# DESIGN AND CONSTRUCTION OF A PRECRACKING FOR FATIGUE FOR THE DETERMINATION OF FRACTURE TOUGHNESS

**Juan Pablo Cañizales**
jpcanizalez@uao.edu.co

**Alvaro Jose Toro**
ajtoro@uao.edu.co

**Héctor Enrique Jaramillo**
hjsuarez@uao.edu.co

**Nelly Alba de Sánchez**
nalba@uao.edu.co

Universidad Autónoma de Occidente, calle 25 # 115-85 Km 2 Vía Cali – Jamundi, Cali – Colombia
Grupo de Investigación Ciencia e Ingeniería de Materiales, GCIM; Centro de Excelencia en Nuevos Materiales, CENM

***Abstract.*** *In this work is shown the design of a fatigue crack generator. This machine is used for generating a crack, which is sufficiently sharp to provide a valid result from the fracture toughness test for metallic materials. This precracking for fatigue make cracks in flexion specimens type Bend and stress compact type C(T) in agreement to the norm ASTM E399 - 90, E813 - 89 and E1290 – 89. This is necessary in the determination of the* $K_{IC}$*, CTOD and* $J_{IC}$ *factors, for the characterization of the analyzed material. The functional principle of this equipment is based in charging cyclically the schemed specimens between the levels of maximum stress and minimum tension loads, the applied load is the result of the radial movement of a rigid bearing of balls, which is mounted in a double gear excentricity device. This excentric is designed in steel AISI 4340, with a maximum excentricity of 0.6 mm, which can be changed by the relative movement of the gear. The device consists of an engine with driving frequency, which transmits power to a shaft and that to the excentric. The structure was made in 1020 and 4340 AISI steel. Another of the advantages of the present design it's low cost and easy manufacture, allowing the implementation and use in research processes of materials characterization.*

***Keywords****: Fracture toughness, Fatigue crack generator, Stress Intensity Factor, CTOD, J- Integral*

## 1. Introduction

Failure for fatigue constitutes 90% (Martin, 1999) of the causes for which a component ceases to operate; crack growth due to fatigue is one of the many forms in which the degradation of a material can arise. Fracture Mechanics, as a discipline of knowledge – through mechanical fracture studies, offers tools and methodologies that permit the carrying out of analysis, design, and evaluation of cracked materials. $K_{IC}$, $J_{IC}$, and $CTOD_C$ parameters are of great use when studying the behavior of materials in the presence of intrinsic defects; parameter $K_{IC}$, also denominated as toughness to fracture in plane strain, a property of the material that quantifies the resistance to the unstable propagation of the crack, is used as a fracture parameter. For such, it is compared to the stress Intensity Factor (K), which defines the magnitude of the stress at the tip of the crack. If $K < K_{IC}$, the integrity of the component against the unstable growth of the crack is assured, (Gonzalez, 1994), (Vedia, 1986).

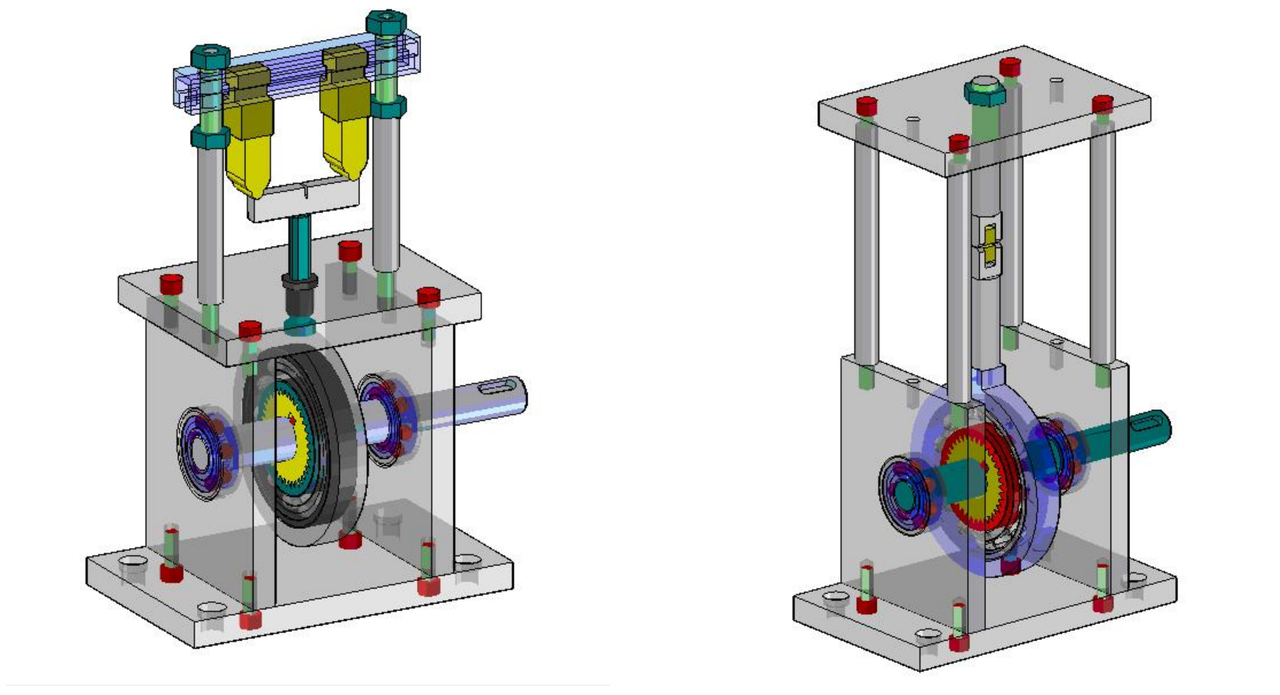
In cases where big plastic strain are produced at the tip of the crack, the mechanical principle of Elasto-plastic fracture is used, involving two fracture parameters: the integral J parameter, which characterizes resistance to fracture when there is a stable propagation of the crack before the material's final fracture is produced; the second fracture parameter is the crack tip opening displacement CTOD, based on the measurement of the crack opening.

Of the fracture parameters previously mentioned, the CTOD presents less complexity for its determination and also permits the carrying out of analyses both of the elastic lineal fracture mechanics and the elasto-plastic fracture mechanics. It is also a favorable method because it allows the testing of materials when there is high ductility and small quantities of the material available. Specimens geometries most often used are the Bend type three-point flexion and the compact tension C(T), differentiating one from the other by the way it is loaded and which have to be elaborated under the specifications of ASTM norms E399-90, E 813, E 1152, and E 1290, (Martín, 1999), (Anglada, 2002), (Guimarães, 2001).

This work show the design and construction of a crack generator by fatigue in specimens of three-point flexion (Bend type) and compact tension C(T), used in the test to measure the $K_{IC}$, $J_{IC}$, and $CTOD_C$ parameters. Crack generation by fatigue is one of the steps that requires the most time when doing a mechanical fracture study of materials, since it is carried out in expensive universal tension machines equipped for such purpose. It is inadequate to run the test in conventional universal machines, given that when the crack grows, very high tension levels are generated; thereby, invalidating results later obtained. For the previous, we see the need to have an independent system with low-cost and for the basic research in which we can perform pre-Cracking by fatigue.

**2. Mechanical Design of the pre-Cracking**

The figure 1 (a) and Figure 1 (b) are the models in three dimensions of the system of generation of crack by fatigue for each type of test tube that were designed.

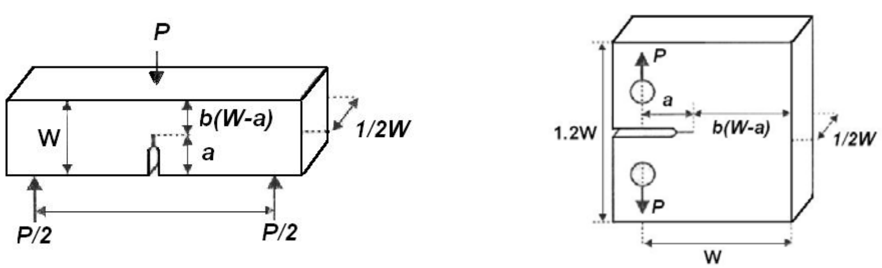


a) b)

Figure 1. Pre-Cracking by fatigue devise

a) System for Specimens in Bend flexion b) System for C(T) Tension Specimens

To design each part of the system, we bore in mind primarily the recommendations in norms ASTM 399-90 and ASTM 1290-89. Very special care was exercised with the pre-Cracking central shaft, since this element supports the whole load generated in the system. For such a purpose we defined the specimens sizes with which we worked. For the flexion specimens, the width is equal to 19.05 mm, and for the tension specimens, the width will not be greater than 21.59 mm; the remaining dimensions related to the width of the specimens are shown in figure 2.




a) b)

Figure 2. Normalized Specimens for the determination of fracture toughness

a) Bend Flexion Specimens; b) C(T) Tension Specimens

### 2.1. Design of the pre-Cracking central shaft

To undergo the analysis of the load supported by the central shaft, we began with the maximum load to be applied onto the system for the tension specimens C(T), since the pre-cracking load is lower for the Bend type flexion specimens. This load was determined through an Excel spreadsheet, involving dimensions and property of the specimens material.

Equations (1) and (2) are recommended by ASTM 1290-89 norm to determine the maximum load the pre-cracking should generate in the case of the flexion and tension specimens, respectively. Where: $a_o$, is the size of the initial crack; $\sigma_y = ½ (S_{UT} + S_Y)$, are the ultimate and yield strength, respectively; W, is the width of the specimens; B, is the thickness of the specimens; $b_o$, is the binding of the (W- $a_o$) specimens; S, is the length between supports.

$$P_{f(BEND)} = 0.5\left(\frac{Bb_o^{\ 2}\sigma_y}{S}\right) = 2789\ N \tag{1}$$

$$P_{f(C(T))} = 0.4\left(\frac{Bb_o^{\ 2}\sigma_y}{2W + a_o}\right) = 6900N \tag{2}$$

The central shaft was designed according to the theory of maximum stress (Mott, 1995) for which a minimum diameter of 21.5 mm was obtained for the case of static load; for a dynamic condition we obtain:

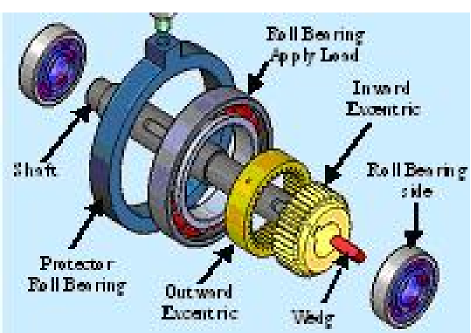
$$d = \left\{\frac{32 f.s}{\pi}\left[\left(\frac{K_f M_{Max}}{Se}\right)^2 + \frac{3}{4}\left(\frac{K_{fTor} T_{Max}}{S_y}\right)^2\right]^{1/2}\right\}^{1/3} = 30mm \tag{3}$$

From equation (3): F.S, is the safety factor defined with a value of 2; $K_{f(Flexion)}$=1.33 (factor of stress concentration in flexion); $M_{Max}$=213 N.m; Se= $C_{load}$* $C_{Size}$ *$C_{Surface}$ *$C_{Temperature}$ *$C_{Reliability}$ *$S'_e$ =205.3MPa; where C is coefficients $T_{Max}$=53.43Nm; $K_{f(Torsion)}$=1

The potency of the system is supplied by coupling the pre-cracking axel to the shaft of the 3-HP tri-phased motor, which rotates at 1800 RPM. Its velocity is varied through a 220A 240 VAC Yascawa variator.

### 2.2. Design of double Eccentric mechanism

To generate the crack, the norms recommend cyclical loading of the simple between maximum and minimum levels of tension. Cyclical loading is provided through the toothed double eccentric mechanism shown in figure 3 (a), which produces a senosodial load profile with a 0.6mm amplitude, both in the tension as in the compression. The objective of each tooth on the gear is to make relative movements between these and to have different eccentricities. The gear has 36 teeth and they were constructed from heat treatment AISI 4140 steel.



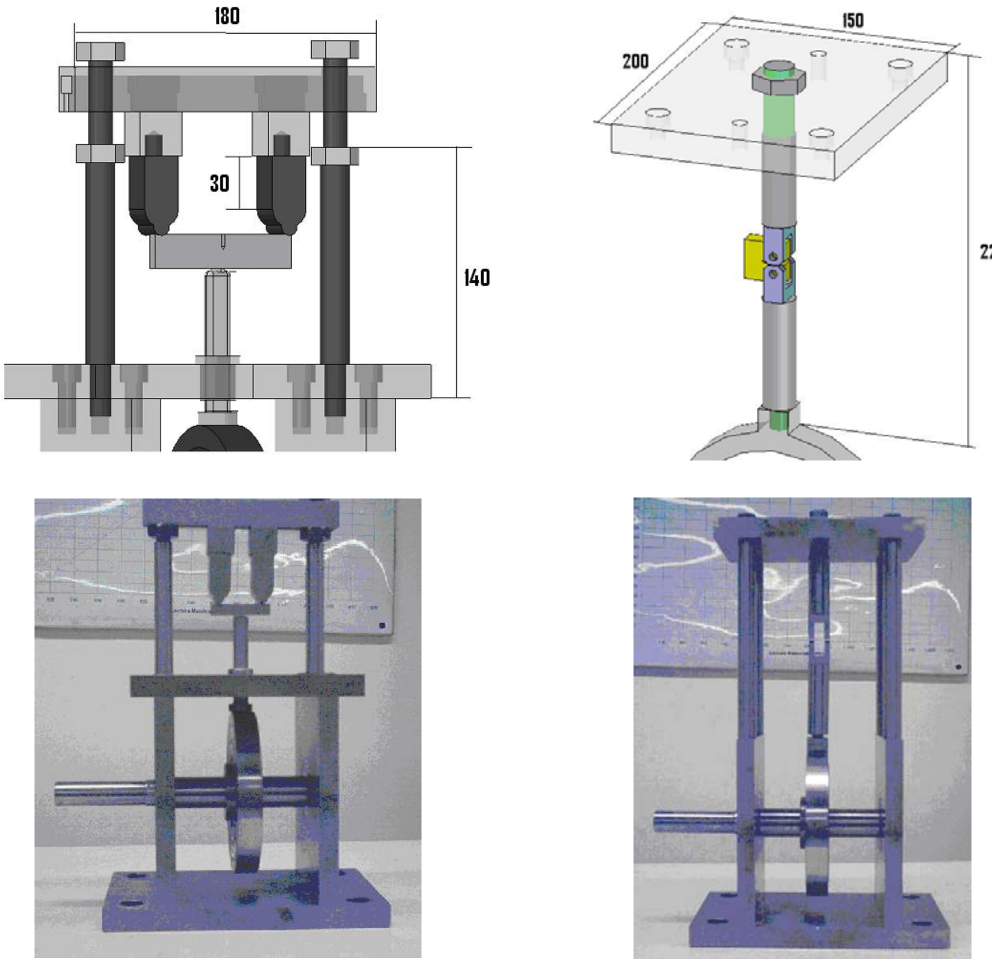
a)


b)

figure 3. Double eccentric mechanism
(a) Assembly of the double eccentric mechanism on the pre-cracking axel, (b) Assembly of constructed double eccentric mechanism.

### 2.3. Load-application system

The load-application system serves the purpose of being the interface between the bearing disc protector and the specimens. These elements were designed bearing in mind that the force applied had to be uniformly distributed, and for such we built the accessories – shown in figure 4 – as recommended by norm ASTM 399-90 for the toughness test. Each mechanism was designed to support the maximum loads generated during the test, (Vedia, 1986), (Guimarães, 2001).




(a) (b)

Figure 4. Load-application mechanism and the resistance calculations of some elements (a) Bend-flexion Mechanism (b) (C(T)) Tension Mechanism

The upper support profile for the flexion test was defined as shown in figure 5 and its load considerations are shown in figure 6.

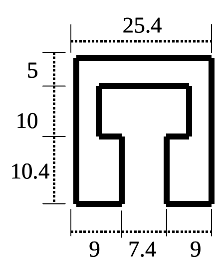



Figure 5. Cross section of the support girder (dimensions in mm)

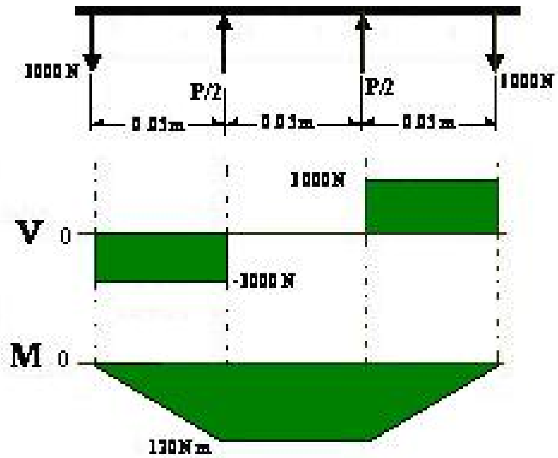



Figure 6. Upper support diagrams of cutter and flexor moment

Based on the load diagrams, figure 6 was checked for the structural integrity of the component according to equations (4) and (5). A load of 6000N was considered and the module of the profile section was greater than the required minimum section.

$$S = \frac{I_{Total}}{C} = 1.409 * 10^{-6} m^3 \quad (4)$$

$$S_{(Minima)} \geq \frac{M}{\sigma_{adm}} = \frac{120Nm}{393 * 10^6} = 3.05 * 10^{-7} m^3 \quad (5)$$

In the case of the device in the tension test, the element to be designed is the simple holder, where the thread design is fundamental. An M20-0.5 thread was selected and its revision was done in equations (6) and (7), based on criteria recommended by (Mott, 1995).

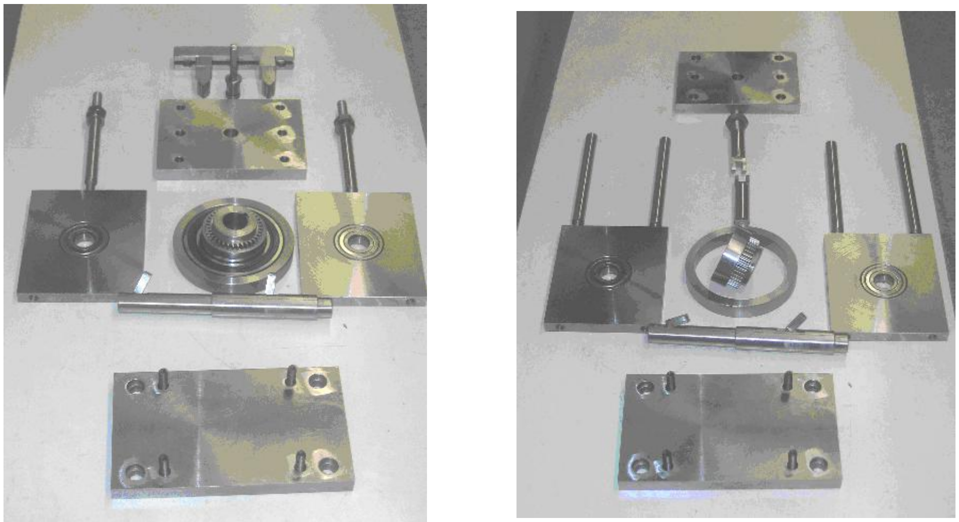
$$A_T = (0.7854)(D - 0.9382\,p)^2 = 299.6mm^2 \quad (6)$$

$$A_{T(Minima)} = \frac{P}{\sigma_{Adm}} = \frac{7100}{\left(393/2\right)} = 36.4mm^2 \quad (7)$$

From the previous equations, the area achieved is greater than the minimum necessary area, which guarantees adequate performance of the thread.

### 2.4. Support structure

The structure that supports the shaft and the different components is composed of two lateral plates; a base plate, an upper plate with a 19.05-mm thickness, four support bars (for the tension cases), and two 20-mm diameter bars (for flexion cases). All these components were made on AISI 1020 steel, treatment with a chromed surface to avoid corrosion.



(a) (b)

Figure 7. Components of the System pre-cracking due to fatigue (a) Bend-flexion Mechanism (b) (C(T)) Tension Mechanism

**2.5. Load and crack size sensors**

For the importance these two parameters have, measuring elements will be available in the system to allow the determination of the values of both the applied load and the size of the crack – as they are generated during the test.

The load applicator has a Rosetta type strain gauge attached, which permits the sensing of the applied load during the test. This sensing is done with the aid of a data acquisition system. This equipment allows for the reading and storage of the micro-deformities produced in the load applicator. The calibrating of the load applicator is done on an INSTRON 3300 universal test machine.

The crack by fatigue is one of the variables on which we need to be especially careful before, during and after subjecting the specimens to the cyclical load, since the norms are very rigorous as to its size, orientation, and uniformity. As far as size is concerned, three patterns are available for size of crack. The first pattern consists of marking two lines normal to the crack trajectory. In the second pattern we measure the crack mouth opening displacement with a Clip Gauge, and lastly, with the count of the number of load cycles required for a desired crack size.

Figures 8 and 9 are illustrating the methods used to follow up on the growth of the crack. Figure 7, shows the two lines normal to the trajectory of the crack growth, living a vision of the orientation and size of the crack that is being generated.

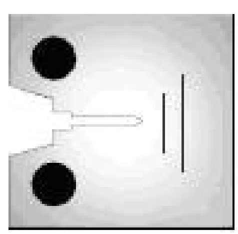


Figure 8**.** Tension specimens showing lines normal to the trajectory of crack growth

Figure 9 displays the assembly carried out to measure the crack mouth opening displacement, and how with this opening we measure the length increase of the crack, using the equation recommended by ASTM E399-90 norms and the specimens flexibility equation determined by Saxena and Hudak, (equations (8) and (9)).

Once we know the micro-strain produced in the load applicator, we determine the load in any instance; load used in the equations recommended by ASTM E399-90 norms and Saxena, 1979.

$$\frac{a}{W} = C_0 - C_1 U + C_2 U^2 - C_3 U^3 + C_4 U^4 - C_5 U^5 \qquad (8)$$

$$U = \frac{1}{\left[1 + \left(\frac{E' B V_m}{P}\right)^{1/2}\right]} \qquad (9)$$

Where: a= size of crack; W=Width of sample; E´=Module of elasticity; P=Applied Load; B=thickness of specimens; $V_m$ crack mouth opening displacement; $C_0$ ,$C_1$ ..... $C_n$ are coefficients that depend on the author used.

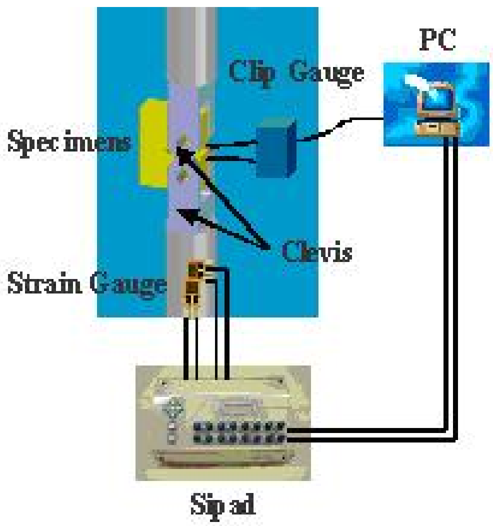



Figure 9. Assembly for the sensing of a crack through the measure of the groove opening

By using an Excel spreadsheet, we determined the number of cycles necessary to produce a determined crack size from Paris' equation (12). This is carried out by making length increases to the crack to determine the behavior of the maximum and minimum loads produced by this increase. These data are used to determine the variation behavior of the stress intensity factor in equation (11) with respect to these increases.

Then, once this behavior is known, we made the variation graph of the intensity factor and the crack increase (ΔK vs. a), such being the independent variable, the resulting equation was used to carry out the numerical integration, equation (13), and thus obtain the value of the number of cycles necessary, (Hinostroza, 2004)

$$K = \frac{YP}{BW^{1/2}} \qquad (10)$$

$$\Delta K = K_{Max} - K_{Min} \qquad (11)$$

$$\frac{da}{dN} = C(\Delta K)^n \qquad (12)$$

$$\int_{a_0}^{a_f} \frac{da}{(\Delta K)^n} = C \int N \qquad (13)$$

## 3. Conclusions

With this device, we can carry out the behavior characterization of metallic materials with crack, since for the simulation of an intrinsic defect (imperfections, inclusions, tears, or manufacturing defects) that, in the course of the load cycle, can become a crack and produce a fracture in a structural component.

The device for crack generation by fatigue is of great use when carrying out the analysis, design, and evaluation of components under the concept of fracture mechanics, given that it facilitates the determination of $K_{IC}$, $J_{IC}$, and CTOD fracture mechanical parameters used to determine the integrity of the structures.

Compared to similar systems and to methodologies that involve analysis through finite elements, this device is an advantageous since it carries out monitoring in real time of the crack length.

For basic research, this is a great contribution, because it is easily built, managed, and maintained; aside from the lower cost, allowing it to be of easy access.

## 4. Future work

The continuation of this work will center on the calibration of the system designed as a crack generator by fatigue in samples in Bend flexion and C(T) type tension to determine fracture toughness in metallic materials. The first tests will be done on national carbon steels of the series AISI 1020, 1045, and 1090, to determine their behavior.


## 5. Acknowledgements

This work was carried out in a joint effort between *Universidad Autónoma de Occidente* and *Colciencias* within the program: Young Researchers and Innovators. The authors thank the office of the Vice-Rector of Research and Technological Development at *Universidad Autónoma de Occidente*. We are also grateful for the wholehearted collaboration from the researchers: Martin Meizoso (Spain), Valdir A. Guimarães (Brazil), and the school of Mechanical Engineering at *Universidad del Valle* (Colombia), who offered us advice during the design process. We extend our thanks to the lab assistants at the materials resistance laboratory at *Universidad Autónoma*.


## 6. References


ASTM E 1290-89 “Crack- Tip Opening Displacement (CTOD) Fracture Toughness Measurement”, Annual Book of ASTM Standards Vol. 03.01

ASTM E 1820 “Standard Test Method for Measurement of Fracture Toughness”, Annual Book of ASTM Standards Vol. 03.01

ASTM E 399-90 “Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials”, Annual Book of ASTM Standards Vol. 03.01

BERROCAL L. 1998, O. Elasticidad, tercera edición, Mc Graw Hill, España, pp. 1

GONZÁLES, J. L. Mecánica de la Fractura, Bases y Aplicaciones, Noriega editores, S.A. México, pp. 10-20,

HERNÁNDEZ Héctor Albañil. Edgar Espejo Mora, 2002, Mecánica de Fractura y Análisis de Falla, , Editorial el Malpensante S.A. Universidad Nacional de Colombia. pp. 14-83

Luis A de Vedia. 1986 “Mecánica de Fractura”, Argentina pp. 51-126

MJ Anglada, ed.–J Alcalá, LM Llanes-AM Mateo-MN Salán, 2002, *Fractura de materiales*, Edición UPC Barcelona España, pp. 13-30,

MEIZOSO Antonio Martin, José Manuel Martínez Esnaolo, 1999, Mecánica de la Fractura, impreso en España © Los autores, Cap 4. pp.1-20, Cap 7. pp.1-7, Cap 8. pp. 1-8

OSCAR ANDRES HINESTROZA G., 2004, Diseño Y Construcción De Un Banco Prefisurador De Probetas Tipo Flexión En Tres Puntos Para La Determinación De La Tenacidad CTOD Del Acero SAE 1045, Tesis de grado Escuela de Ingeniería Mecánica Univalle, Colombia, pp. 25- 90

ROBERT L MOTT , 1995, Diseño de Elementos de Maquinas, Mexico pp. 283-313, 744-749

V.A. Guimarães, L.R.O. Hein, J. Zangrandi Filho; 2001, Sistema De Baixo Custo Para Nucleação De Pré-Trincas Por Fadiga; Materials Research Vol. 4 pp. 1-5