A STUDY OF THE EFFECT OF IMPACT LOADING ON DSIFs AND CRACK PROPAGATION IN PLATE

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Abstract

In this work, a study of the effect of impact loading on dynamic crack propagation in thin and isotropic thick plates for two types material, stainless steel and aluminum, are investigated analytically and numerically to give a complete study of 3D crack growth of simple supported plate with internal crack at the center of plate. The dynamic stress intensity factor (DSIFs), velocity of dynamic crack propagation and the deep of crack normal to the crack face for different angles from crack tip have been calculated when Contact of a cylindrical impactor on isotopic plates is considered, to support the analytical result for DSIFs with a numerical package result (Ansys-10). This based on finite element method used to investigate the stress and the values of dynamic stress intensity factors at the crack tip by full transient dynamic Analysis using 3D (element, Solid-90). The results from Airy stress function method gives good agreement with the results of Ansys for long time duration in impact loading while the energy method is agreement with the Ansys package for some time and then become limited. In addition, the DSIFs and crack propagation velocity are increasing with angel from crack tip and velocity impact increasing.

Keywords: Dynamic Stress Intensity Factor, Finite Element Analysis, velocity impact, Crack angle, Crack Propagation.

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دراسة تأثير حمل الصدمة على معامل شدة الاجهاد الديناميكي

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الخلاصة

تم اجراء تحليل و دراسة تأثير حمل الصدمة على حركة انتشار الشق في الصفائح الرقيقة والسميكة الايزوتروبية ولنوعين من المعادن الحديد المقاوم للصدأ و الالمنيوم نظريا وعدديا لاعطاء دراسة في حركة نمو الشق في الابعاد الثلاث لصفائح متشققة في حالة اسناد بسيط.تم حساب معامل شدة الاجهاد الديناميكي، سرعة الحركة لانتشار الشق مع اختلاف العمق العمودي للشق بالنسبة لوجه الشق واختلاف الزوايا من طرف الشق عند تماس اسطوانة صادمة لصفائح ايزوتروبية، تم دعم النتائج التحليلية لمعامل شدة الاجهاد الديناميكي مع رزمة نتائج عددية بالاعتماد على نظرية العناصر المحددة لتحقيق الاجهاد ومعامل شدة الاجهاد الديناميكي عند طرف الشق بالتحليل الديناميكي الانتقالي الكامل مستخدما عنصر ثلاثي الابعاد. النتائج التي تم الحصول عليها كانت متوافقة بشكل جيد بين نظرية ايري للاجهاد مع النتائج العددية طول فترة الركود الزمنية للصدمة. بينما التطابق بين نظرية الطاقة والنتائج العددية كان لفترة من زمن الصدمة واصبحت محددة. بالاضافة لذلك تم ملاحظة ان معامل شدة الاجهاد الحركي وسرعة انتشار الشق يزداد بزيادة الزوايا من طرف الشق وسرعة الصدمة.

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Nomenclature

A	plate width
B	plate length
D	flexural rigidity of the plate
DSIF	dynamic Stress intensity factor
E_1, E_2	young's modulus of steel cylinder and the plate
G_{ic}	critical strain energy
M	equivalent mass
P_o	peak overload observed when $t = zero$
$P_{(t)}$	total instantaneous over load
R	radius of the steel cylindrical
S	velocity of impacter
$Thc.$	plate thickness
a_o	crack deep
c^c	correct factor
c_o	length of crack
$k_{1,2}$	effect stiffness
m,n	integer numbers from 1 to ∞.
n	parameter depended on properties of material
r_p	readies of plastic zone
r_{pC}	critical plastic zone
u, v	the length and width of the equivalent area
σ_{ys}	yield stress
$\sigma_{1,2}$	principles stresses
β	property characterizing take fixing $=0.23$
v_1, v_2	Poisson ratio for the steel cylinder and the plate
α	angle of crack front
α_o	decay factor, $\alpha_o = 0.2$ (Mario, 1980).
α_p	principle angle of crack front
ξ, η	location of load

Introduction

One of the fundamental requirements of any engineering structure is that it should not fail in service and much of the skill of the structural engineer lies in recognizing that there are several possible modes of failure and in guarding against them in his design (Knott, 1976).

In the recent years, the important increased to know the remaining service lifetime of mechanical parts that have a crack in it before that part retires from service. This interest increased after catastrophic failures in ships and airplane structures. In order to calculate the stresses around the crack tip, three common methods are introduced for calculating the crack propagation and stress intensity factor such as

a- *Stress intensity factors* (K_I, K_{II}, and K_{III}) associated with the three basic modes of fracture.

b- *J-integral*, this may be defined as a path-independent line integral that measures the strength of the singular stresses and strains near a crack tip.

c- *Energy release rate* (G), which represents the amount of work associated with a crack opening or closure.

Impact Loading Model

i- Contact loading

When the plates impacted in their middle with steel cylindrical of Radius (*R*) = 10 *mm*, weight = 75 *gm*, *E* = 206.843 G. pa and Poisson's ratio = 0.3 at various impact velocities (8 *m/s*, 4 *m/s*, 2 *m/s* and 1 *m/s*). The static force caused from impact was calculated by the following Eq.(1) (Zukas,1982).

$$P_o = \left(\frac{4\sqrt{R}}{3\left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right)} \right)^{2/5} \left(\frac{5(v)^2}{4M} \right)^{3/5} \tag{1}$$

Since the force that resulted from impact is now calculated, the stresses due to impact can be found by dividing it over the area of the contact of the cylinder to the plate in order to reduce the time of the numerical calculation. (Timoshenko,1959)

ii- Loading from impact velocity

The total response of materials and structures to intense impulsive loading is quite complex because a effective time is very short (Zukas,1982). The empirical form used to describe the impact load as $p_{(t)}$ in Eq. (2). Where the major part of energy is transmitted at contact time divided to two sections, first over load (positive phase) decreases to zero and second goes below zero (negative phase) within a short time as shown in **Figure (1)** could be taken as (Dharni,2005) Eq. (2) represents the load on the plate from impacted at any time but not all loads in plate at this time. For calculated the total load in the plate using multiple-segment of trapezoidal rule for divided the time for equal segment in positive phase only (Steven,1990).

$$P_{(t)} = po \, (1 - t / t_d) \exp(-\alpha_o t / t_d) \tag{2}$$

iii- duration impact and stress in plate

The maximum load $P_{(t)}$ occurs at a time ($td = 0.5 t_o$) where (t_o) is the impact duration as shown in Eqs. (3), and (4), (Zukas,1982).

$$t_o = 2.94 \left(\frac{5}{4 \, Mns^{1/2}} \right)^{2/5} \tag{3}$$

$$t_d = 0.5 \, t_o \tag{4}$$

The load from impact for any time ($0 \le t \le t_d$) obtained from substitution Eqs. (1) and (4) into Eq. (2) gives the final form to calculated the loading with time Eq.(5).

$$P_{(t)} = (n)^{\frac{2}{5}} \left(\frac{5(s)^2}{4M} \right)^{\frac{3}{5}} \left[1 - \frac{t}{1.47\left(\dfrac{5}{\sqrt{4Mns}} \right)^{\frac{2}{5}}} \right] \exp\left(\frac{-0.2t}{1.47\left(\dfrac{5}{\sqrt{4Mns}} \right)^{\frac{2}{5}}} \right) \tag{5}$$

The in plane stresses that caused from impact must be calculated in order to apply it on the crack faces. The following equations Eqs. (6), (7) and (8)) are used in order to calculate the σ_x, σ_y and τ_{xy} that caused in the plate due to impact (Bairagi,1986).

$$\sigma(x)_{x,y,t} = -E \cdot thc \left[-\frac{16 po\left(1 - \dfrac{t}{td}\right) e^{\left(\frac{0.2t}{td}\right)} Smn \cdot \sin\left(\dfrac{mx\pi}{A}\right) m^2 \sin\left(\dfrac{ny\pi}{B}\right)}{u^2 \pi^4 D\, A^2 mn\left[\dfrac{m^2}{A^2} + \dfrac{n^2}{B^2}\right]^2} - \frac{16 \cdot v \cdot po\left(1 - \dfrac{t}{td}\right) e^{\left(\frac{0.2t}{td}\right)} Smn \cdot \sin\left(\dfrac{mx\pi}{A}\right) \sin\left(\dfrac{ny\pi}{B}\right) n^2}{u^2 \pi^4 D\, B^2 mn\left[\dfrac{m^2}{A^2} + \dfrac{n^2}{B^2}\right]^2} \right] \Bigg/ \left(1 - v^2\right) \tag{6}$$

$$\sigma(y)_{x,y,t} = -E \cdot thc \left[-\frac{16 po\left(1 - \dfrac{t}{td}\right) e^{\left(\frac{0.2t}{td}\right)} Smn \cdot \sin\left(\dfrac{mx\pi}{A}\right) \sin\left(\dfrac{ny\pi}{B}\right) n^2}{u^2 \pi^4 D\, B^2 mn\left[\dfrac{m^2}{A^2} + \dfrac{n^2}{B^2}\right]^2} - \frac{16 \cdot v \cdot po\left(1 - \dfrac{t}{td}\right) e^{\left(\frac{0.2t}{td}\right)} Smn \cdot \sin\left(\dfrac{mx\pi}{A}\right) m^2 \sin\left(\dfrac{ny\pi}{B}\right)}{u^2 \pi^4 D\, A^2 mn\left[\dfrac{m^2}{A^2} + \dfrac{n^2}{B^2}\right]^2} \right] \Bigg/ \left(1 - v^2\right) \tag{7}$$

$$\tau(xy)_{x,y,t} = -16 \cdot E \cdot thc \left[-\frac{po\left(1 - \dfrac{t}{td}\right) e^{\left(\frac{0.2t}{td}\right)} Smn \cdot \cos\left(\dfrac{mx\pi}{A}\right) m \cdot \cos\left(\dfrac{ny\pi}{B}\right) n}{(1+v)u^2 \pi^4 DABmn\left[\dfrac{m^2}{A^2} + \dfrac{n^2}{B^2}\right]^2} \right] \tag{8}$$

Where

$$Smn = \sin\left(\frac{m\pi\xi}{A}\right) \cdot \sin\left(\frac{n\pi\eta}{B}\right) \cdot \sin\left(\frac{mu\pi}{2A}\right) \cdot \sin\left(\frac{nu\pi}{2B}\right)$$

Results And Discussion

Since the in plane stresses due to low velocity impact are known, they are resolved into components because the crack angle sometimes is oblique. One of the components is perpendicular to the crack face while the other is parallel to it. The parallel component is equal to zero, leading the *KII* value due to impact is zero, while the perpendicular component causes the *KI* mode causing an increase in the resultant of *KI* mode that happens in the plate at the crack tip. **Figure (2)** and **Figure (3)** shows the impact force distribution in the center of plate and crack front respectively , for Stainless Steel plate of dimensions 100×100×4.5*mm* obtained numerically by ANSYS-10.

The Dsifs Evaluation

The (KI, KII, KIII) are a constant, which gives the magnitude of the elastic stress field; there are called the stress intensity factors. Dimensional analysis chose that KI must be linearly related to stress and directly related to the square root of a characteristic length. When a higher initial KI means a higher initial crack driving force. The SIF is divided to the two types depended on the crack growth. When the amount of unstable crack growth is very limited, the dynamic effect on stress intensity can be neglected. In this case, the dynamic stress intensity factor mast be calculated $KI^{dynamic}$ (Wanhill,1989).

There are three types of crack modes, depending on the loading condition (David,1989), the *opening mode* (D*KI*), the *shearing mode* (D*KII*), and the *tearing mode* (D*KIII*), The first mode is the most widely mode that occurs, while the second and the third modes do not occur individually, they occur with combination with mode *I*. The third mode was neglected in this study because of its small value that can be neglected comparing to the values of the first and the second modes.

Eq.(9) is finely form to calculates the magnitude of DSIFs on mode *I* .

$$KI(t) = c^c \sigma_{normal} \sqrt{co\pi} \frac{\left(\sin^2 \alpha + \dfrac{ao^2}{co^2} \cos^2 \alpha \right)^{\frac{1}{4}}}{\dfrac{3\pi}{8} + \dfrac{\pi}{8} * \dfrac{ao^2}{co^2}} \tag{9}$$

Where

$$\sigma_{normal} = \sigma_{1n} = \sigma_1 \cos^2 \alpha_p + \sigma_2 \cos \alpha_p \sin \alpha_p$$

Figure (4) and **Figure (5)** shows the stress distribution in the crack front and tip respectively ,plate of dimensions 100×100×4.5*mm* made from Stainless Steel obtained numerically by ANSYS-10.

Using Eqs.(6-9) to calculated the principle stresses and DSIFs. With this way, the DSIFs were calculated for both the Stainless Steel and Aluminum plates at variable crack angle and variable aspect ratios. **Figure (6-9)** shows the DSIFs (D*KI*) and their relation with the crack angle and duration time for a plate of 100×100×4.5*mm,crack 7×2 mm* in dimensions and made from Stainless Steel. **Figure (10)** and **Figure (11)** shows the behavior of D*KI* with the increase in deep of crack and aspect ratio when the impact velocity is *1m/s* .

Crack Tip Plasticity (Dugdale Model).

Dugdual's analysis assumes that all plastic deformation concentrates in a strip in front of the crack. This type of behavior does indeed occur for a number of materials, but certainly not for all. For applied Dugdale theory Eq.(10), assume of elastic-perfectly plastic behavior (Giacomin,1996)

$$r_p = \frac{\pi}{8} \left(\frac{KI}{\sigma_{YS}} \right)^2 \tag{10}$$

If $KI_C = KI$ then $r_{pc} = \frac{\pi}{8} \left(\frac{KI_c}{\sigma_{YS}} \right)^2$; If $r_p \geq r_{pc}$ the crack is propagation

A care must be taken in calculating readies of plastic zone value for different impact velocity for determiner the area of crack propagation. **Figure (12-15)** shows the plastic zone animation relation with the aspect ratio and duration time for a plate of $100{\times}100{\times}4.5mm, crack\ 7{\times}2\ mm$ in dimensions and made from Stainless Steel.

Model Of Crack Growth

Fracture mechanics deals with the study of how a crack or flaw in a structure propagates under applied loads. It involves correlating analytical predictions of crack propagation and failure with experimental results or numerical solution. The analytical predictions are made by calculating fracture parameters such as stress intensity factors in the crack region, which was used to estimate crack growth rate. Typically, the crack length increases with each application of some cyclic load, such as cabin pressurization-depressurization in an airplane. Further, environmental conditions such as temperature, extensive exposure, or dynamic loading to irradiation can affect the fracture property of a given material (Ansys,2005).

Some typical fracture growth may evolve are:
i- Static growth, this state happens in equilibrium condition of crack propagation (stably, slowly, controlled).
ii- Quasi static growth, this state happens without kinetic-energy production, the potential energy will gradually approach zero since the fractured pieces obviously are free of stress.
iii- Dynamic growth, this state happens with kinetic-energy production. The crack driving force is large that in quasi-static.

The dynamic crack growth may be considered in terms of an energy balance. After initiation of energy which increases during crack growth. By the time, the crack has reached a length a_i i.e. the total excess energy has converted to kinetic energy in crack tip (Wanhill,1989).

Simple expression for the stored kinetic energy is obtainable from the opening displacement of the crack flanks as shown in Eq. (11)

Get $\quad \dot{a} = \sqrt{\frac{E}{\rho}} \left(1 - \frac{ao}{ai} \right) \left(\frac{\sigma_{normal}}{\dot{\sigma}_{normal}} \right)$ \tag{11}

Where

$$\dot{\sigma}_{normal} = \frac{\partial}{\partial t} \left(\sigma_1 \cos^2 \alpha_p + \sigma_2 \cos \alpha_p \sin \alpha_p \right)$$

In this section a comparison results obtained from Eq. (11), with the reference (Sheng,2004), which is illustrated in the appendix A. Applied eq. (A-4) for one state only where this equation

depended on the energy release rate theory. When a stainless steel plate (100x100x4.5mm), is impacted by steel cylinder at velocity 2 and 8 m/s the crack   velocity calculated by Eq. (A-4) see **Figure (16)**, and compare the result with Eq. (11). We noted the good agreement and the average rate error is decreasing when the velocity impact are increasing. **Figure (17-19),** and **Figure (20)** show the crack velocity relation with the aspect ratio and duration time for a plate of 100×100×4.5*mm,crack 7×2 mm* in dimensions and made from Stainless Steel.

ENERGY METHOD

When a plate element is acted by external loading, the internal fibers of the material body absorb energy in the form of the potential energy and as a result, the body shows deformed shape externally. On removal of the loads, the stored potential energy is converted to kinetic energy so that the body wholly or partially regains its original position or shape. The absorbed potential energy of the internal forces stored within the structural body is often termed as strain energy (SE) or U , and its magnitude is equal to the work done due to the internal forces (in the opposite sense). The potential of the external force V is defined as the work done by the external force (in the opposite sense) during deformation between the initial and final position. The dynamic kinetic energy DKE add to the plate from impacter is, $(\frac{1}{2} \cdot mass_{impacter} \cdot st^2)$ where the st is velocity of impacter during the time of impact. The total energy in plate Π_1 is give by (Bairagi,1986) Eq.(12).

$$\Pi_1 = U + V + DKE \tag{12}$$

or

$$\Pi_1 = \frac{1}{8} DW_{mn}{}^2 AB\left(\alpha_m{}^2 + \beta_n{}^2\right)T(t)^2 - \frac{4ABq(t)}{mn\pi^2}W_{mn}T(t) + \frac{1}{2}m_{imp.}s(t)^2 \tag{13}$$

By impacting a flat plate when diameter of impacter is large compared to its thickness in a direction perpendicular to its surface, a plane wave can be generated. Before the arrival of release waves from the edges of the plate, the center portion is in a confined state of one-dimensional or uniaxial strain (Loya,2006). The total strain energy for uniaxial strain Eq. (14)

$$\Pi_2 = \frac{1}{2}\sigma_{impacter}{}^2 \cdot \frac{(1+v)(1-2v)}{E(1-v)} \tag{14}$$

The total strain energy in Eq. (13) sum as energy in Eq. (14) i.e.($\Pi_1 = \Pi_2$) , solving for calculated normal stress.

The energy method is very important for comparison, because depended it on summations of all energy inter the plate from impact, solving Eq. (13), and Eq.(14) for calculated the normal stress on crack faces, and compared with result from airy equation for st. steel plates (100x100x4.5mm) at difference velocity impact. Draw the relation for this tow method, these results is display in **Figure (21-25)** noted the energy in plates are given good agreement with the airy method but not for all time, because the energy translated from impact to plate not continues to all time, but it reach to constant value. In addition, noted when the impact velocity is increasing the result from energy method is increasing the exactitude.

Conclusions

The major observation and conclusion from study dynamic analysis, simply supported stainless steel and aluminum cracked plated, under various impact velocities by cylindrical steel are listed as follow:

1. The results of DSIFs and velocity of crack propagation obtained by the building of programs by FORTRAN bower station-90, for impact loading. These results have been obtained by two different ways. First by using classical method, and secondly by energy method. These two ways is gives the some results with percentage error is lowest than (15%).
2. In the case of internal crack the values of dynamic stress intensity factors (DSIFs), is depended on the depth of crack and angle of local (alpha).
3. The duration of time impact is decreasing when the velocity of impact is increasing, and when the young modulus is increasing the duration time decreasing i.e. the duration of time depended on the properties of material.
4. The crack propagation activity at location when maximum DSIFs along the crack front. Also the plastic area is large then compared with a critical plastic area (Dugdale model).
5. The velocity of crack propagation in steel is larger than in aluminum because deferent by young modulus.
6. The velocity of crack propagation in plain stress is larger than in plain strain, i.e. the crack velocity is decreasing when thickness of plates is increasing.
7. The velocity of crack propagation is decreasing when the aspect ratio is increase. In addition, increasing velocity of crack when velocity impact increase, when deep of crack increase the crack velocity increasing. This behavior as applied for path material and plane stress and plane strain.
8. The strain energy method is applied for all velocity impact and gives good agreement when velocity impact increasing more than 20 m/s. Where the percentage error for result between the airy method and energy about (13%).

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Appendix A:
Speed of crack propagation for varying energy release rate.

From reference (Sheng,2004), a simulation equation to calculate the propagation velocity of successive crack as a function of energy release rate. The energy release G averaged over the advancing front of a semi-infinite crack is

$$G = \frac{\pi}{2} \frac{\left(1-\upsilon^2\right)\cdot h \cdot \sigma^2}{E} \cdot g(\alpha \cdot \beta) \tag{A-1}$$

Where h is the plate thickness, σ is the stress in the plate normal to the crack line, and E and υ are the young modulus and Poisson ratio of the plate, respectively. The function

$$g(\alpha,\beta) = \frac{2 \cdot L}{\pi \cdot h} \tag{A-2}$$

Where $L = \sqrt{\dfrac{h \cdot H \cdot E}{\mu_s}}$

Where H is the substrate thickness, and μ_s is the shear modulus of plate. Putting the function (A-2) into (A-1), we obtain as energy release rate G.

$$G = \frac{1-\upsilon^2}{E} \sqrt{\frac{h \cdot H \cdot E}{\mu_s}} \cdot \sigma^2 \tag{A-3}$$

Crack propagation velocity V as a function of energy release rate G was given,

$$V = Vo \cdot \sinh\left[\beta\left(\frac{G}{G_{ic}} - 1\right)\right] \qquad \text{(A-4)}$$
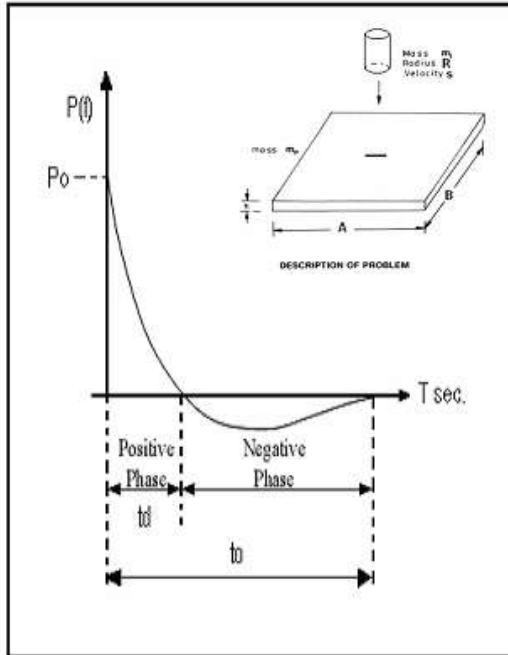
Figure (1) Behavior of impact (Dharni, 2005)   Figure (2) Impact load in Ansys
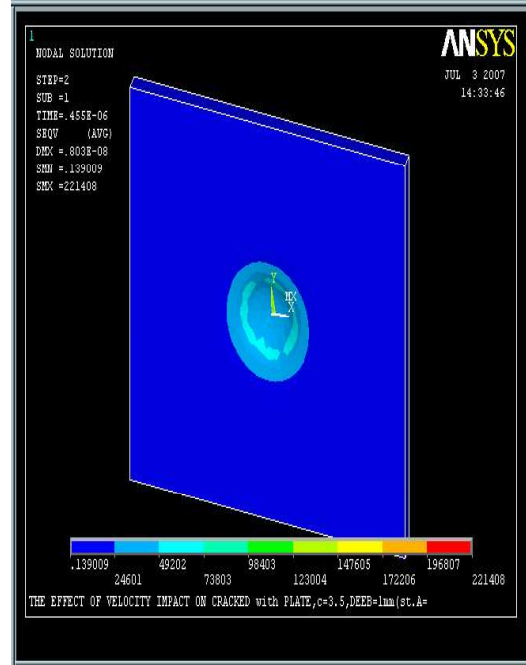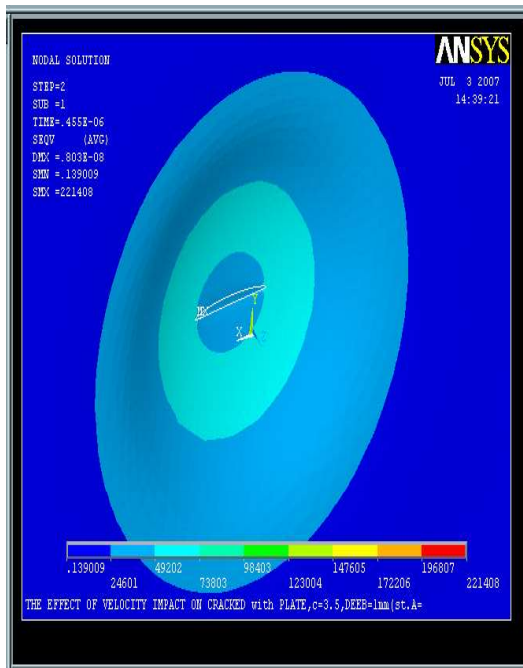
Figure (3) Crack opening in Ansys   Figure (4) Stress distributed crack
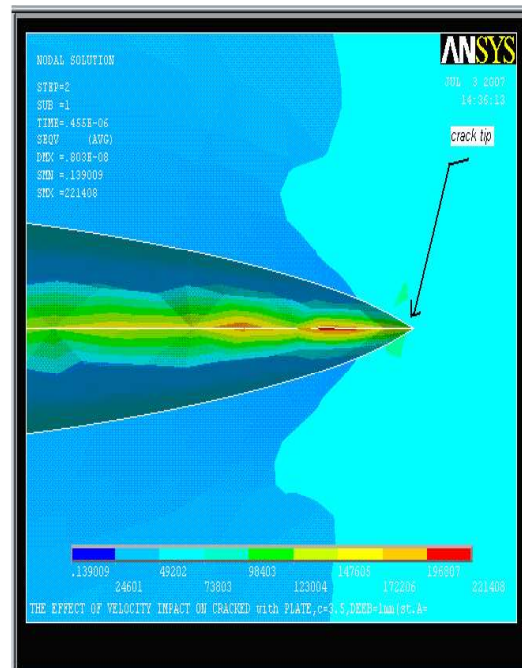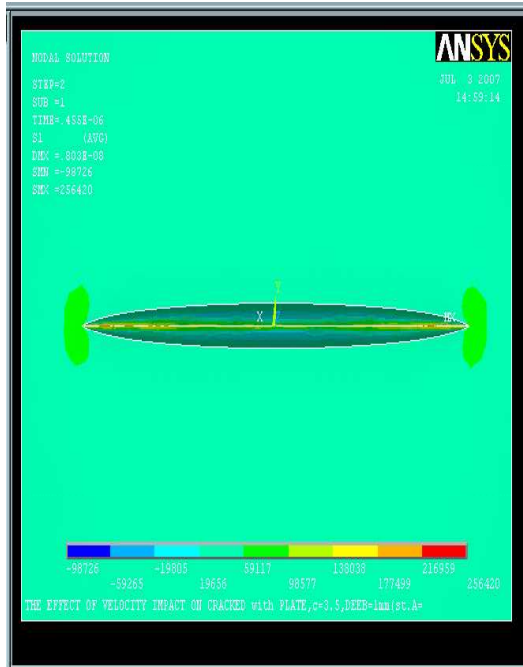
Figure (5) DSIF's in Ansys
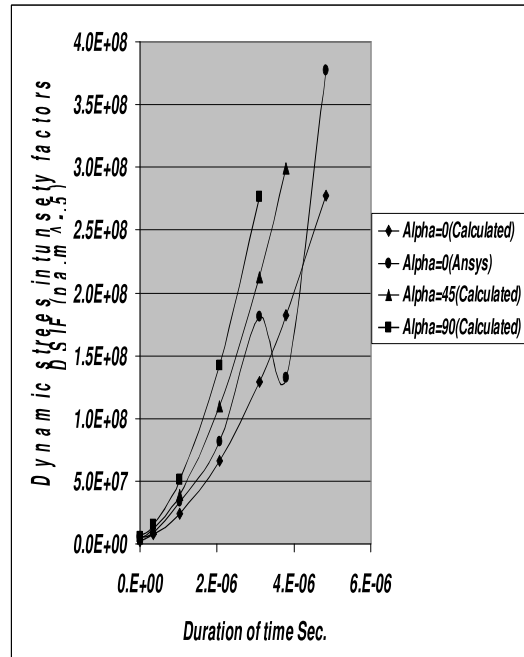
Figure (6) Impact Velocity 1 m/s
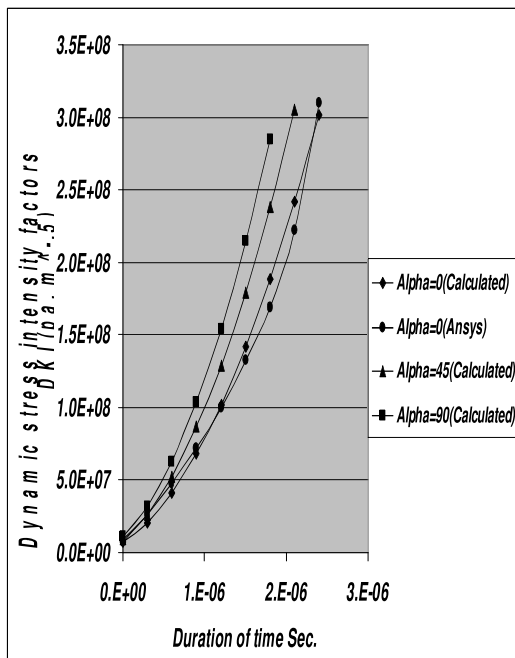
Figure (7) Impact Velocity 2 m/s
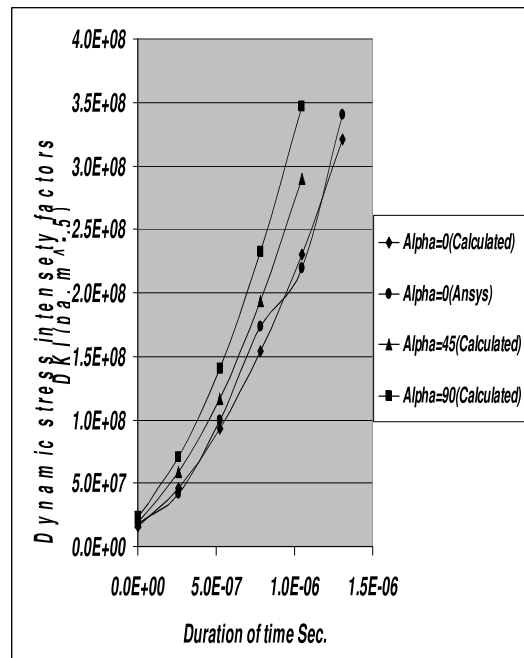
Figure (8) Impact Velocity 4 m/s
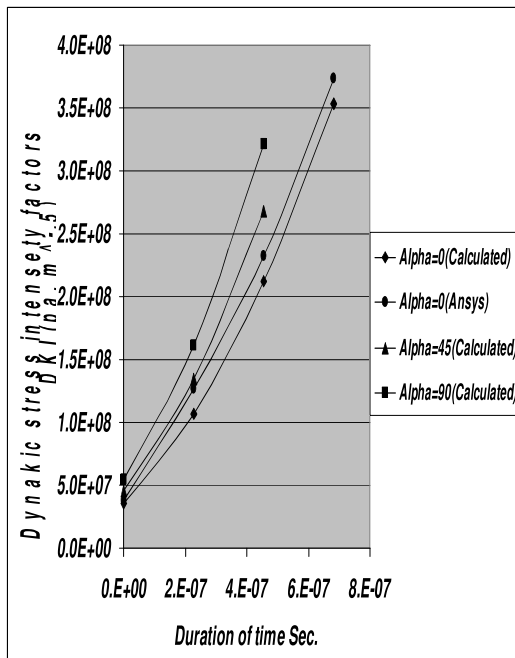
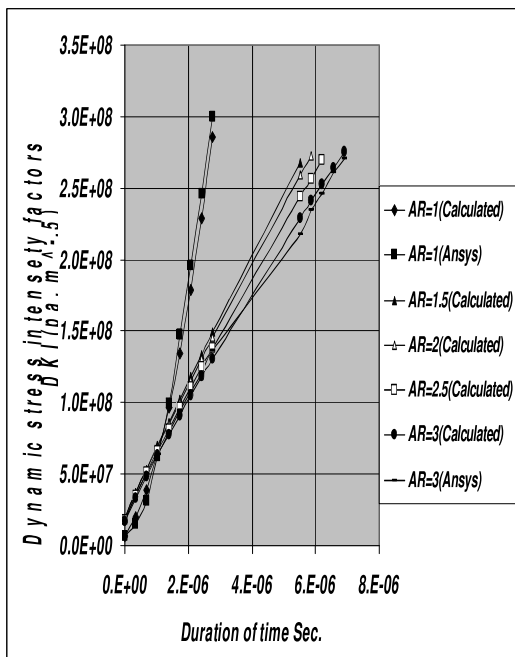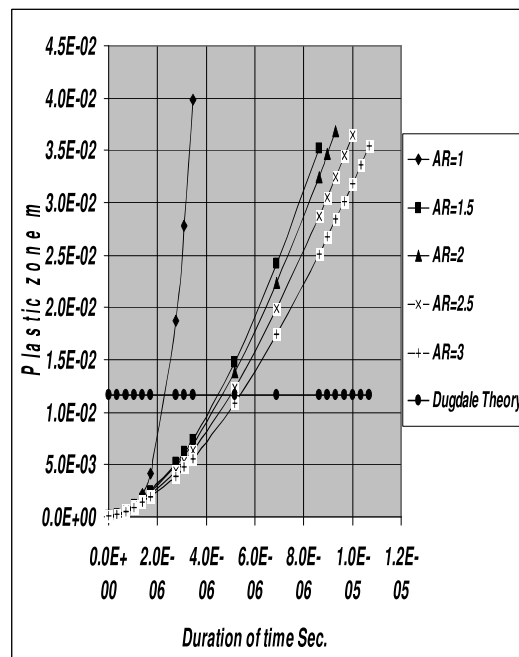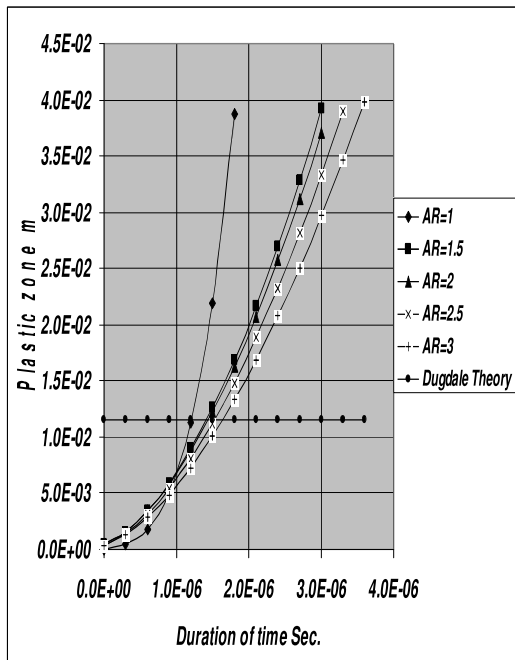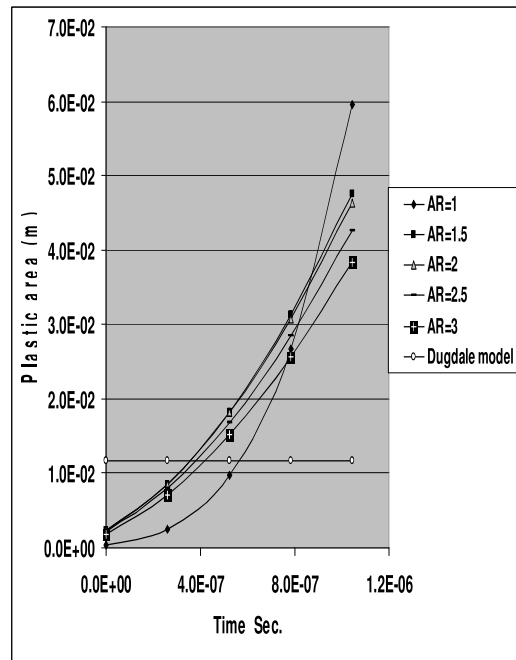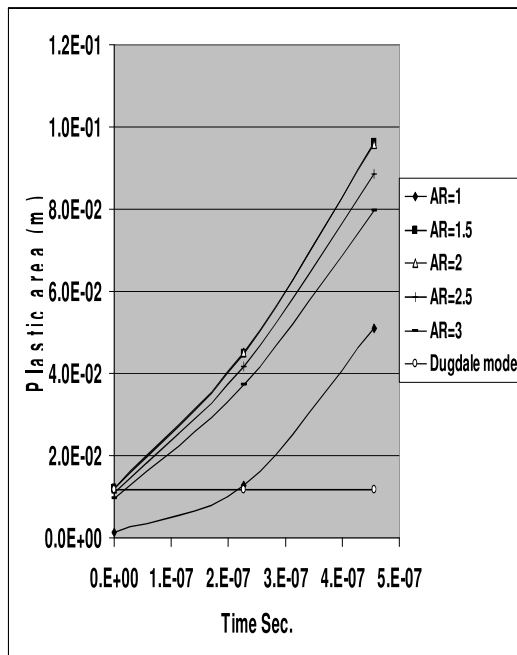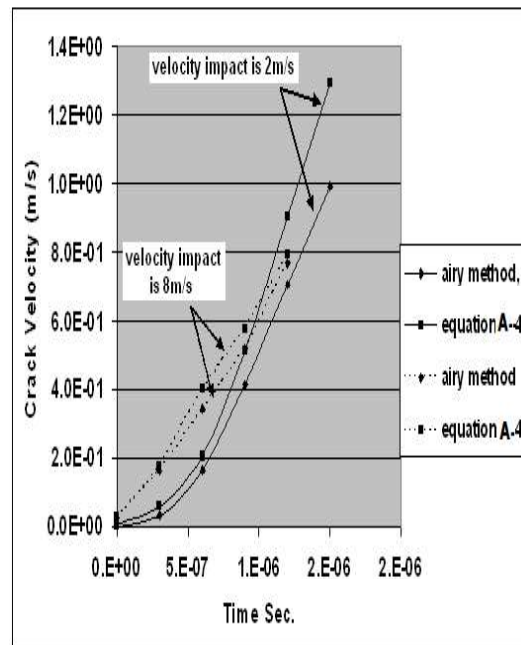Figure (9) Impact Velocity 8 m/s
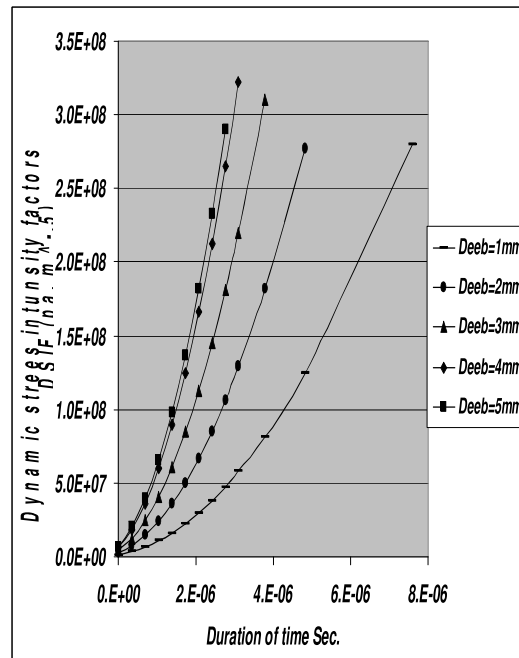
Figure (10) Impact Velocity is 1m/s

Figure (11) Impact Velocity is 1m/s

Figure (12) Impact Velocity is 1m/s

Figure (13) Impact Velocity is 2m/s

Figure (14) Impact Velocity is 4m/s

Figure (15) Impact Velocity is 8m/s

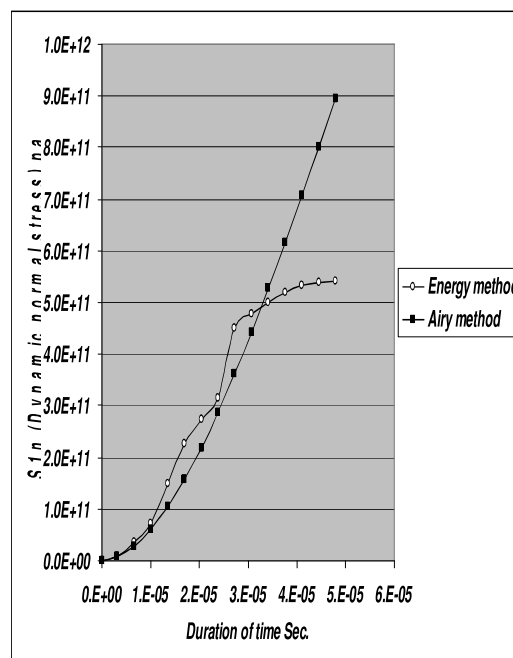Figure (16) Velocity Compared
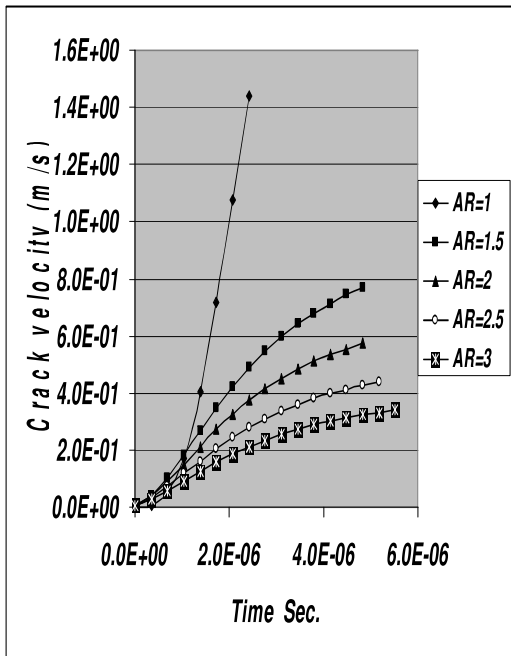
Figure (17) Velocity impact is 1 m/s
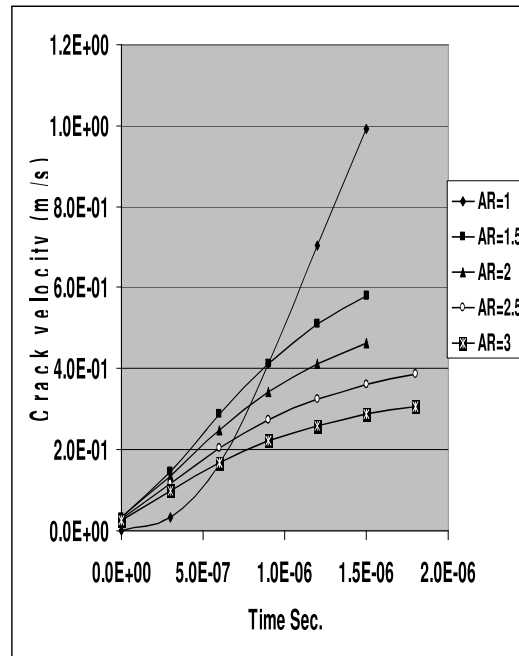
Figure (18) Velocity impact is 2 m/s
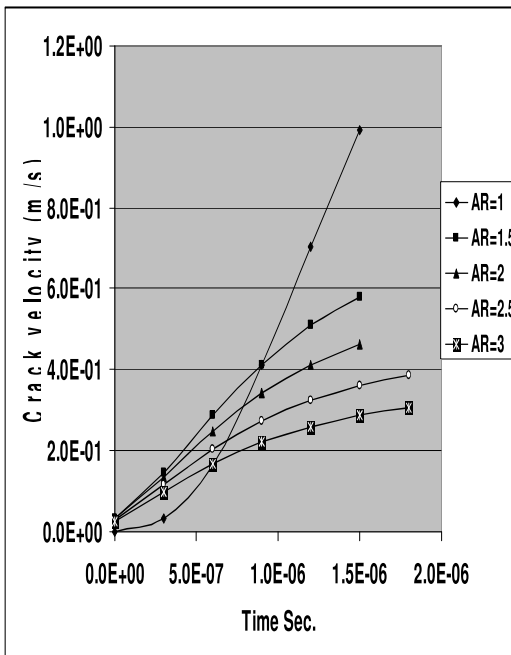
Figure (19) Velocity impact is 4 m/s
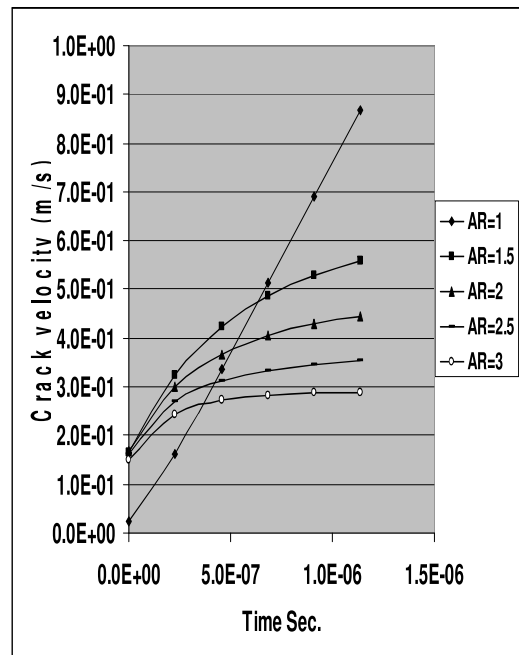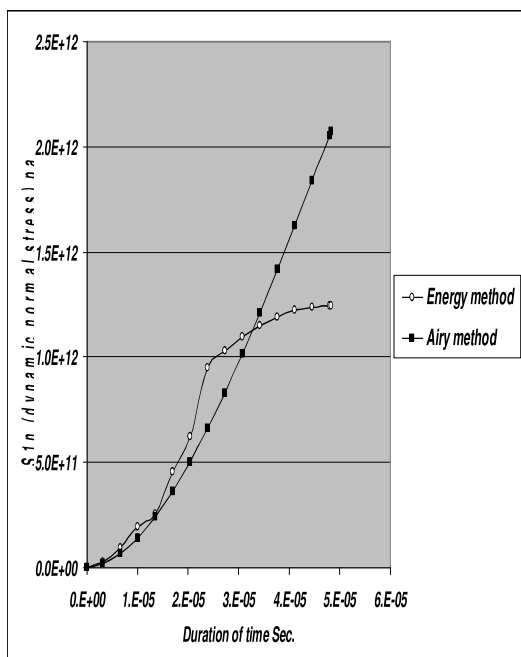
Figure (20) Velocity impact is 8 m/s
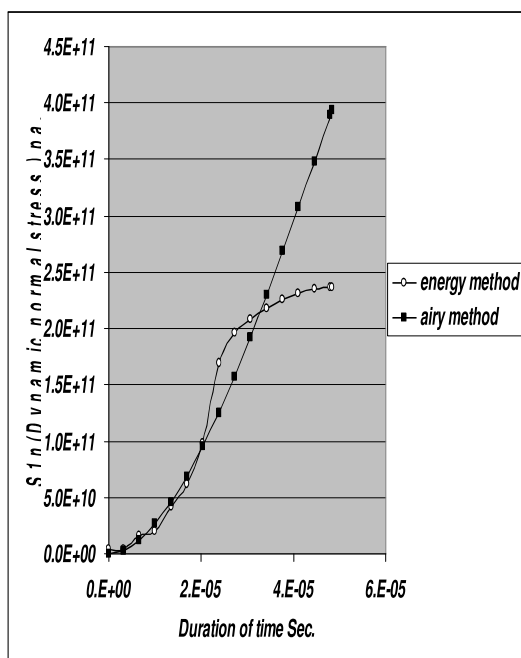
Figure (21) Velocity of impact =1 m/S

Figure (22) Velocity of impact =2 m/s

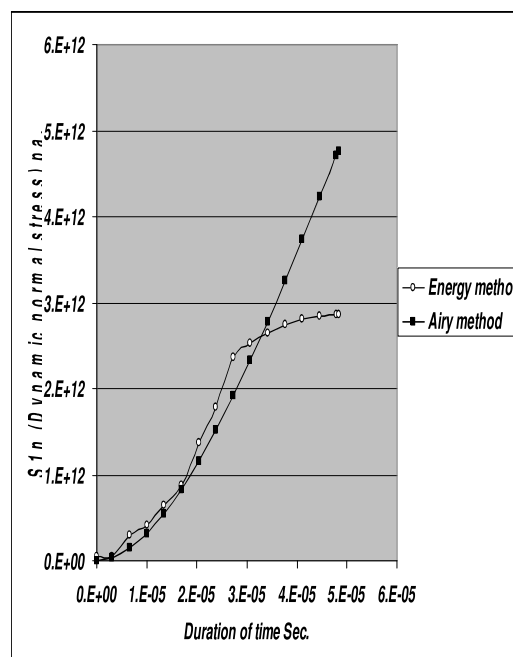
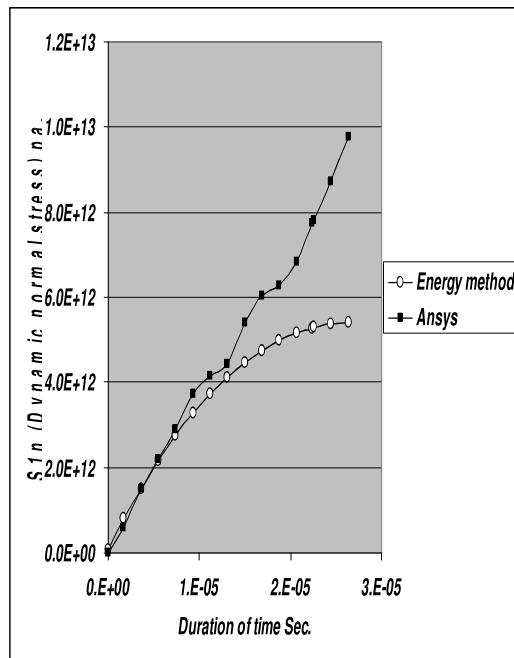
Figure (23) Velocity of impact =4 m/s

Figure (24) Velocity of impact =8 m/s

Figure (25) Velocity of impact =20 m/s