Study of Fracture Energy for Plain Concrete by the Use of the Finite Element Method

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ABSTRACT

Failure of plain concrete in tension is characterized by softening, which is accompanied by the development of regions of highly localized strains. The main objective of this research is to study the fracture energy (the value of tensile strain) ε_{tu} in the concrete and its effects on the load for plain concrete beams. Beams were tested by Bosco and analysis by the use of computer program ANSYS. The three dimensional brick element was used to represent the concrete element.

The results confirmed that the plain concrete beams do not fail when the first crack is obtain, but depends on the value of the tensile strain ε_{tu} (fracture energy), where the increase in the value of the tensile strain due to increases in the load applied on the beam.

Keywords: Fracture Energy, Tensile Strain, Plain Concrete Beam, Tensile Failure, rack Pattern.

دراسة طاقة الكسر في الخرسانة الاعتيادية باستخدام طريقة العناصر المحددة

الخلاصة

الفشل في الخرسانة العادية عند منطقة الشد عبارة عن ليونة في خصائص الخرسانة ويكون عادة مصحوب بتوسيع المنطقة التي فيها انفعال عالي جدا لذلك فان الهدف الأساس من هذا البحث هو دراسة طاقة الكسر(قيمة انفعال الشد) ε_{tu} في الخرسانة وتأثيراتها على تحمل العتبات الغير مسلحة حيث تم أخذ عتبات فحصت من قبل Bosco وتم تحليلها باستخدام برنامج ANSYS واستخدام العنصر الطابوقي المتكون من ثمان عقد لتمثيل العناصر الخرسانية.

الدراسة أكدت أن العتبات الخرسانية لا تفشل عند حصول أول تشقق بل تعتمد على قيمة انفعال الشد (طاقة الكسر) ε_{tu} حيث عند زيادة قيمة انفعال الشد يزداد تحمل الأعتاب الخرسانية.

INTRODUCTION

The tensile fracture of the plain concrete is as a rule regarded brittle, because concrete does not have the yield behavior, which is very typical for metals. Its tensile stress-strain constitutive law is nearly linear up to the critical point, but after that, it starts to descend. In spite of that, the concrete still has

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considerable toughness. The reason is the formation of the fracture process zone and the phenomenon called strain localization. This zone is estimated to be of the order of 100 - 200 mm, or even greater [1]. Because of this large damage zone, the methods of the Linear Elastic Fracture Mechanics LEFM cannot be directly applied for concrete. It was pointed out by Petersson [2], that the application of LEFM to concrete is closely related to the dimensions of the structure into consideration. It was shown that, when the structural sizes are increased, the material becomes more and more "brittle", i.e. the final collapse can only be described by means of Fracture Mechanics. As the structural sizes are decreased, the final collapse mode is approaching "plastic" state and can be described by some of the plasticity models. This fact is the reason for the unsuccessful early applications of LEFM to concrete. This dependency is called size effect and is very well described in the book of Bazant and Planas, reference [1]. Of course, there is an intermediate case of the structural sizes where the material behavior is considered as "quasi-brittle". The theory of fracture mechanics, applicable to quasi-brittle materials has taken a definite form in the last decade. As mentioned in Karihaloo [3], there is a reasonable consensus among researchers that the introduction of this theory into the design methodology of plain and reinforced concrete structures, which are likely to fail in a brittle manner, can lead to significant benefits.

Objective

The objectives of this study are:-

1. To study the fracture energy in nonlinear behavior of plain concrete beams.
2. To simulates the behavior of concrete crack beam.

BEHAVIOR OF CONCRETE

Behavior under Uniaxial Compression

A typical uniaxial compressive stress-strain is shown in Figure (1). It can be noted that the concrete behaves as linear elastic material when the stress level is less than 30 % of the uniaxial compressive strength $f_c{}'$. This stress level is called the point of onset of localized cracking [3].

$$f_c{}' = \varepsilon * E_c \qquad 0 < \varepsilon < \varepsilon_{c1} \qquad \text{... (1)}$$

At the level ranging between 0.3 $f_c{}'$ and 0.5 $f_c{}'$ the stress strain curve exhibits a slight nonlinearity due to the extension of stress concentrations at crack tips, thereafter when the stress level increases from $0.5f_c{}'$ to $0.75f_c{}'$ mortar cracks and other cracks continue and grow slowly with a gradual increase in curvature of the curve.

$$f_c{}' = \frac{\varepsilon * E_c}{1 + \left[\frac{\varepsilon}{\varepsilon_{co}}\right]^1} \qquad \varepsilon_{c1} < \varepsilon < \varepsilon_{co} \qquad \text{... (2)}$$

$$\varepsilon_0 = \frac{2 * f_c}{E_c} \qquad \text{... (3)}$$

Beyond this level of stress, the rate of crack propagation increases rapidly and the stress-strain curve bends shapely until the peak stress level is reached. Beyond the peak stress level, concrete shows a softening response, which is represented by the descending portion of the stress–strain curve [4].

$$f_c{}' = f_c \qquad \varepsilon_{co} < \varepsilon < \varepsilon_{cu} \qquad \text{... (4)}$$

Behavior under Uniaxial Tension

The strength of concrete in tension f_r is approximately a tenth of the compression strength $f_c{}'$. A typical tensile stress-strain response of concrete is linear up to a stress level of about 60% of cracking stress f_r as shown in Figuer (1).

$$f_t{}' = \varepsilon * E_t \qquad 0 < \varepsilon < \varepsilon_{t1} \qquad \text{... (5)}$$

Beyond this level bond micro-cracks start to grow and nonlinearity of the curve starts of to increase as the stress level increase until peak stress is reaches. The area of triangular (abc) represent the fracture energy, it is needed to provide discrete crack capability in the element loaded [6]:

$$f_t{}' = f_t * \frac{(\varepsilon_{tu}-\varepsilon)}{(\varepsilon_{tu}-\varepsilon_{t1})} \qquad \varepsilon_{t1} < \varepsilon < \varepsilon_{tu} \qquad \text{... (6)}$$

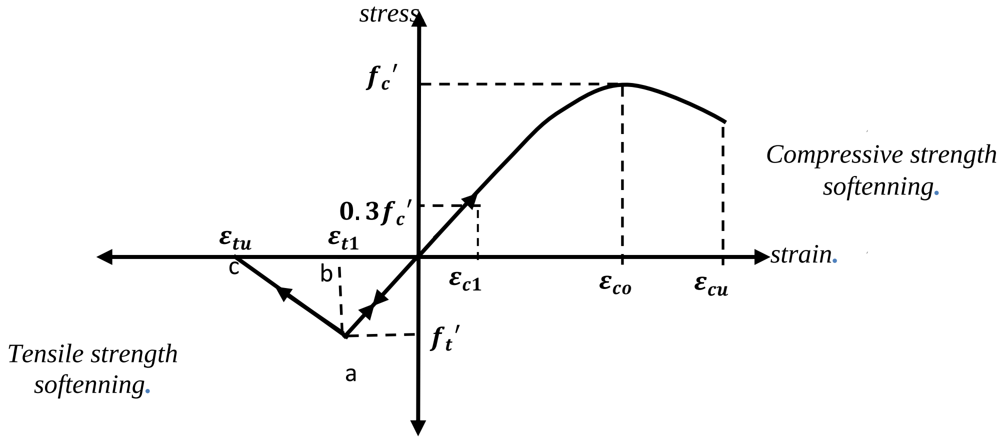


Figure (1) Stress-strain curve in concrete [7].

FINITE ELEMENT MODELING

The finite element analysis calibration study included modeling a plain concrete beam with the dimensions and properties corresponding to the beams tested.

Modeling of the Concrete

Solid65 element was used to model the concrete. This element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. This element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. A schematic descrejotion of the element is shown in Figure (2). Smeared cracking approach has been used in modeling the concrete in the present study.

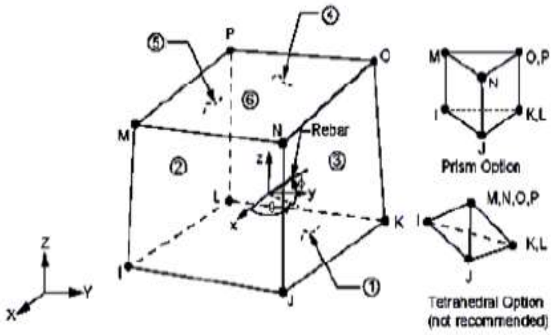


Figure (2) Solid 65 element geometry [9].

The following properties must be entered in ANSYS:

* Elastic modulus ($E_c = 4730\sqrt{f_c'}$) (MPa) [5].
* Ultimate uniaxial compressive strength (f_c') (MPa).
* Ultimate uniaxial tensile strength (modulus of rupture, ($f_r = 0.65\sqrt{f_c'}$) (MPa) [8].
* Poisson's ratio (ν) = 0.2 [5].
* Shear transfer coefficient (β_t) which represents conditions of the cracked face [7].

Geometry and materials properties

Five beams with different maximum tensile strength (ε_{tu}) were tested by Bosco [6] and analyzed using the proposed ANSYS finite elements model. Table (1) shows all beams evaluated in this study. See Figure (3).

Table (1) Beams Property.

Symbol Beam	Length cm	Width cm	Depth cm	Ec GPa	f_c' MPa	f_t MPa	ε_{tu}	ε_{cu}
PC1	300	30	50	220	21	2.1	0.0015	0.0033
PC2	300	30	50	220	21	2.1	0.0010	0.0033
PC3	300	30	50	220	21	2.1	0.0005	0.0033
PC4	300	30	50	220	21	2.1	0.0003	0.0033
PC5	300	30	50	220	21	2.1	0.00015	0.0033

P

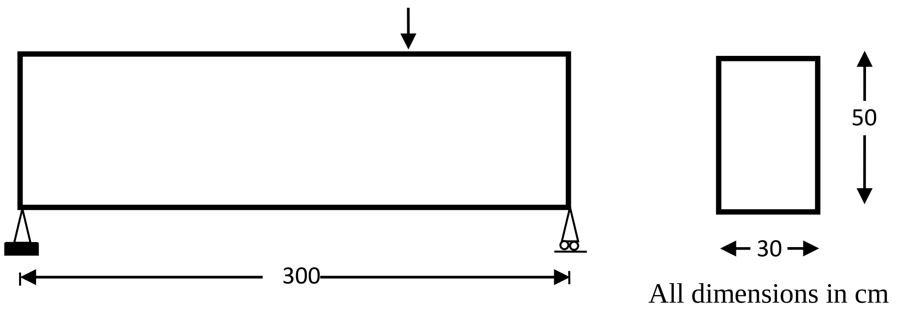


Figure (3) Properties of beams.

RESULTS AND DISCUSSION

Load - deflection curve

The test beams were loaded to failure. The first crack occurred at the same load as shown in Table (2) for all the experiments. The failure load was different for different beams as shown in Table (2). The variation of load at beams due to applied different values of fracture energy (maximum tensile strain), the failure load increased with increasing fracture energy and decreased with decreasing fracture energy. This value is compared with experimental value which is acceptable. See Figure (4).

Table (2) The first crack and failure load in beams.

Beam simple	Program Load N 1st crack	Experiment Load N 1st crack	Program Def. 1st crack	Experiment Def. Mm 1st crack	Program Failure Load N	Program Failure Def. mm
PC 1	3750 - 4000	3765	0.033129	0.032727	7250	0.104795
PC 2	3750 - 4000	3765	0.033131	0.032727	6750	0.083641
PC 3	3750 - 4000	3765	0.033138	0.032727	6000	0.069394
PC 4	3750 - 4000	3765	0.033151	0.032727	5250	0.050936
PC 5	3750 - 4000	3765	0.033258	0.032727	4500	0.038307

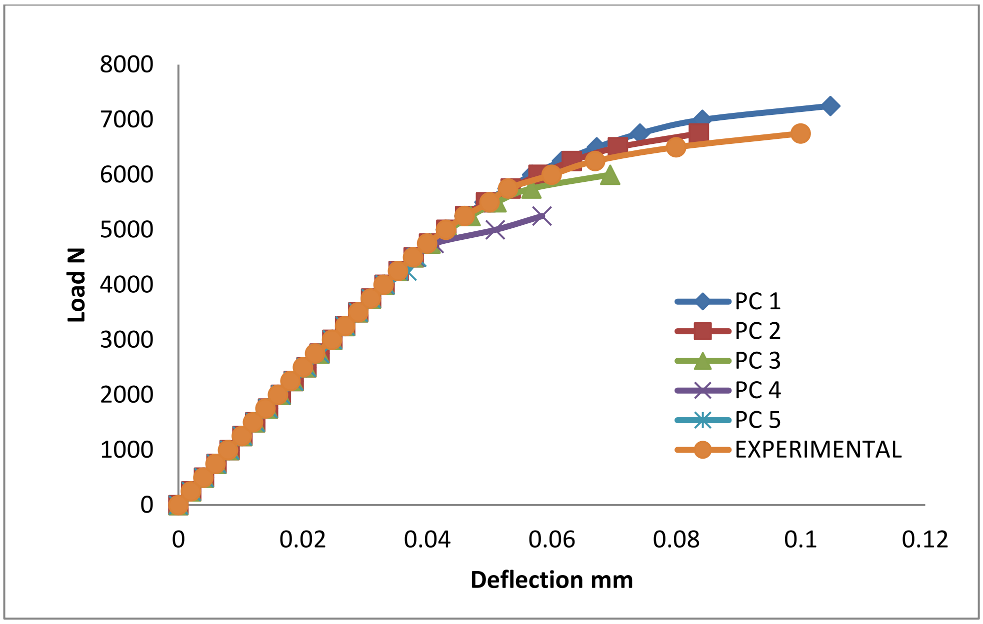


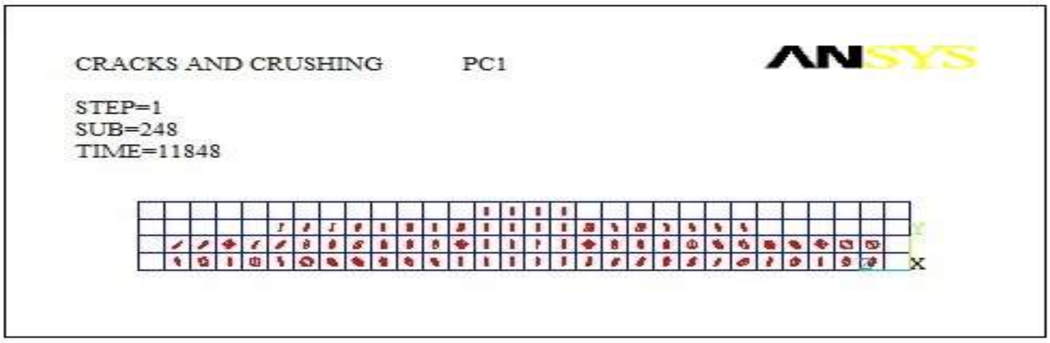
Figure (4) Load-deflection curve for beams.

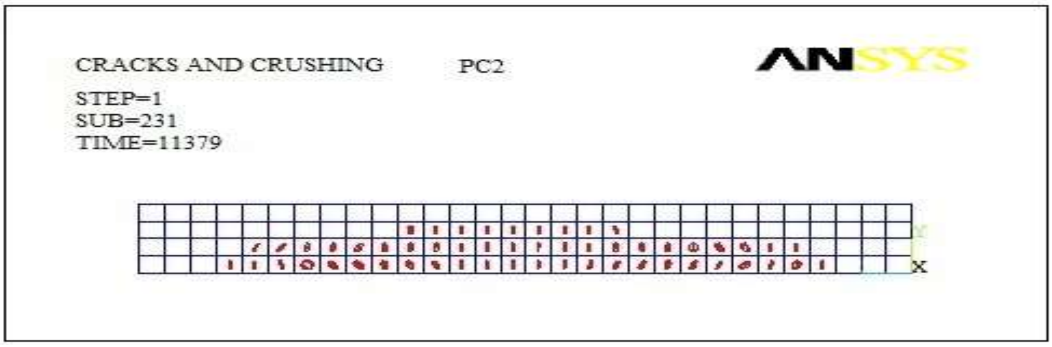
Beam Cracks

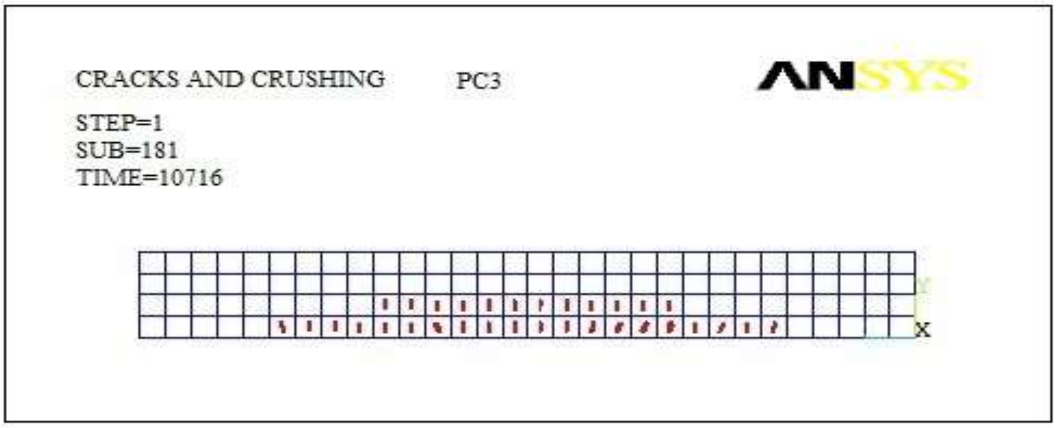
The ANSYS program records a crack pattern at each applied load step. Figure (5) shows evolution of the crack patterns developing for beams at the last loading step. ANSYS program displays line at locations of cracking in concrete elements. Cracking is shown with a line outline in the plane of the crack. The failure modes of the finite element models show good agreement with observations and data from the experimental full-scale beams.

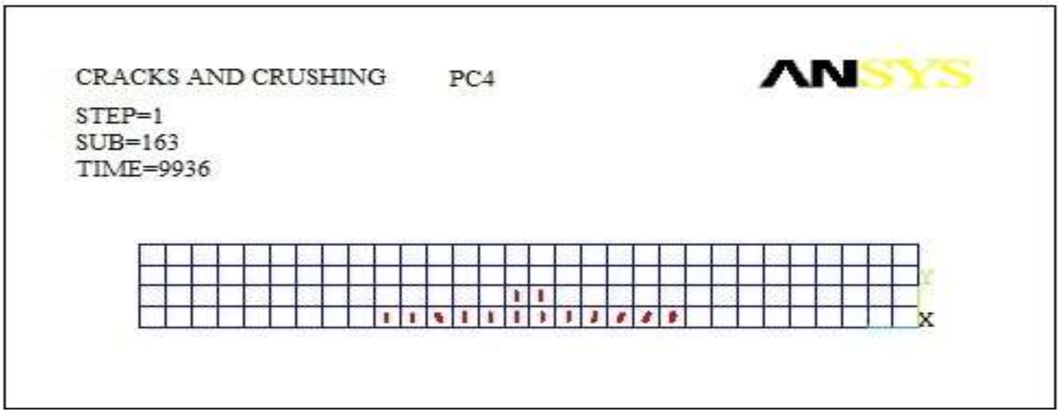
Figure (5) shows the crack pattren at these beams. It is depended on the tensile strength of concrete and the value ε_{tu} of concrete. This figure shows the deferent length of crack at beams. These cracks are still carried tensile stresses.

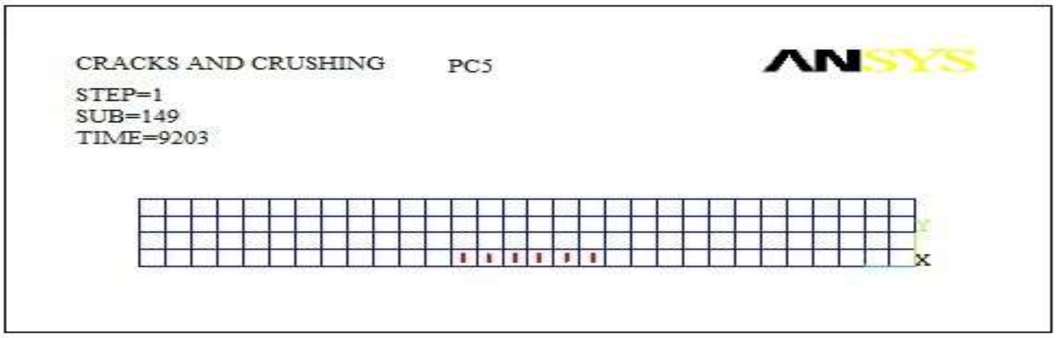
This experiment shows that the effect of fracture energy in the plain concrete beam, this energy is increase the durability of concrete beam, an increase of load intransitive to fail the concrete. Also the Figure (5) shows the high level of cracks for each beam.


CRACKS AND CRUSHING
PC1
ANSYS
STEP=1
SUB=248
TIME=11848
Y
X


CRACKS AND CRUSHING
PC2
ANSYS
STEP=1
SUB=231
TIME=11379
Y
X


CRACKS AND CRUSHING
PC3
ANSYS
STEP=1
SUB=181
TIME=10716
Y
X


CRACKS AND CRUSHING
PC4
ANSYS
STEP=1
SUB=163
TIME=9936
Y
X



Figure(5) Shows the high level of cracks for each beam.

Failure load due to increasing the area under the curve of softening which represents the fracture energy. The first crack begins when the stress reaches the strain ε_{t1} . After that the crack extends in depth. The failure load depends on the maximum tensile strain (fracture energy). Beam PC1 with maximum tensile strain (0.0015) is required value of load equal to (7250 N) to fail, but the beam PC5 with maximum tensile strain (0.00015) is required value of load equal to (4500 N) to cause the failure.

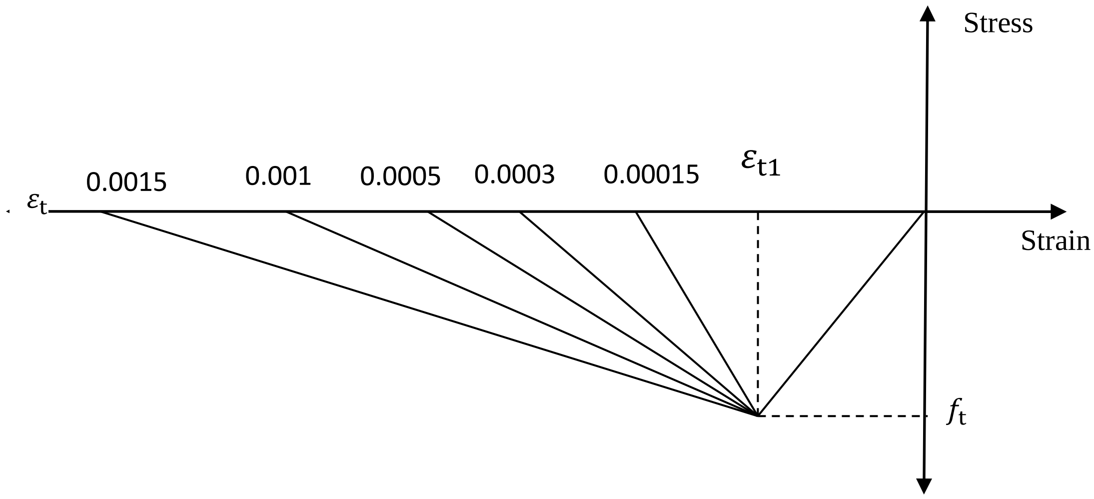


Figure (6) The fracture energy.

CONCLUSIONS

Based on the analytical results obtained in the present study, the following main conclusion can be concluded:

1- The plain concrete dose not fail at the appearance of the first crack as expected. The beam with this is one word stands more load due to the fracture energy which means that the beam losses its stiffness gradually.

2- The increase of maximum tensile strain (increase fracture energy) leads to increase in the durability of concrete beams, and the beam fails at high load.

3- The nonlinear finite element analysis is proved to be capable of predicating the state of stresses, deformation, yielding, and crack patterns throughout the load history and that it can predicate the first crack and the collapse load with the high accuracy.

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