and practical measuring methods for three-point bending notched beams, International Journal of Fracture 1998,98: 151-177.

Tada H, Irwin GR. Stress Analysis of Crack Handbook. Del Research Corporation, Hellertown USA, 1972.

Xu S & Zhang XF. Determination of double-k criterion for crack propagation on quasi-brittle fracture, Part II: Analytical evaluating and practical measuring methods for three-point bending notched beams, International Journal of Fracture 1998,98: 151-177.