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ANSYS Creep Modeling in a Beam with a 45° of Opening Crack

Ghouilem Kamel
University Mouloud Mammeri of Tizi – Ouzou

Atlaoui Djamal
University Mouloud Mammeri of Tizi – Ouzou

Mehaddene Rachid
University Mouloud Mammeri of Tizi – Ouzou

Merakeb Seddik
University Mouloud Mammeri of Tizi – Ouzou

Abstract: The main of this study is yo presents a prediction of creep behavior beam with opening crack at 45° subjected to a constant load during 12hours (720mn) and describe a procedure for modeling the primary creep law using ANSYS ® software. The procedure modeling of creep behavior consist to applied the finite element method (FEM) based on a model called (Modified Time hardening model) using the computer code ANSYS 17.1. This paper illustrates a new approach of study crack and creep behavior by the FEM in the elements structural. Crack analysis is typically accomplished using either the energy criterion or the stress-intensity-factor criterion. For the energy criterion, the energy required for a unit extension of the crack (the energy-release rate) characterizes the fracture toughness. For the stress-intensity-factor criterion, the critical value of the amplitude of the stress and deformation fields characterizes the fracture toughness. ANSYS ® 17.1 software has been used to perform the numerical calculation in this paper. The main objective of this study is to determine the distribution of stresses, creep strains as well as the mechanical behavior around crack. Results show that creep strain rate, and the resulting axial stresses will gradually increase at the spring line of the final lining.

Keywords: ANSYS, Creep, Finite element model, Crack, Time hardening model

Introduction

Crack growth and fracture is a problem that can be seen both in nature, and in man-made structures. Where the common cause of the propagation is the presence of tensile or shear stress within the material (Bjorheim, 2019). To solve the crack mechanics problems, a fracture analysis is a combination of stress analysis and fracture mechanics parameter calculation. The stress analysis is a standard linear elastic or nonlinear elastic plastic analysis. Because high stress gradients exist in the region around the crack tip, the finite element modeling of a component containing a crack requires special attention in that region. The stresses near a crack tip in linear elastic fracture mechanics can be described by the following equation given in (Anderson 2005):

$$\sigma_{ij} = \left(\frac{k}{\sqrt{r}}\right) f_{ij}(\theta) + \sum_{m=0}^{\infty} A_m r^{\frac{m}{2}} g_{ij}^{m}(\theta) \tag{1}$$

Where: σi is the Stress tensor, r is Distance from crack tip, θis the angle in relation to crack plane, k is the Constant and fij is the dimensionless function of θ in the leading term. This formula can be found in Anderson (2005) and this solution is exact according to Tada et al. (2000). 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 considerable toughness. The reason is the formation of the fracture process zone and the phenomenon called strain localization. Because of this long damage zone, the methods of the linear elastic fracture mechanics (LEFM) can not be directly applied for concrete.

$$K_I = \sigma cos^2(\beta)\sqrt{\pi a} \quad (2)$$

$$K_{II} = \sigma sin(\beta)\, cos(\beta)\sqrt{\pi a} \quad (3)$$

Where: σ is the remote stress, β is the angle of the slanted crack and ais a half crack length. Figure.2 illustrate the concrete beam crack test produced in the LGEA laboratory

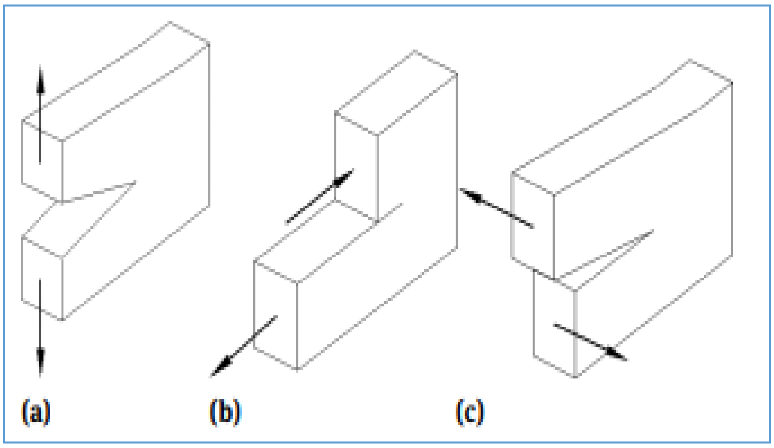

Figure 1.Three modes of fracture, (a) mode I - opening, (b) mode II - in plane shear, (c) mode III - out-of-plane shear (DTD Handbook 2005)

Figure 2. Beam crack test at 45°

It was pointed out by (Petersson 1981), that the application of LEFM to concrete is closely related to the dimensions of the structure into consideration. He has shown that, when the structural size increases, the material becomes more and more “brittle”, i.e. the final collapse can only be described by means of fracture mechanics. As the structural size decreases, the final collapse mode is approaching “plastic” type and can be described by some of the plasticity models. That fact was 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,1998). Of course, there is an intermediate case of the structural sizes where the material behaviour is considered as “quasi-brittle”. The theory of fracture mechanics, applicable to quasi-brittle materials has taken a definite form in the last decade. The size of the concrete element (in most cases we use the height of the beam D, as a characteristic size) is closely related to its behavior and the mode of fracture, see figure 1 above , where three typical failure modes are shown, depending on the size of the concrete beam.

Creep involves time dependent deformation under constant compressive stress and temperature level. In materials science, creep is the tendency of a solid material to move slowly or deform permanently under the influence of stresses. the yield strength of the material. Creep is more severe in materials that are subjected to heat for long periodsand near their melting point. Creep always increases with temperature. In general, the creep equation is following:

$$\dot{\varepsilon}_{cr} = \frac{C\sigma^{m}}{d^{n}} e^{-\frac{Q}{KT}} \quad (4)$$

Where, $\dot{\varepsilon}_{cr}$ is the creep strain rate, C are a constant dependent on the material and the particular creep mechanism, m and n are exponents dependent on the creep mechanism, Q is the activation energy of the creep mechanism, σ is the applied stress, d is the grain size of the material, k is Boltzmann’s constant, and T is the absolute temperature

Finite Element Modeling of Crack region

Stress and deformation fields around the crack tip generally have high gradients. The precise nature of these fields depends on the material, geometry, and other factors. To capture the rapidly varying stress and deformation fields, use a refined mesh in the region around the crack tip (ANSYS 2016). For linear elastic problems, the displacements near the crack tip (or crack front) vary as

$\sqrt{r}$ where r is the distance from the crack tip. The stresses and strains are singular at the crack tip, varying as

$1/\sqrt{r}$ to produce this singularity in stresses and strains, the crack tip mesh should have certain characteristics:

- The crack faces should be coincident.

- The elements around the crack tip shown in Figure 3, Should be quadratic, with the mid side nodes placed at the quarter points. (Such elements are called singular elements)

The recommended element type for a 2-D fracture model is PLANE183, the 8-node quadratic solid. The first row of elements around the crack tip should be singular, as illustrated (figure 4). The PREP7 preprocessor's KSCON command which assigns element division sizes around a key point is particularly useful in a crack model. It automatically generates singular elements around the specified key point. Other fields on the command allow you to control the radius of the first row of elements, the number of elements in the circumferential direction, and more. Figure 3 shows a fracture model generated with the help of KSCON.

The use of singularity elements was adopted for FEM, because it was found to reduce the required refinement near the crack tip, also when the interaction integral is applied. An illustration of how the mesh is user defined near the crack tip, is shown in Figure 4. RRAT is here 0,5, as it can be seen that the CTSize is twice as large as CTSize*RRAT. Figure 5 shows how the refined region near the crack tip, when 4 rows of elements are used, and RRAT is set to 0,5. The rows of elements are numbered 1, 2, 3 and 4, and these are also the rows of elements that the interaction integral will be performed along. Thus, contour number 1 is the interaction integral performed along the 1st row of elements, contour number 2 would be the interaction integral performed along the 2nd row of elements

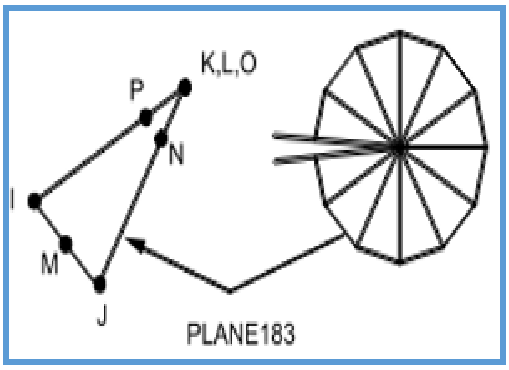

Figure 3. Singular finite element on ANSYS [5]

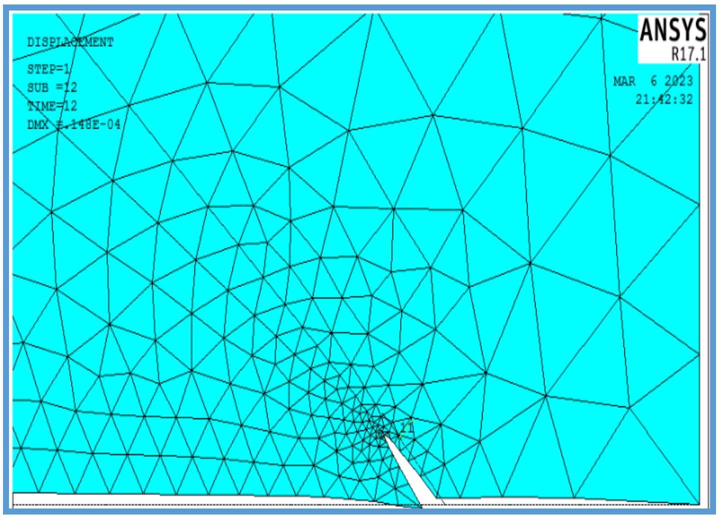

Figure 4. 2-D FEM crack modeling

The topic of the paper is to modeling the fracture mechanics, where the behavior of linear elastic fracture mechanics (LEFM) is taking into account. The general theory of LEFM, criteria and models for simulate the crack opening depending of time due to static loading is described. The finite element program Mechanical APDL 17.1, called ANSYS, is used to programme APDL code that simulate the crack of a 2D structure subjected for a load case. In order to conduct the APDL code user-friendly it is implemented in the ANSYS user interface menu GUI, by the user interface design language (UIDL).

Linear Fracture Mechanics Parameter Calculation

The fracture mechanics parameters describe either the energy-release rate or the amplitude of the stress and deformation fields ahead of the crack tip. The following parameters are widely used in fracture mechanics analysis:

- Stress-intensity factor
- Energy-release rate
- J-Integral

The stress intensity factor and energy-release rate are limited to linear elastic fracture mechanics. The J-Integral is applicable to both linear elastic and nonlinear elastic-plastic materials.

Stress-Intensity Factor

To evaluate stress distribution a stress intensity factor (SIF) is defined. The stress intensity factors represent the magnitude of the stresses around the tip of the singular point. The stress intensity factor (SIF) is considered to be the main parameter of the linear fracture mechanics. George Irwin formulates three different fracture modes (deformation) at the crack tip – opening, sliding and tearing shown at Figure 1. When it comes to determining the stress intensity factors (SIF) analytically, there are some closed form solutions. Where the required parameters to calculate the SIF are the geometry of the crack and the remote loading. SIF for the slanted through thickness crack in an infinite plate are given by:

$$\sigma_{ij} = -\frac{K}{\sqrt{r}} f_{ij}(\theta) \tag{5}$$

$$\varepsilon_{ij} = -\frac{K}{\sqrt{r}} g_{ij}(\theta) \tag{6}$$

Where K is the stress-intensity factor, r and θ arecoordinates of a polar coordinate system. These equations apply to any of the three fracture modes. For a Mode I crack, the stress field is given as:

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}}\cos(\frac{\theta}{2})\left(1 - \sin\left(\frac{\theta}{2}\right)\sin(\frac{3\theta}{2})\right) \tag{7}$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}\cos(\frac{\theta}{2})\left(1 + \sin\left(\frac{\theta}{2}\right)\sin(\frac{3\theta}{2})\right) \tag{8}$$

$$\sigma_{xy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos(\frac{3\theta}{2}) \tag{9}$$

Energy-Release Rate

The energy-release rate is based on the energy criterion for fracture proposed by Griffith and further development by Irwin. In this approach, the crack growth occurs when the energy available for crack growth is sufficient to overcome the resistance of the material (Anderson,2005).The energy-release rate G is defined in elastic materials as the rate of change of potential energy released from a structure when a crack opens. For example, the following Figure. 5 shown a crack of length 2a in a large elastic body with modulus E subject to a tensile stress (σ).

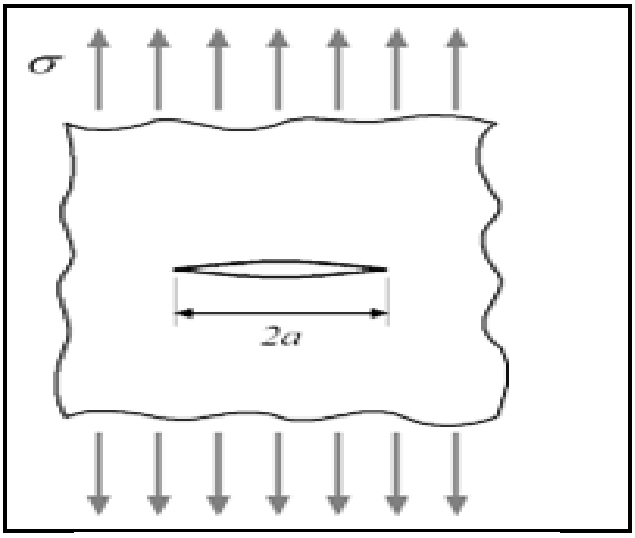

Figure 5. 2-D large plate with a 2a long crack

The energy-release rate is given by:

$$G = \frac{\pi\sigma^2 a}{E} \tag{10}$$

J- Integral

J-Integral is one of the most widely accepted parameters for elastic-plastic fracture mechanics. The J-Integral is defined as follows (Rice,1968):

$$J = \lim_{\Gamma \to 0} \int_{\Gamma_0} \left[(w + T)\delta_{ij} - \sigma_{ij}\frac{\partial U_j}{\partial X_i}\right] n_i \, d\Gamma \tag{11}$$

Where W is the strain energy density, T is the kinematic energy density, σij represents the stresses, U is the displacement vector, and Γ is the contour over which the integration is carried out.For a crack in a linear elastic material, the J-integral represents the energy-release rate. Also, the amplitudes of the crack-tip stress and deformation fields are characterized by the J-integral for a crack in a nonlinear elastic material.

Elastic Plastic Fracture Mechanics

Fracture/crack growth is a phenomenon in which two surfaces are separated from each other, or material is progressively damaged under external loading. The material in front of a propagating crack will be highly strained and all the points of the curve will be represented. Three different zones can be separated around the crack tip.

- The linear elastic zone: in this crack zone the stress is so low that the material behaves in a linear elastic way.
- The plastic zone: in this zone the stress – strain relation is non linear and the stress increases or at least remains constant as the strain increases
- The fracture zone: in this zone the stress decreases as the strain increases

The following parameter C*-integral characterizes the crack tip conditions in homogenous materials undergoing a secondary (steady-state) creep deformation (Riedel, 1980, Riedel, 1981) is widely used in fracture mechanics analysis:

$$C^* = \int_A \left[\sigma_{ij}\frac{\partial \dot{U}_j}{\partial X_i} - \dot{w}\,\delta_{ij}\right]\frac{\partial q}{\partial X_i}\,\mathrm{dA} \qquad (12)$$

Where σij is the stress tensor, $\dot{U}_j$ is the displacement rate vector, $\dot{w}$ is the strain energy rate density, δ_{ij} is the Kronecker delta, X_i is the coordinate axis, and q is the crack-extension vector.

Modeling Creep Behavior

Creep is a rate dependent material nonlinearity in which the material continues to deform under a constant load ANSYS (2016). Creep is highly time dependent and it displays its effects over a long time. Creep has 3 stages: Primary, Secondary, and Tertiary creep as depicted in Fig 6. Descriptively, these stages areassociated with transient, steady state, and accelerating creep, respectively Betten(2002).The three phases of creep are described as follows:

- First Stage: It is considered by the work-hardening behavior of the material. It makes the material more difficult to deform under strain.
- Second Stage: Creep in this stage is steady state. In this stage, there is a balance work-hardening and thermal-softening which causes a constant and steady creep. (minimum creep rate)
- Third Stage: In this stage, creep accelerates due to the accumulating damage which will cause rupture at the end of the stage.

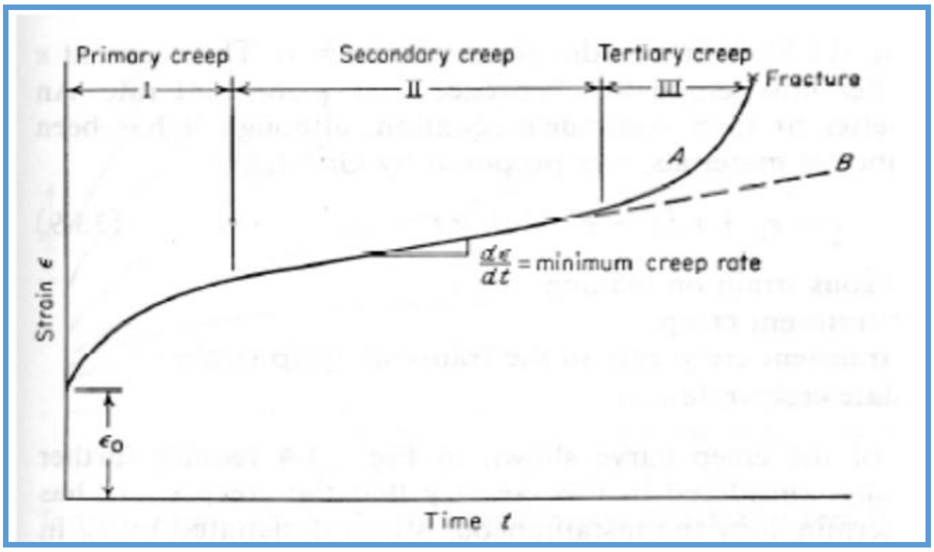

Figure 6. Creep curve typic under moderate load (1) and intense loading (2)
(Dieter, 1988; Ashby a& Jones, 1991)

Strain as a function of time due to constant stress over an extended period for a viscoelastic material. In the initial stage, or primary creep, the strain rate is relatively high, but slows with increasing time. This is due to work hardening. The strain rate eventually reaches a minimum and becomes near constant. This is due to the balance between work hardening and annealing (thermal softening). This stage is known as secondary or steady-state creep. This stage is the most understood. The characterized "creep strain rate" typically refers to the rate in this secondary stage. Stress dependence of this rate depends on the creep mechanism. In tertiary creep, the strain rate exponentially increases with stress because of necking phenomena.

General Creep Equation

The general creep equation is described as follows. $\dot{\varepsilon}_{cr}$ follows an Arrhenius type Law.

$$\dot{\varepsilon}_{cr} = \frac{C\sigma^{m}}{d^{b}} e^{-\frac{Q}{kT}} \tag{13}$$

Where $\dot{\varepsilon}_{cr}$ is the creep strain, C is a constant dependent on the material and the particular creep mechanism, m and b are exponents dependent on the creep mechanism, Q(J/mol) is the activation energy of the creep mechanism, σ is the applied stress, d is the grain size of the material, k(8.314 J/mol.K) is Boltzmann's constant, and T(Kelvin)is the absolute temperature.

At high stresses (relative to the shear modulus), creep is controlled by the movement of dislocations. For dislocation creep, Q = Q(self-diffusion), m = 4-6, and b = 0. Therefore, dislocation creep has a strong dependence on the applied stress and no grain size dependence In the Nabarro-Herring creep, atoms diffuse through the lattice causing grains to elongate along the stress axis; k is related to the diffusion coefficient of atoms through the lattice, Q = Q(self-diffusion), m = 1, and b = 2. This type of creep called (diffusion creep). Creep can be formulated as a function of several equations such as:

Primary Creep Equations

Traditionally, the transient creep observed in the primary creep stage is accounted for using Andrade's law for primary creep of the form Eq. (14).

$$\varepsilon_{cr} = \varepsilon_0 + At^{1/q} \tag{14}$$

Where: ε_0 is instantaneous creep, $At^{1/q}$ is a coefficient, and q is a unitless exponent. The constant q has been experimentally observed to be 3 for most materials (Andrade, 1910; Dvorkin,1994). A number of authors have attempted to disprove the uniformity of this constant with limited success (Nabarro, 1997). A more advantageous formulation for primary creep is based around a power law of the simple form Eq. (15):

$$\varepsilon_{cr} = A\sigma^{n}t^{m} \tag{15}$$

When stress is assumed to be constant, a primary creep time-hardening strain rate equation can be developed of the form Eq. (16):

$$\dot{\varepsilon}_{cr} = Am\sigma^{n}t^{m-1} \tag{16}$$

Where:σ (MPa) is the applied stress and A (MPa –nhr -m), n, and m are temperature-dependent primary creep constants (Pantelakis, 1983).

Secondary Creep Equations

The classical approach to modeling the secondary creep behavior for materials is the Norton power law Eq. (17) for secondary creep (Norton, 1929)

$$\dot{\varepsilon}_{cr} = A\sigma_{eq}^{n} \tag{17}$$

Where:A and n are the secondary creep constants, and σ_{eq} is an equivalent stress. ANSYS software give us a multitude formulation of secondary creep such as:

- Generalized Garofalo (Secandary stage):

$$\dot{\varepsilon}_{cr} = \{C_1 \sigma^{C_2} [(C_3 + 1)\varepsilon_{cr}]^{C_3}\}^{1/(C_3+1)} e^{(-C_4/T)} \tag{18}$$

- Time Hardening (primary +secondary models):

$$\dot{\varepsilon}_{cr} = \frac{C_1 \sigma^{C_2} t^{(C_3+1)} e^{-\frac{C_4}{T}}}{C_3 + 1} + C_5 \sigma^{C_6} t e^{(-C_7/T)/} \tag{19}$$

Finite Element Modeling of Creep

The Finite Element Analysis (FEA) method is a powerful computational technique for approximate solutions. ANSYS is engineering software, worldwide used by researchers for simulation. It develops general purpose of finite element analysis. To create the finite element model in ANSYS there are multiple tasks that have to be completed for the model to run properly. Models can be created using command prompt line input or the Graphical User Interface (GUI).

- The first step is to modeling the finite element structure by choosing an appropriate item to the type of analysis to be performed. As part of this work, we limited ourselves to address the problem in two-dimensional finite element used the element (PLANE 183) see Figs.7-8 bellow. In this model, the number of elements structural is approximately 177 elements.
- The 2nd step is divided into three, namely:

- Step pre-processor: who is to introduce the geometry of the problem, material properties and Boundary conditions.
- While in the solution phase, we choose the type of analysis that must be performed.
- Finally, the results of the completed solution are observed in the post-processing step.

In order to modeling the creep behavior, we have introduced the model equation called (***Modified Time hardening model***) see Eq. (20) bellow. It is considered that the material is isotropic, and the basic solution method used is that of Newton-Raphson

$$\varepsilon_{cr} = C_1 \sigma^{C_2} t^{C_3} e^{(-C_4/T)} \tag{20}$$

With: ε_{cr}: Creep strain, σ : Equivalent stress, t: Time at end of sub – steps, C1, C2, C3, C4 : Creep parameters : C1 = 41.10-8 1/s, C2 = 1.48, C3 = -0.63, C4= Q/K=0, T : Temperature in Kelvin

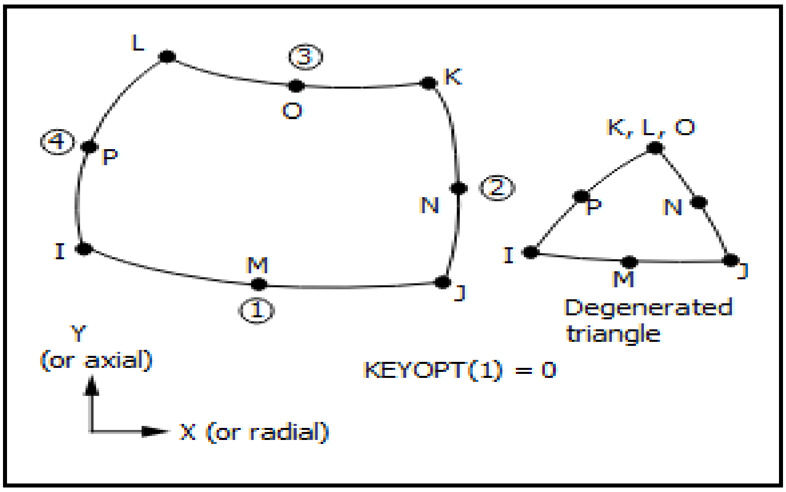

Figure. 7. PLANE 183 Geometry (ANSYS technology guide 2016)

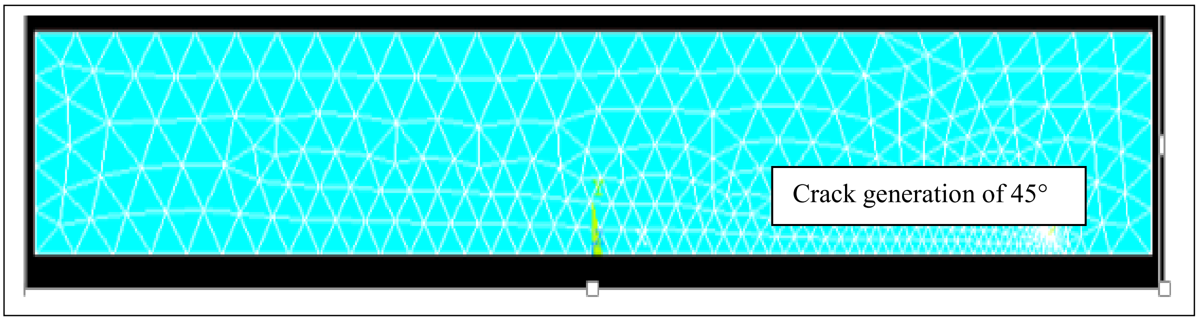

Figure 8. Beam cross section modeling

Results and Discussion

In order to conduct time-dependent numerical modeling, the finite element code ANSYS occurs the different results shown in the following figures. This Item illustrate a time-dependent behaviour of beam with crack opening subjected to a constant load. The following Figures 9, Figure 10, Figure 11, illustrate the stress contour plot, $(\boldsymbol{\sigma}_{xx})$, $(\boldsymbol{\sigma}_{yy})$ and the shear stress $(\boldsymbol{\tau}_{xy})$ of mode I obtained according to the equation 1 above and simulation resluts during 12 hours of constant loading.

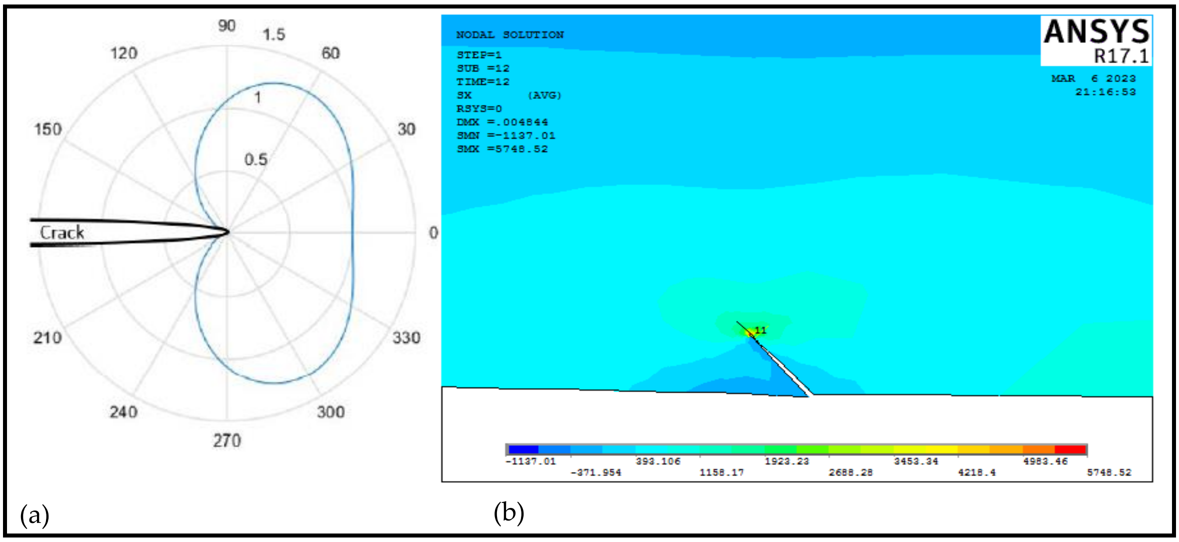

Figure 9. Contour plot of σ_{xx} stress components from Eq. 1 (a) and numericals results simulation of mode I

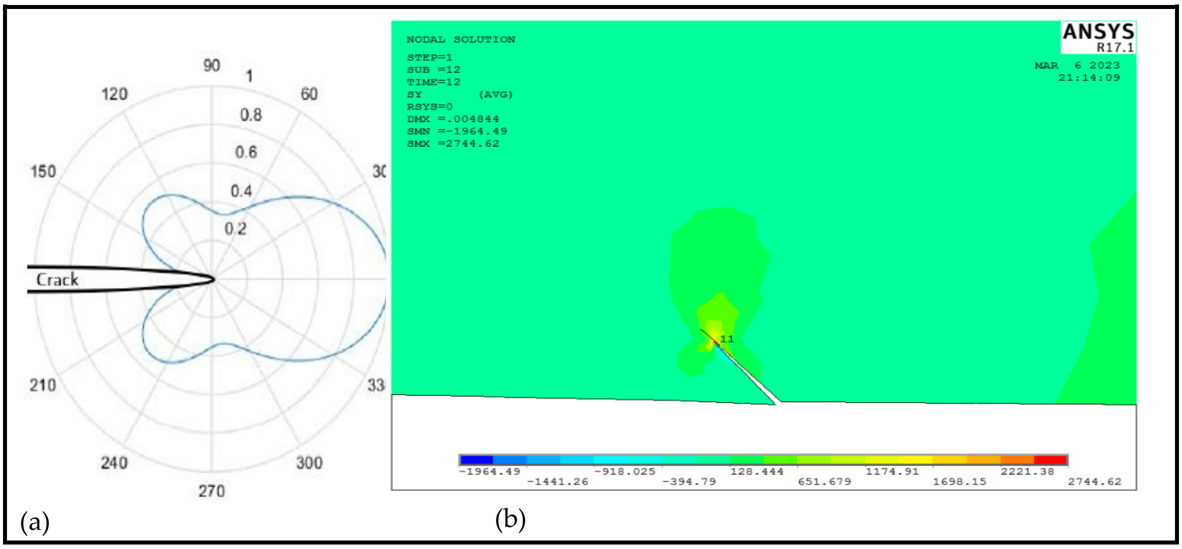

Figure 10. Contour plot of σ_{yy} stress components from Eq. 1 (a) and numericals results simulation of mode II

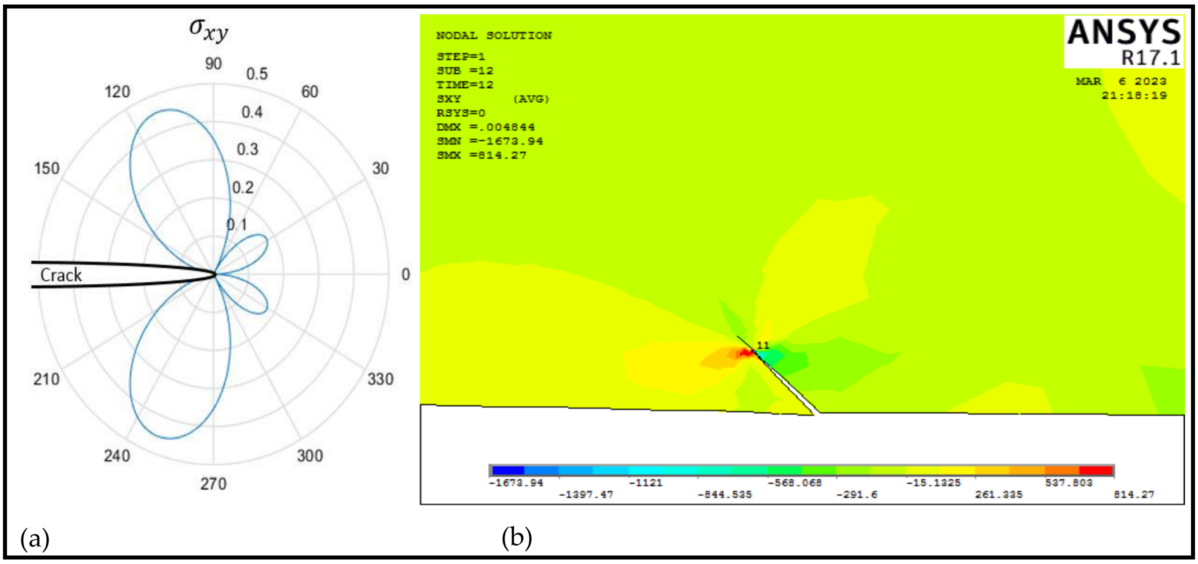

Figure 11. Contour plot of τ_{xy} Shear stress components from Eq. 1 and numericals results simulation of mode I

The following Figure 12 and Figure 13 illustrates the contour plot Creep Strain $(\varepsilon_X^{cr}, \varepsilon_Y^{cr})$ respectively obtained by the implemation of the creep equation 5 above, in the programme ansys softwar. Figure 14 illustrate the creep curve under different loading values of stress, such us 10 MPa; 25 MPa and 75 MPa respectively after 720mn (12hours).

According the figure, we can say than the creep strain curves are characterized by three steeps namely:

- 1st steep: t= 0 days: we note an initial strain (ε_0),
- 2nd steep: 0 days < t < 240 min : The Creep strain increase rapidly
- 3rd steep: 240 min < t < 720 min: The Creep strain increase slightly

From these results of creep curves obtained, we can be seen that the creep strains rate reaches 30% after 250 min. At 720min from loading, these deformations reach 6 times the initial strain. In terms of results of the creep behaviour simulation, the curves obtained according to the time hardening model correlate approximately with the experimental creep curve illustrated in figure 4 above. The difficulties encountered in the experimental test is how to determine the stress intensity factors in order to be able to compare them with the numerical results. The mains of these papers are to cite the creep behaviour and crack opening modelling with ANSYS softwar. Creep curves strain and shear creep curves numerical results of the different load values are show's in the above figures. In terms of perspective, we intend to compare the numerical results to the experimental results.

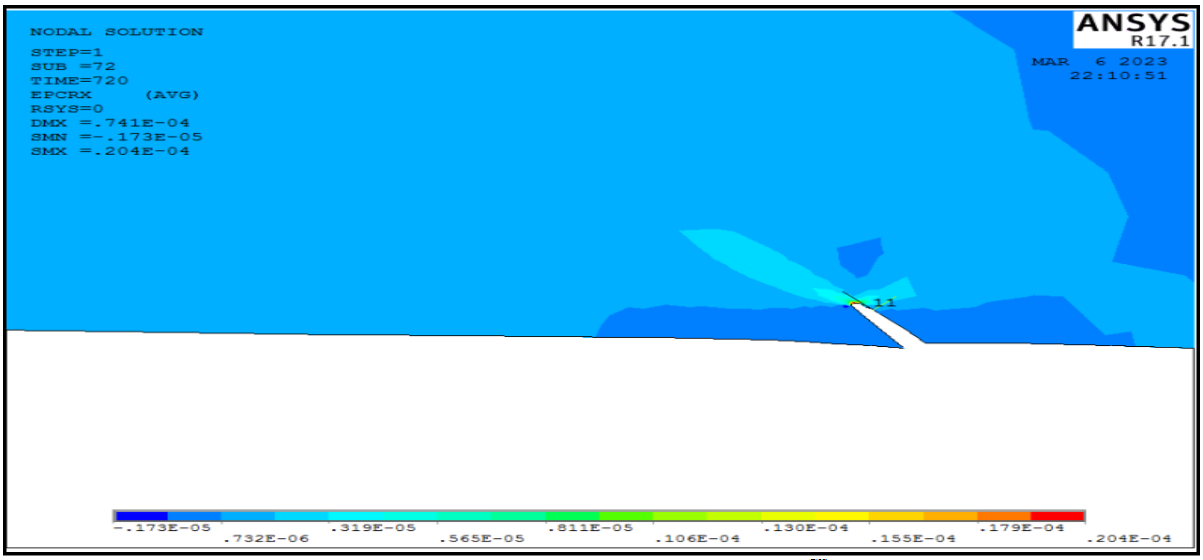

Figure 12. Contour plot of creep strain ε_x^{cr}

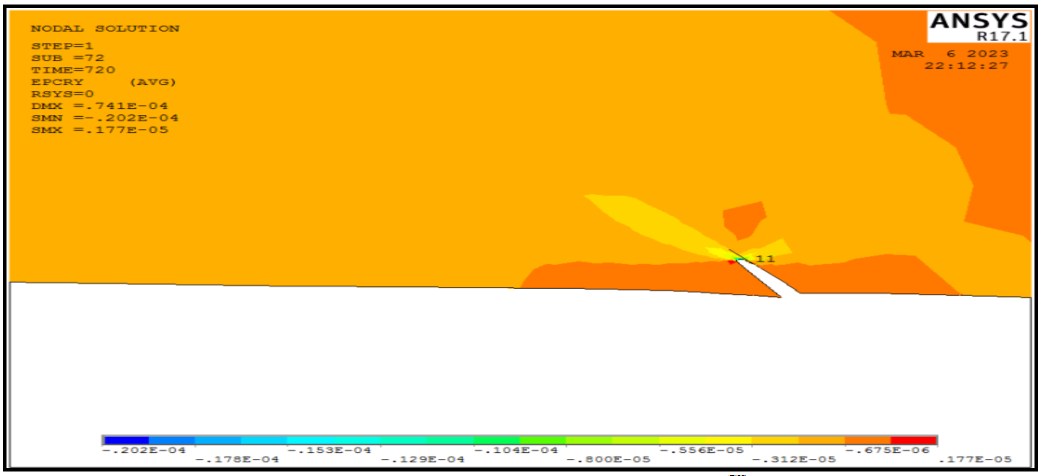

Figure 13. Contour plot of creep strain ε_Y^{cr}

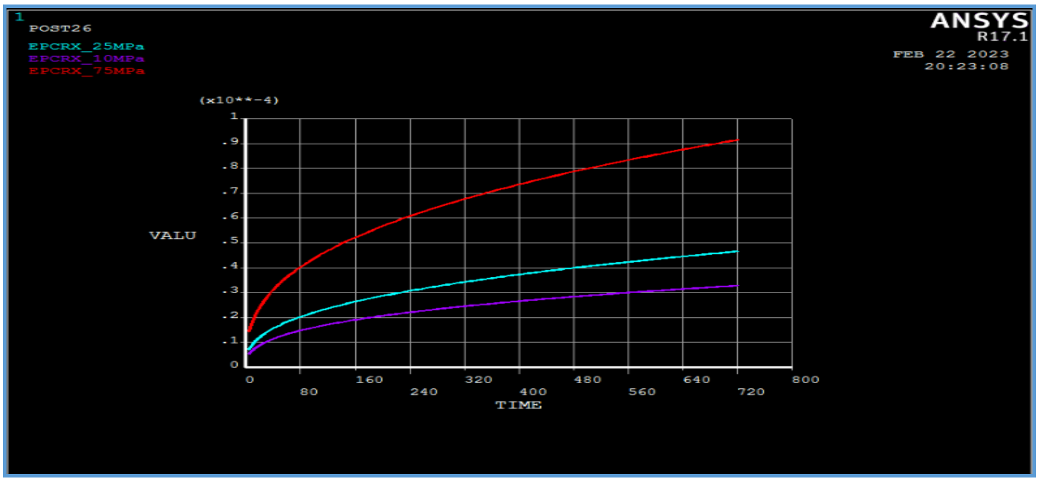

Figure 14**.** Creep curve (ε_{cr}) under different constant load after 720mn

Conclusion

A fracture analysis is a combination of stress analysis and fracture mechanics para calculation. The stress analysis is a standard linear elastic or nonlinear elastic plastic analysis. The work presented in this paper is a part of a research program, aimed at developing a model fracture mechanical suitable for analysing the micro and macro – fracture in the reinforced concrete beam and similar materials. In terms of conclusion, the creep behavior simulation, and the creep curves obtained according to the time hardening model correlate approximately with the experimental creep curve illustrated in figure 4 above. The difficulties encountered in the experimental test are how to determine the stress intensity factors in order to be able to compare them with the numerical results. The mains of these papers are to cite the creep behaviour and crack opening modelling with ANSYS software. Creep curves strain and shear creep curves numerical results of the different load values are show’s in the above figures. in terms of perspective, we intend to compare the numerical results to the experimental results. The difficulties encountered in the experimental test is how to determine the stress intensity factors in order to be able to compare them with the numerical results. The mains of these papers are to cite the creep behaviour and crack opening modelling with ANSYS softwar. Creep curves strain and shear creep curves numerical results of the different load values are show’s in the above figures. In terms of perspective, we intend to compare the numerical results to the experimental results.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Notes

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Author Information

Kamel Ghouilem
University Mouloud MAMMERI of Tizi - Ouzou
Ummto, BP 17 RP, Tizi-Ouzou 15000, Algeria
E-mail: kamel.ghouilem@ummto.dz

Atlaoui Djamal
University Mouloud MAMMERI of Tizi - Ouzou
Ummto, BP 17 RP, Tizi-Ouzou 15000, Algeria

Mehaddene Rachid
University Mouloud MAMMERI of Tizi - Ouzou
Ummto, BP 17 RP, Tizi-Ouzou 15000, Algeria

Merakeb Seddik
University Mouloud MAMMERI of Tizi - Ouzou
Ummto, BP 17 RP, Tizi-Ouzou 15000, Algeria

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