Advances in Aeronautical Science and Engineering
ISSN: 1674-8190

Numerical Investigation of Crack Behavior in Concrete Under Different Load Conditions

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KEYWORDS: crack propagation; stress intensity factor; three points bending beam test; fractures mechanics; three-dimensional medium.

ABSTRACT

Concrete is a brittle material with high compressive strength, low tensile strength and poor toughness, where cracks of different degrees and different forms can be developed, which compromises the durability and the lifetime of concrete structures. In this article we present a numerical simulation that allows describing and studying the damage of concrete works subjected to various stress types. In this study, the propagation of cracks in the concrete was analyzed, which requires having a thorough knowledge of the mechanical behavior of the material. The analysis is carried out by using fracture criteria while being based on the determination of the critical stress intensity factors, for three-point bending concrete beam that subjected to a various stress types. The analysis is carried out in a three - dimensional medium by using the ANSYS software. The results obtained are compared with the analytical solutions. The results show that; (i) with an increase in beam size, the stress intensity factor increases, (ii) with an increase in width of beam, the stress intensity factor decreases.

INTRODUCTION

Safety is an essential concept of engineering design and it tends to receive greater attention when the consequences of failure are severe. The concept of designing solely for strength and using highest strength material without regard to fracture toughness is unreliable [1]. concrete have the advantages with abundant availability, simple process, well fireproof, lower cost and wide adaptability [2], However, it is a brittle material with high compressive strength, low tensile strength and poor toughness, it makes that cracks of different degrees and different forms occur in using process and even in construction process which makes the durability of concrete structure deteriorates and lifetime shortens. In modern times profuse experiments and engineering practices show that: cracking of concrete structure is almost inevitable; according to current economy and technique level, it is reasonable that concrete cracking could be controlled in the harm allowable range [3]. Simulating concrete fracture behaviour is the main way to achieve aforesaid aims. A lot of researches on concrete fracture behaviour have developed many effectual concrete fracture models.

Fracture in Concrete

Fracture is a problem that society has faced for as long as there have been man-made structures. The problem may actually be worse today than in previous centuries, because more can go wrong in our complex technological society. Fracture mechanics is a branch of solid mechanics which deals with the behavior of the material and conditions in the vicinity of a crack and at the crack tip. The concept of linear elastic fracture mechanics has been well developed for more than past 40 years and successfully applied to metallic structures. Concrete is a heterogeneous anisotropic non-linear inelastic composite material, which is full of flaws that may initiate crack growth when the concrete is subjected to stress. Failure of concrete typically involves growth of large cracking zones and the formation of large cracks before the maximum load is reached. This fact several properties of concrete, point toward the use of fracture mechanics. Furthermore, the tensile strength of concrete is neglected in most serviceability and limit state calculations. Neglecting the tensile strength of concrete makes it difficult to interpret the effect of cracking in concrete.

Different non-linear fracture models are established for calculating the different fracture parameters. Those models are Fictitious crack model, Crack band model, Size effect model, effective crack model, Two Parameter Fracture Model, Double G Fracture model, Double K fracture Model, Smeared Crack model, Discrete Crack model etc. The main fractures parameters can calculate from the models are Stress Intensity Factor, Crack Tip Opening Displacement and Strain Energy Release Rate etc.

Stress Intensity Factor (SIF)

The mechanical behaviour of a solid containing a crack of a specific geometry and size can be predicted by evaluating the stress intensity factors (KI, KII, and KIII) shown in ***Fig.1.*** [4]

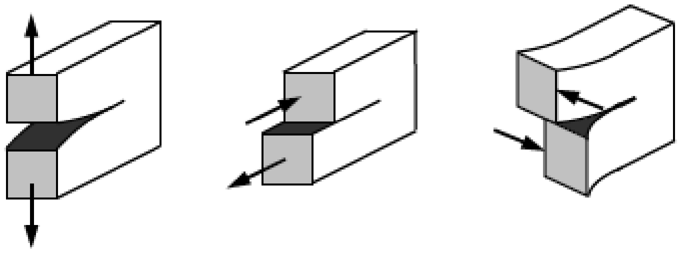

Fig.1. Fracture modes: a) mode I – opening; b) mode II – sliding; c) mode III – tearing.

If crack growth occurs along the crack plane perpendicular to the direction of the applied external loading mode, then the stress intensity factors are defined according to the American Society for Testing Materials (ASTM) E399 Standard Test Method as

$$K_I = \lim_{r\to 0}\left(\sigma_{yy}+\sqrt{2\pi r}\right) f_I(\theta)$$

$$K_{II} = \lim_{r\to 0}\left(\tau_{xy}+\sqrt{2\pi r}\right) f_{II}(\theta)$$

$$K_{III} = \lim_{r\to 0}\left(\tau_{yz}+\sqrt{2\pi r}\right) f_{III}(\theta)$$

Here, $f_I(\theta)$, $f_{II}(\theta)$ and $f_{III}(\theta)$ are trigonometric functions

Introduction of FEM

The finite element analysis is a numerical technique. In this method all the complexities of the problems, like varying shape, boundary conditions and loads are maintained as they are but the solutions obtained are approximate. It started as an extension of matrix method of structural analysis. Today this method is used not only for the analysis in solid mechanics, but even in the analysis of fluid flow, heat transfer, electric and magnetic fields and many others. Civil engineers use this method extensively for the analysis of beams, space frames, plates, shells, folded plates, foundations, rock mechanics problems and seepage analysis of fluid through porous media. Both static and dynamic problems can be handled by finite element analysis. The FEM is a highly suited method for approximating the solution to the differential equation governing the addressed problem. . Some popular Finite Element packages are STAAD-PRO, GT-STRUDL, NASTRAN, ABAQUS and ANSYS. Using these packages one can analyze several complex structures.

Fanella and Krajcinovic [5] studied the effect of size on the rupture strength of plain concrete by focusing on the phenomena in the meso-scale of the material. Bazant and Kazemi [6] reformulated Bazant's size effect law applied to rock and concrete for the nominal stress at failure in a manner in which the parameters are the fracture energy and the fracture process zone length. From experimental as well as TPCM model they observed that, for three-point bend beams, TPFM predicts that the nominal strength decreases with increasing beam size, but approaches to a minimum constant value when sizes of the beam become very large. Tang, Shah, et al., [7] used Two Parameter Concrete Model (TPCM) to study the size effect of concrete in tension. Kotsovost and Pavlov [8] investigated the causes of size effects in structural-concrete experimentally and computationally. Their results demonstrated that the finite element package used can also provide a close fit to experimental values.

METHODOLOGY

Determination of stress intensity factors is a critical task in fracture mechanics, numerical methods such as the finite element and boundary element methods [9] which have successful applications in various fields of engineering problems. It is shown that it is applicable to the description of not only different size specimens [10, 11], but also specimens with varying geometry.

Hypothesis of bases

The numerical model used in our study, combines a criterion of the linear elastic fracture mechanics and a distributed model of cracking that leads to taking account the singularity of stress field at the peak of a crack and the influence of geometrical parameters on the development of cracking. This model must also keep on certain basic assumptions:

- The concrete is regarded as an isotropic homogeneous material with an elastic linear behavior describing its mechanics.
- The micro crack zones and the nonlinear behaviour of the material at the point of the cracks are neglected.

Analytical analyses

The fracture toughness of a specimen shown in ***Fig.2*** can be determined using a three-point flexural test. The stress intensity factor at the crack tip of a single edge notch bending specimen is [12]

$$K_I = \frac{4P}{B}\sqrt{\frac{\pi}{W}}\left[1.6\left(\frac{a}{W}\right)^{1/2} - 2.6\left(\frac{a}{W}\right)^{3/2} + 12.3\left(\frac{a}{W}\right)^{5/2} - 21.2\left(\frac{a}{W}\right)^{7/2} + 21.8\left(\frac{a}{W}\right)^{9/2}\right] \tag{1}$$

Where **P** is the applied load, **B** is the thickness of the specimen, **a** is the crack length, and **W** is the width of the specimen.

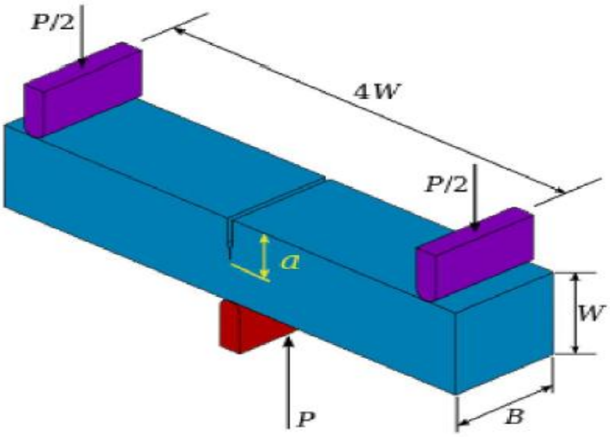

Fig.2. Three-bending Beam Test.

The ASTM D5045-14 [13] and E1290-08[14] Standards suggests the relation

$$K_I = \frac{6P}{BW} a^{1/2} Y$$

$$\text{and} \tag{2}$$

$$Y = \frac{1.99 - a/w\,(1 - a/w)(2.15 - 3.93a/w + 2.7(a/w)^2)}{(1 + 2a/w)(1 - a/w)^{3/2}}$$

The predicted values of KI are nearly identical for the ASTM and Bower equations for crack lengths less than 0.6W.

Numerical analysis of three- point bending test

2.3.1. Material Properties and Geometry

Three-point bending test are developed in the present study, the geometrical data and the principle of the test are schematized in ***Fig.3*** and ***Table 1***. Effect of self-weight of the beam is considered in the numerical model. The grade of concrete taken in the present investigation is M35. The direct local tensile strength of the concrete ft is taken as 2.7 Mpa. The modulus of elasticity of concrete (E) is taken as 35982 Mpa. The value of Poisson ratio (ν) is assumed to be 0.18.

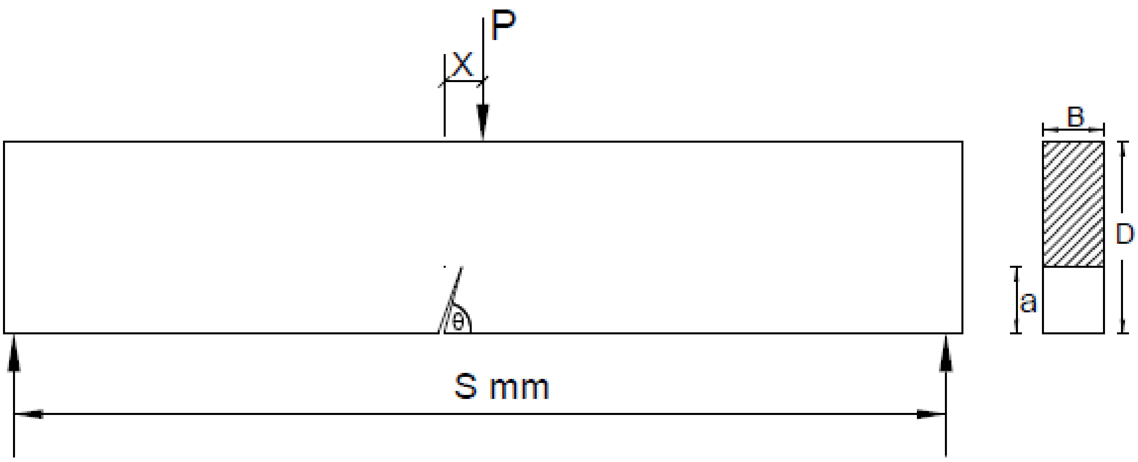

Fig.3. Geometrical data of three-bending Beam Test.

The specimen subjected to the bending test is a beam of concrete where its length is **S** and width **B**, receiving a load **P** located in the middle of the beam. The beam is supposed to have an initial crack of length is **a** with an eccentricity **d.** In the numerical study, the values of stress intensity factor KI is numerically obtained using finite element modeling in a three-dimensional medium by the ANSYS software. Model used in the simulation is represented in ***Fig. 4.***

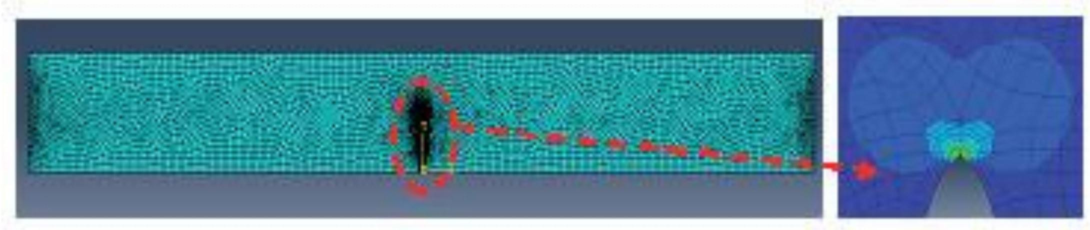

Fig. 4. Geometrical representation by ANSYS of three points bending test

Table 1: Summary of geometric data for three-points bending test

S	The length of the beam	varies from 640 to 1600 mm
D	Beam width	equal to 160 mm
a	Length of the initial crack	varies from 8 to 80 mm
B	Beam thickness	equal to 20 mm
X	Eccentricity of crack	$0\leq d<S$
ϴ	angle of inclination of the initial crack	varies from 30° to 90° mm

RESULTS AND DISCUSSIONS

a) Variation of the stress intensity factor K_I according to the beam size

Fig.5 shows the variation of the stress intensity factor K_I (calculated numerically) according to the beam size; it is observed that the values of K_I increase when the reported S/D increases and the values of K_I increase when the reported a / D increases.

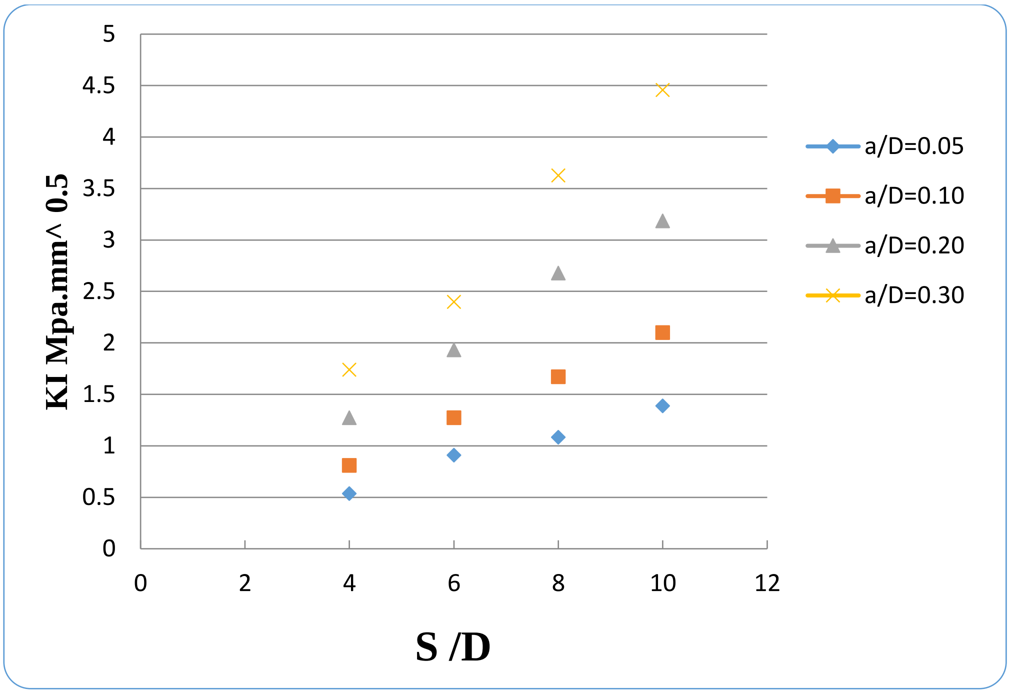

Fig.5. Variation of the SIF KI according to S/D

Fig.6 shows the variation of the crack tip opening displacement (CTOD) according to the beam size, it is observed that the values of CTOD increase when the reported S/D increases and the values of CTOD increase when the reported a / D increases.

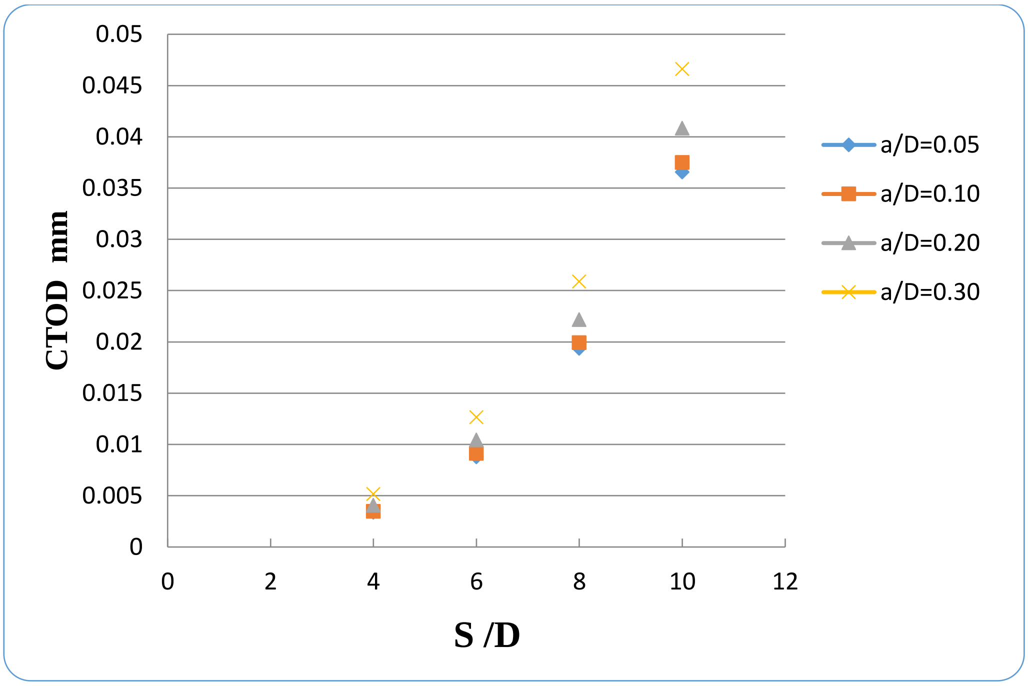

Fig.6. Variation of the CTOD according to S/D

b) Variation of the stress intensity factor K_I according to the beam width

Fig.7 shows the variation of the stress intensity factor K_I (calculated numerically) according to the beam width; it is observed that the values of K_I decrease when the reported B/D increases.

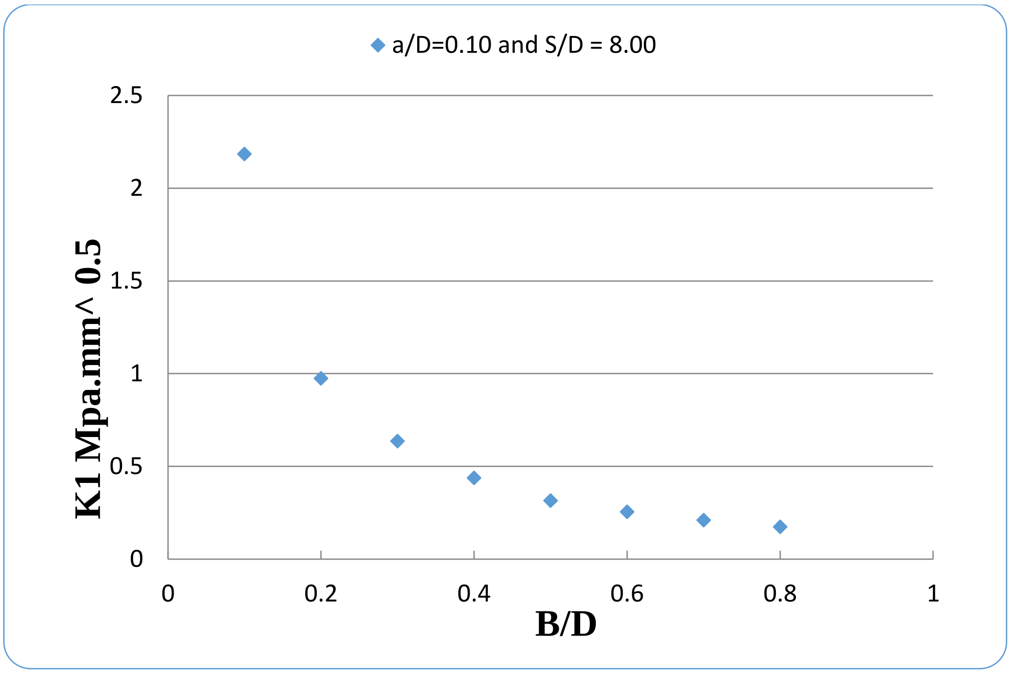

Fig.7. Variation of the SIF KI according to B/D

Fig.8 shows the variation of the crack tip opening displacement (CTOD) according to the beam width, it is observed that the values of CTOD decrease when the reported B/D increases.

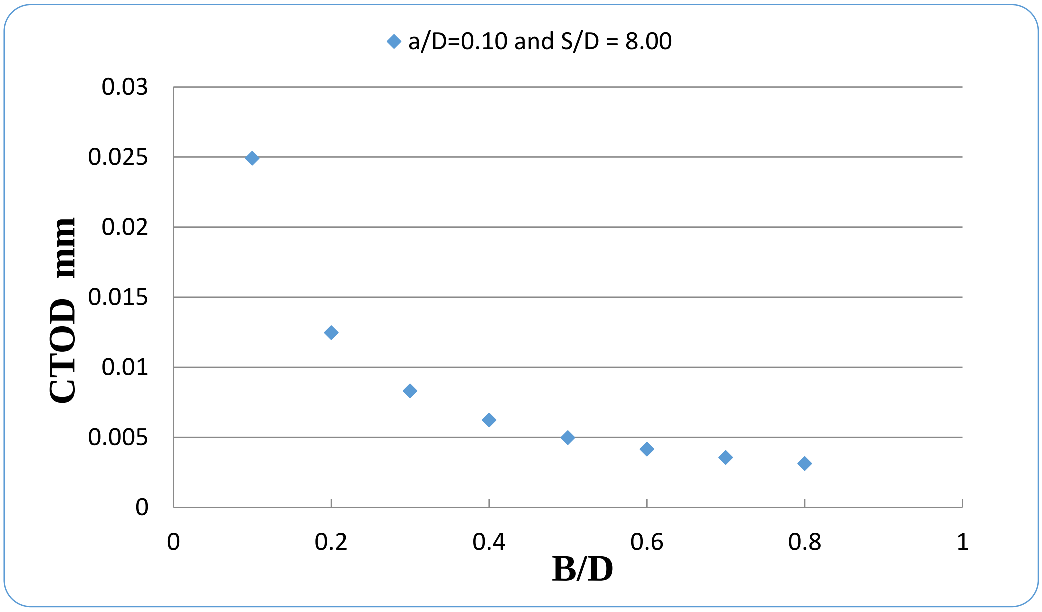

Fig.8. *Variation of the CTOD according to B/D*

c) Influence of the crack's position on the stress intensity factor K_I

Fig.9 represents the variation of the stress intensity factor K_I according to the crack's position; it is noticed that the increase in X / D leads to a reduction of K_I and the values of K_I increase when the reported a / D increases.

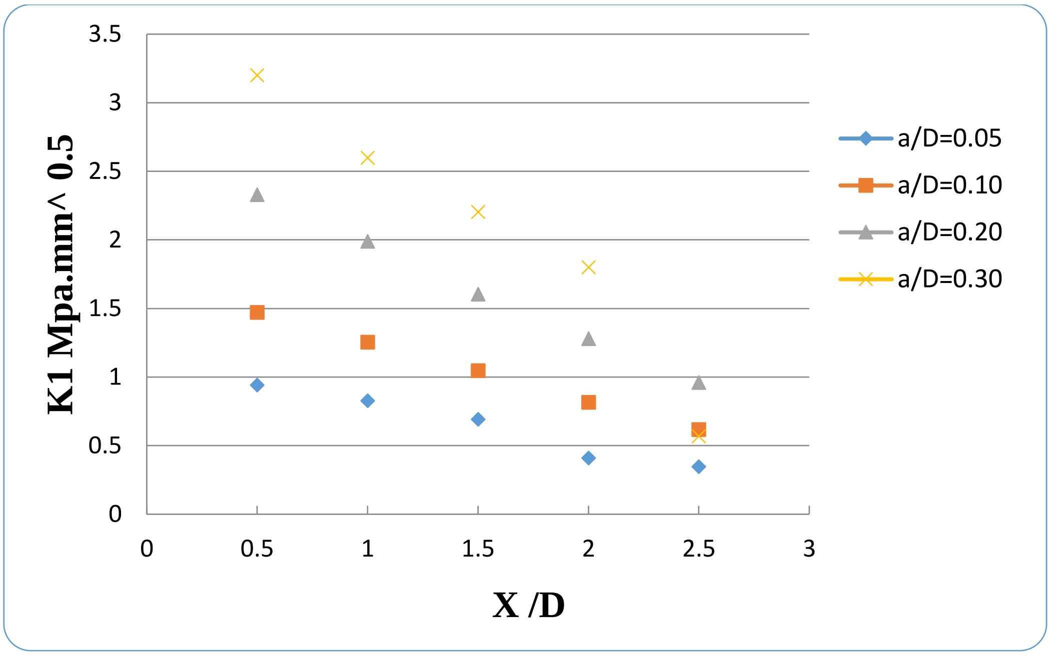

Fig.9. Variation of the SIF K_I according to X / D

d) Influence of the material properties on the stress intensity factor K_I

Fig.10 represents the variation of the stress intensity factor according to the variation of modulus of elasticity; it is observed that the values of K_I don't change with the variation of modulus of elasticity, so the material properties of concrete beam don't effect on the stress intensity factor K_I.

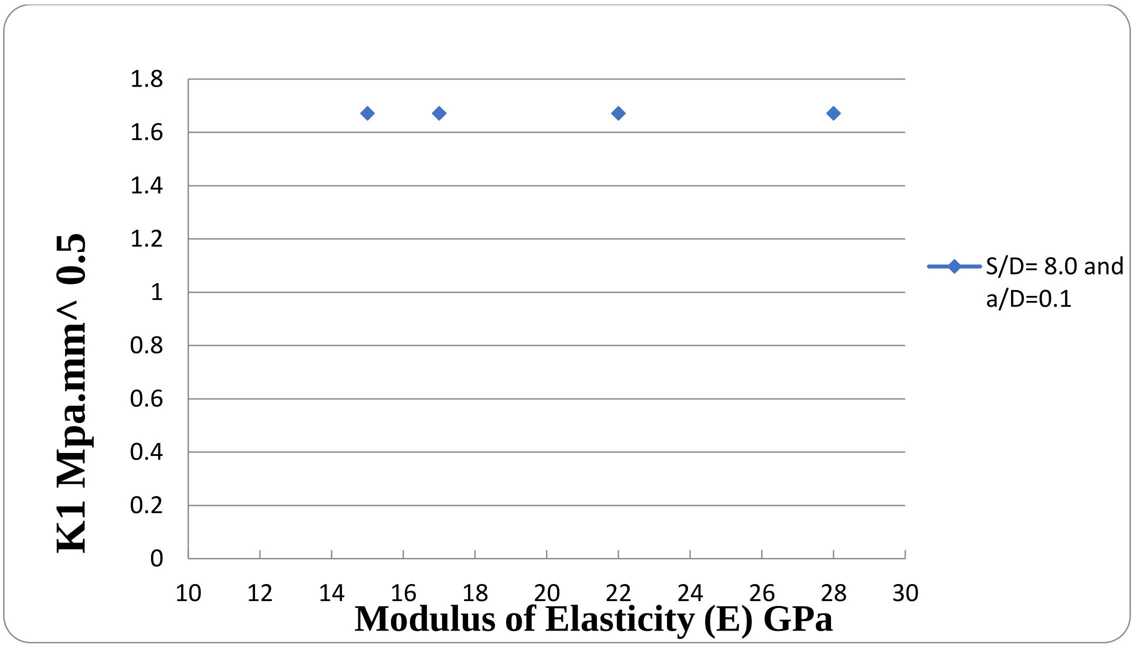

Fig.10. Variation of the SIF K_I according to modulus of elasticity

e) Influence of the crack inclination angle on the stress intensity factor K_I

Fig.11 represents the variation of the stress intensity factor according to the crack inclination angle. It is noted that for values of inclination angle θ range from 30: 90 ° the values of K_I increase with the increases of crack inclination angle.

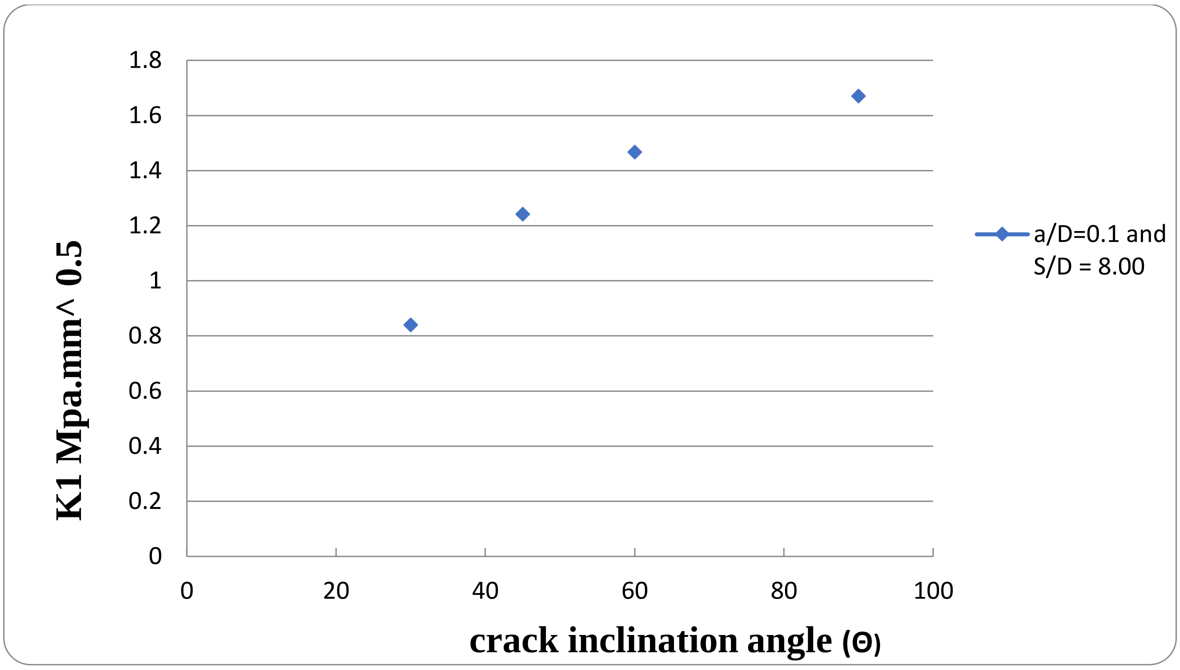

Fig.11. Variation of the SIF K_I *according to the crack inclination angle*

e) Influence of the Opening size and it's location on the stress intensity factor K_I

Fig. 12 shows the position of circular opening under load (P) with variable diameter range from (0.10D to 0.70D).

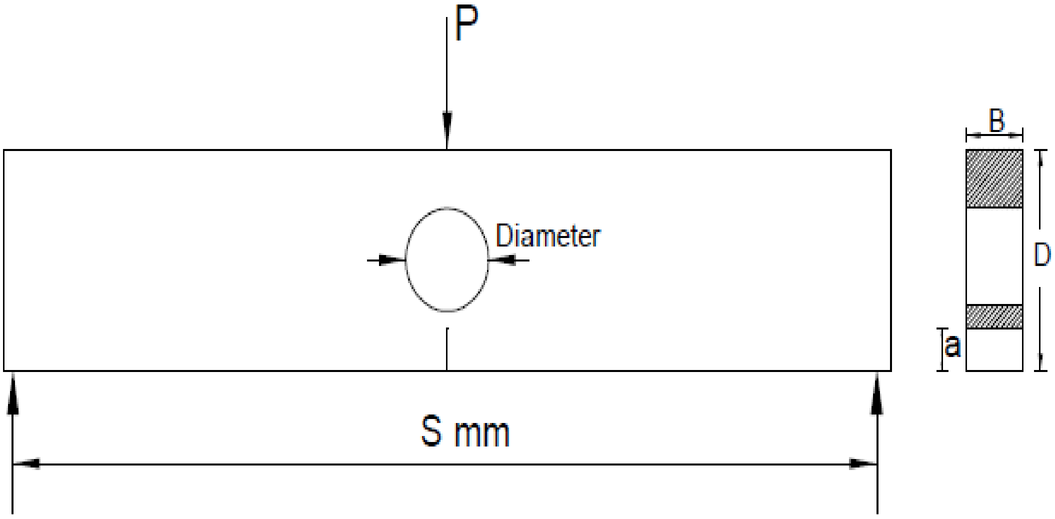

Fig. 12 the position of circular opening under load (P)

Fig. 13 represents the variation of the stress intensity factor according to the opening size. It is observed that the change of values K_I is very small with the increases of opening size.

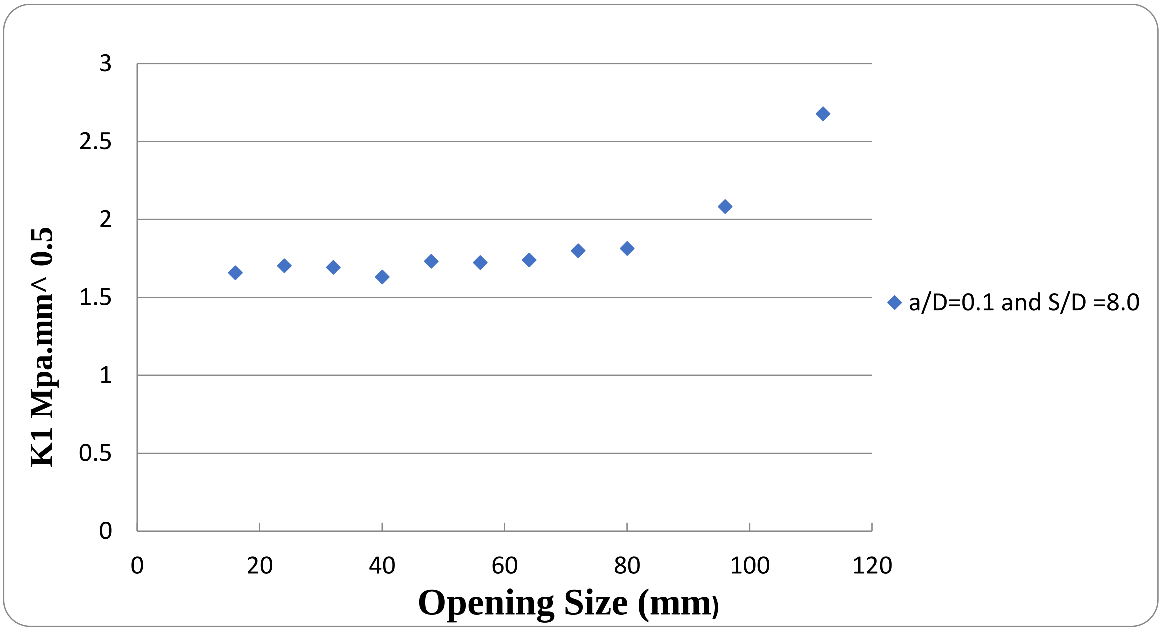

Fig.13. Variation of the SIF K_I according to the opening size

Fig.14 shows the position of circular opening from support with diameter equal to 0.50 D at distance X variable from (0.10 S to 0.40 S).

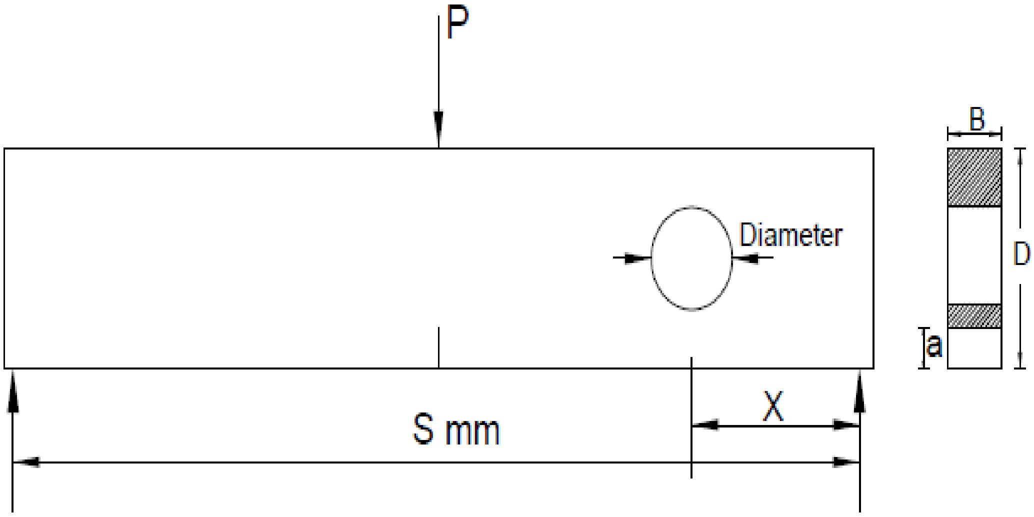

Fig.14. The position of circular opening from support at distance (X)

Fig.15 represents the variation of the stress intensity factor according to the position of circular opening from support. It is observed that the change of values K_I is very small with the increases of distance (X).

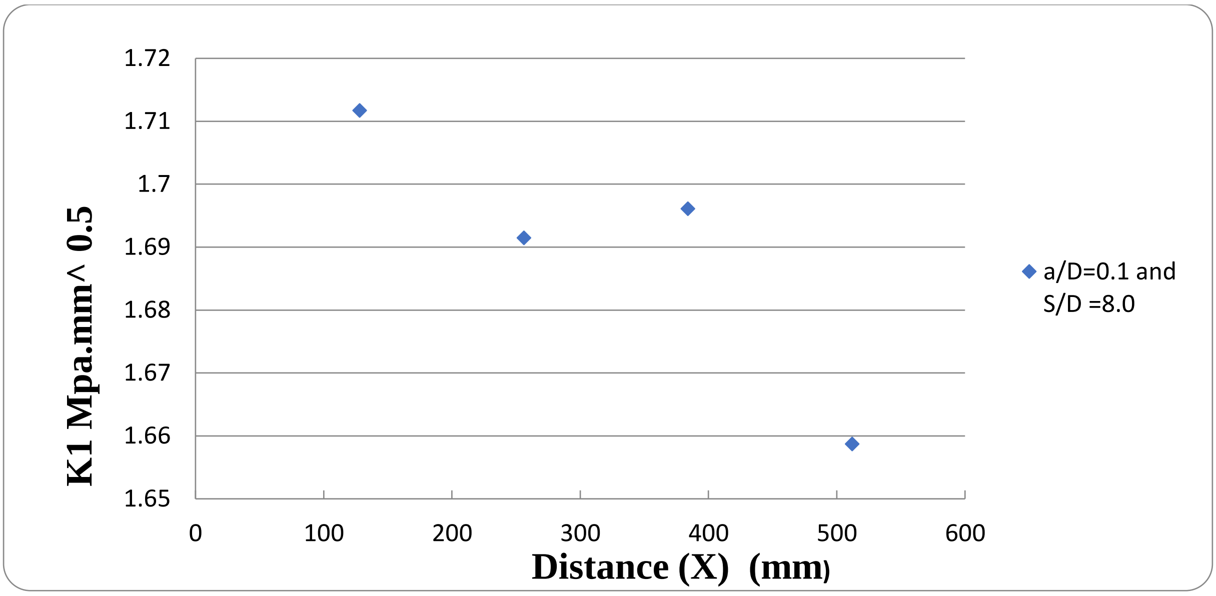

Fig.15. Variation of the SIF K_I according to the position of circular opening from support (X)

NUMERICAL VALIDATIONS

To verify the values of stress intensity factor, which obtained from a 3D simulation of concrete beams by using ANSYS software, the values of stress intensity factor compared with the values obtained from The ASTM D5045-14 [13] and E1290-08[14] Standards for the three-bending beam test with S=4D , a= 16mm and P =100 N. As shown in ***Table 2***, the stress intensity factor K_I obtained from a 3D simulation of the three-bending beam test by using the ANSYS software agree with the value given from the analytical equation.

Table 2. Comparison between analytical and numerical solution of the three-bending beam test

Solution type	**stress intensity factor K_I (MPa.mm^0.5)**
Analytical solution by using equation (2)	1.30
Numerical solution by using the ANSYS software	1.10

CONCLUSION

The following points offer the major outcome of the present study:

1. The phenomenon of crack propagation in concrete structures can be described by the concept of the elastic linear mechanics of failure starting from the criterion of the critical stress intensity factor.
2. Stress intensity factor depends on the beam size, where the values of K_I increase with the increases of beam size and the values of K_I increase with the increases of crack length.
3. Stress intensity factor depends on the beam width, where the values of K_I decrease with the increases of beam width
4. Stress intensity factor depends on the crack's position, where the values of K_I decreases with the increases of distance between load and crack, and the values of K_I are maximum when the distance between load and crack equal zero.
5. The values of K_I not affected by the variation of modulus of elasticity.
6. Stress intensity factor depends on angle of inclination of the crack, where the values of K_I increase for values of inclination angle θ range from 30: 90°.
7. The change of values K_I is very small with the increases of opening size and it's position

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