PETALLING DAMAGE ANALYSIS OF METALLIC PLATE STRUCTURES UNDER LOCALIZED IMPACT LOADING - A REVIEW

Pham Hoang Nam*[1], Djarot Widagdo[1], Sigit Santosa[1], and Ichsan Setya Putra[1]

[1]Faculty of Mechanical & Aerospace Engineering, Institut Teknologi Bandung, Bandung, Indonesia,
e-mail: nambk51@gmail.com

Received Date: January 12, 2015

Abstract

The main objective of this paper is to review the theoretical predictions on the petalling damage of plate structures against highly localized load. There are three existing methods to solve petalling problem. First method of Zaid and Paul (1958) used momentum conservation to calculate high speed projectile perforation of a plate structure. The magnitude and direction of forces and velocities were considered as a function of penetration distance. This method used hole enlargement models, a rather simple method to calculate the momentum conservation of the two impacting bodies. Second method of Landkof and Goldsmith (1983) predicted petalling damage of a plate structure during penetration by using cylindro-conical projectile. This work showed that petalling damage is combination of bending and tearing process. Bending process was calculated due to the action of plastic hinges. The tearing process was formulated by Mode I fracture mechanics. Limitation of the method by Landkof and Goldsmith is in the calculation of all energies such as dishing, bending and tearing energy that was done independently. The third method, which was done recently by Wierzbicki (1999) and Lee (2004) gave a new method to describe petalling problem based on energy conservation. This method showed that tearing and bending process are related through the local radius of petal, while bending process and dishing process are related through the circumferential curvature of the dish. Tearing process was described more proper than before by using crack opening displacement (COD) criterion. In these works of Wierzbicki and Lee, there are some places which could be improved such as consideration of shearing process and modification of tearing model.

Keywords: Ballistic impact, Blast impact, Clamped metal plate, COD criterion, Petalling damage, Plastic flow

Introduction

Plate component is a very basic form of structure in a variety of land-based, aero and marine applications such as skin of tanks, armored vehicles, fuselage of aircrafts and skin of ship. Understanding failures of plate components under highly localized load such as blast or ballistic load will be useful for the design process of various structures which have significant risk of collapse either by accidental or intentional actions. Petalling damage is a common failure mode of thin plates subjected to localized high intensity loading. Some research showed, a dominant part of energy was absorbed by petalling process of plate (70% of total absorbed energy) [1]. Therefore, the understanding of petalling mechanics and process is very important in design of plate structures against highly localized load.

Research about petalling damage was generated on the perforation of thin plate by cylindro conical projectile. Zaid and Paul (1958) used momentum conservation to calculate high speed projectile perforation of a plate structure [2]. This method used hole enlargement models, a rather simple method to calculate the momentum conservation of the two impacting bodies. Second method of Landkof and Goldsmith (1983) predicted petalling damage of a plate structure during penetration by using cylindro-conical projectile [3]. This work showed that petalling damage is combination of bending and tearing process. In the method of Landkof and Goldsmith, calculation of all energies such as dishing, bending and tearing energy that was done independently. The third method, which was done recently by Wierzbicki [4][5] and Lee [6] gave a new method to describe petalling problem based on energy conservation. This method showed that tearing and bending process are related through the local radius of petal, while bending process and dishing process are related through the circumferential curvature of the dish. Tearing process was described by using crack opening displacement (COD) criterion.

From review of previous researches, some future works were proposed to improve existing petalling damage model such as consideration of shearing process and modification of tearing model.

Theoretical Study

Behaviour of Metallic Plate Structure under Localized Blast Load

Failure types of clamped metal plate under localized blast load were revealed by experiments of Nurrick and Radford [1] such as *dishing*, *discing* and *petalling*, see Figure 1.

At low value of blast impulse, $I < I_{cr}$, the plate plastically bends and stretches without rupture (*dishing mode*). In this mode, kinetic energy is transformed to plastic energy of dish process.

$$E_{\text{kinetic}} = E_{\text{dishing}} \tag{1}$$

Dishing problem was analyzed by some researches [7-10].

At critical value of blast impulse, $I = I_{cr}$, plate stretching is followed by tensile rupture (*discing mode*). In this mode, kinetic energy is transformed to dishing energy and discing energy (energy of circumferential crack propagation). This amount of energy called critical energy which makes plate fracture.

$$E_{\text{kinetic}} = E_{\text{dishing}} + E_{\text{discing}} = E_{\text{critical}} \tag{2}$$

Some fracture criterion of thin plate was studied in previous researches [11], [12]

At high value of blast impulse, $I > I_{cr}$, the radial crack is propagated from center to support edges of plate while the petals are bend around plastic hinges (*petalling mode*). In this mode, kinetic energy is equal to total of critical energy and petalling energy.

$$E_{\text{kinetic}} = E_{\text{critical}} + E_{\text{petalling}} \tag{3}$$

Blast impulse I is product of blast pressure $p(t)$ and the time during which it acts t [13]. Blast impulse is usually used to estimate the effect of explosion.

$$I = \int_0^t p(t)\,dt \tag{4}$$

The blast wave (pulses of air) contains as much as 95% of the explosion energy for conventional high energy explosives [13]. The rest of the energy is dissipated through thermal radiation and light generation. So that, the effect of thermal radiation to structures is quite small compared to effect of blast wave.

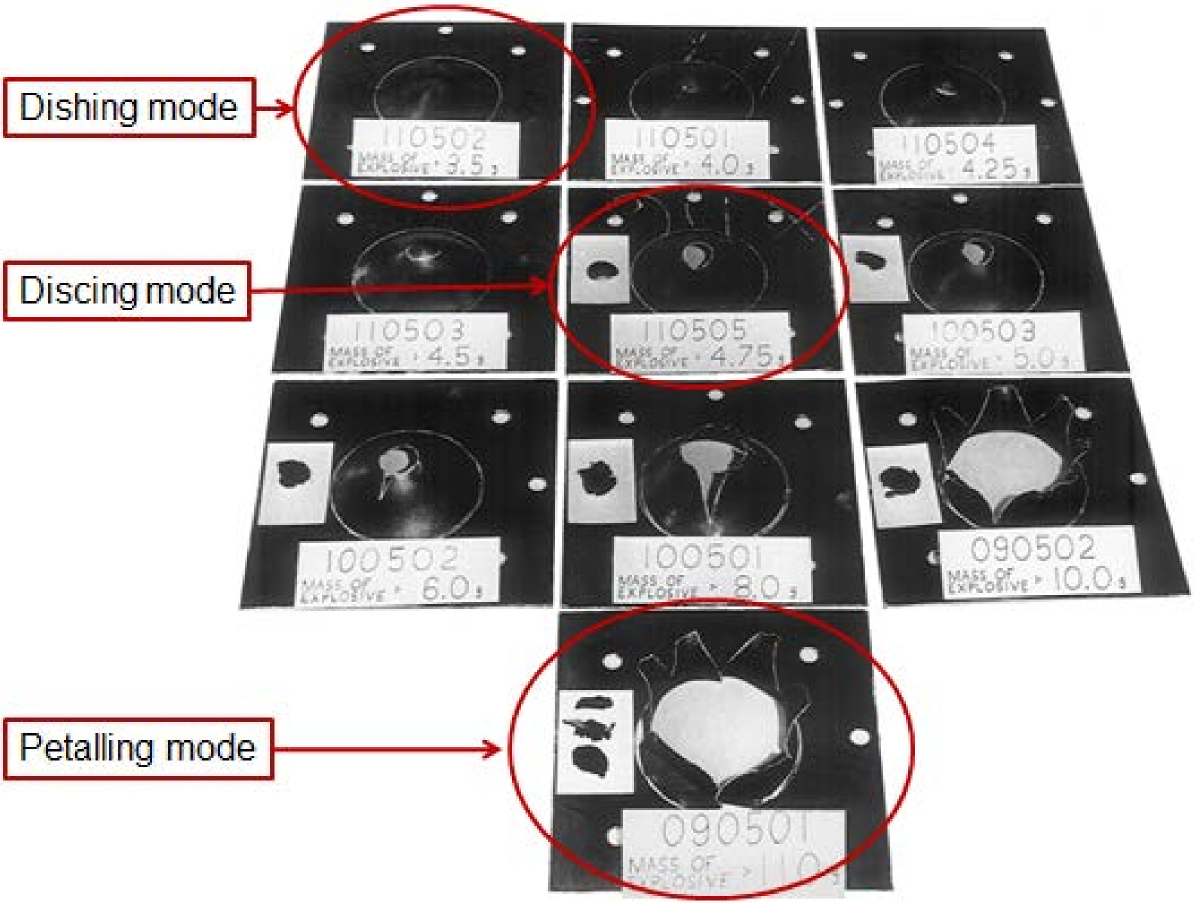

Figure 1. Subsequent stages in the formation of a petalling failure of a steel plate subjected to a localized explosive loading [1]

Petalling Damage Analysis Of Metallic Plate Structure

In the research of Zaid and Paul (1958) [2], a momentum approach was used to describe the problem of perforation. The magnitude and direction of forces, velocity, etc. as a function of penetration distance, $\dot{\xi}$, were derived for the conical projectile under normal impact, see Figure 2.

Conservation of momentum equation:

$$m(v_{initial} - v_{final}) = M_t(x) \tag{5}$$

Where, m is mass of projectile, $v_{initial}$ and v_{final} is velocity of projectile before and after impact, $M_t(x)$ is momentum in x direction of plate.

Momentum approach in x direction is given by

$$dM_t = 2\pi\rho h_0 r_0 \dot{\xi} dr_0 \tag{6}$$

Where, dM_t is momentum in x direction of annulus element dr_0, ρ is mass density of plate, h_0 is thickness of plate, r_0 is distance from center of plate to annulus element, ξ is penetration distance.

Limitation of method of Melvin Zaid and Burton Paul [2] is that fracture parameter was not included in calculation.

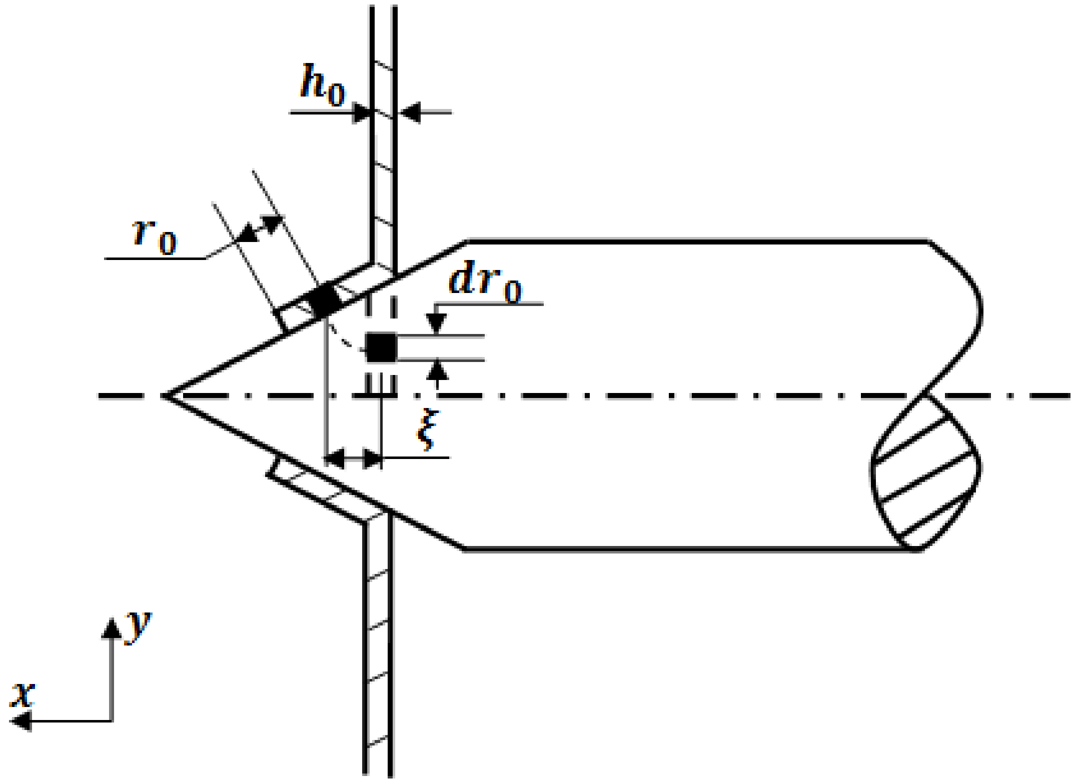

Figure 2. The deformation of thin plate cause by a conical projectile [2]

The first and only available analytical method about petalling damage was due to Landkof and Goldsmith [3]. Their solution was based on an energy balance in which the energy absorbed by the plate consists of that due to crack propagation, petal bending, and plate dishing, can be seen in Figure 3 and 4.

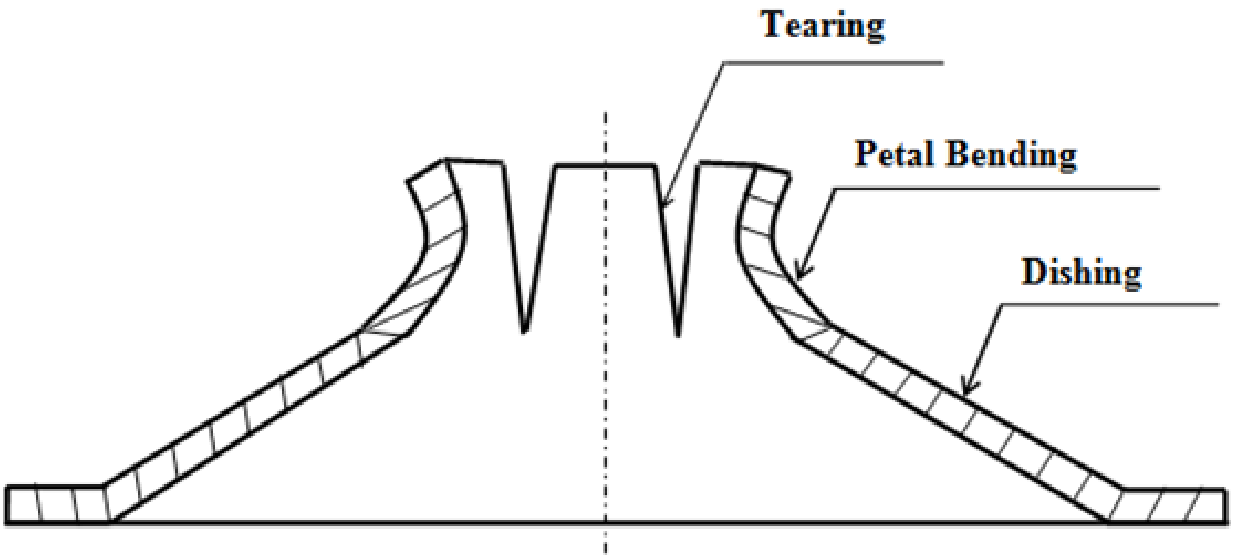

Figure 3. Plate perforation by a conically-tipped projectile showing petal formation, bending and dishing [3]

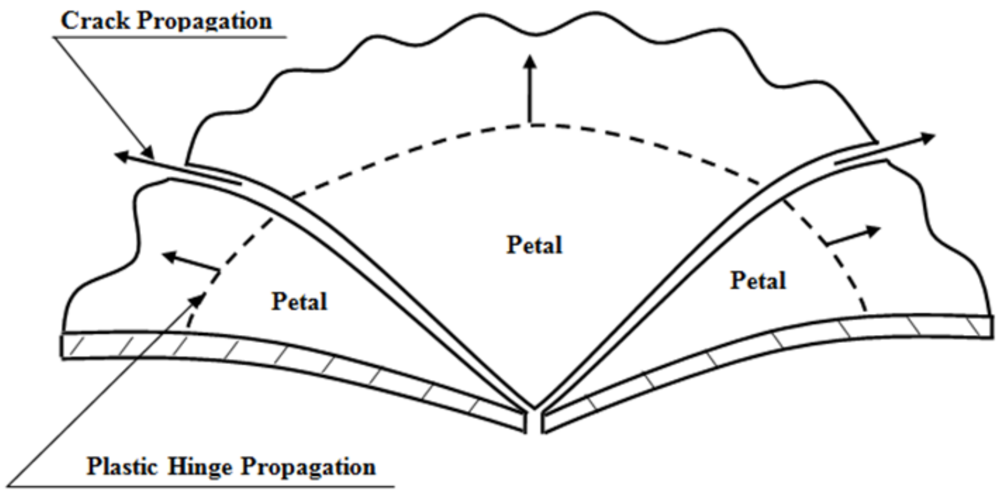

Figure 4. Propagation of the cracks and plastic hinges [3]

The amount of energy that is spent to extend the star-shaped crack will be calculated according to Griffith's postulate, see Figure 5. The amount of energy per unit crack area needed for extension of the crack,G, must be greater than the unit surface energy of the extended crack, G_c, so that $G > G_c$ for the radial crack growth. For the first mode, G is given by

$$G = \frac{{K_I}^2}{E} \tag{7}$$

Where, K_I is stress intensity factor for Mode I, E is Young's modulus

Equation of stress intensity factor,K_I, for Mode I

$$K_I = \sigma\sqrt{\pi a}F(n) \tag{8}$$

Where, σ is stress, a is crack length, F(n) is function of petal number.

Substituting equation of stress intensity factor into energy equation one gets

$$G = \frac{\pi a \sigma^2 F^2(n)}{E} \tag{9}$$

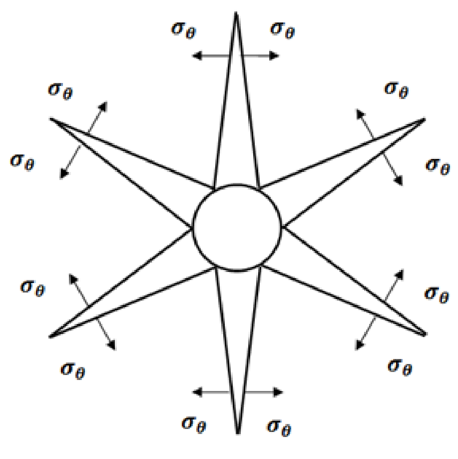

Figure 5. Star crack pattern with 6 petals produced by circumferential stresses [3]

Bending process was calculated due to action of plastic hinges.

Limitation of method of Landkof and Goldsmith [3] is in the calculation of all energies such as dishing, bending and tearing energy that was done independently.

Recently, the works of Wierzbicki [4][5] and Lee, Wierzbicki [6] showed developments of a new petalling model, as can be seen in Figure 6 and 7, in which all of these three energies are coupled. The tearing fracture energy is related to the bending energy through the local radial curvature of the petal. The bending energy is related to the circumferential curvature of the dish.

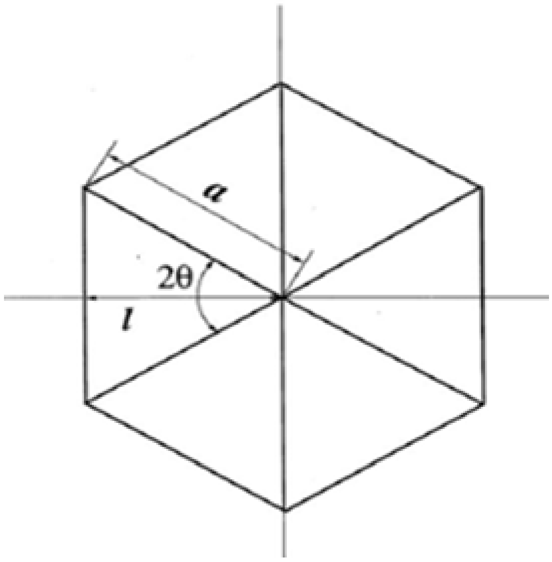

Figure 6. Initial geometry of plate [4]

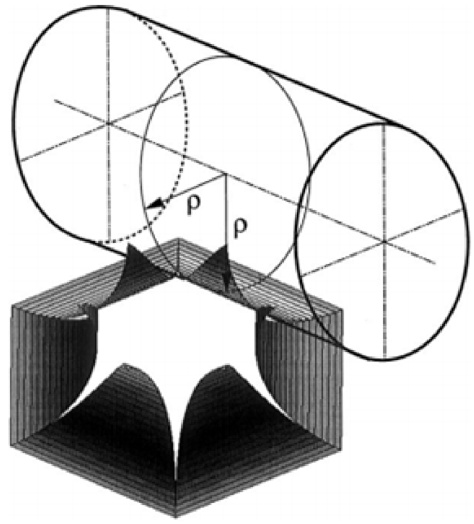

Figure 7. Current geometry of plate [4]

Bending energy equations [4], [5], [6]

The rate of bending energy

$$\dot{E}_b = 2M\dot{\phi}l_{AB} \tag{10}$$

Where, M is bending resistance per unit length of curved plate,

$$M = \eta M_0 \tag{11}$$

M_0 is bending resistance per unit length of flat plate,

$$M_0 = \frac{1}{4}\sigma_0 t^2 \tag{12}$$

And l_{AB} is length of plastic hinge, see Figure 8

$$l_{\mathrm{AB}} = 2l\,tan\,\theta \tag{13}$$

Where $\dot{\phi}$ is rate of rotation of petal, t is thickness, σ_0 is flow stress, θ is semi angle of petal, l is length of petal, see Figure 6, ρ is local radius of petal, see Figure 7.

The rate of bending energy become

$$\dot{E}_{\mathrm{b}} = 4M\frac{\dot{l}}{\rho}l\,tan\,\theta \tag{14}$$

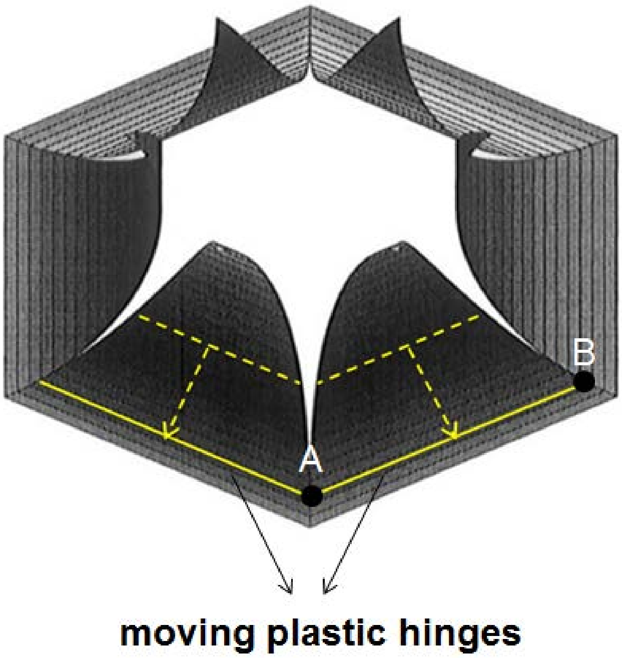

Figure 8. Plastic hinges propagation in bending process [4]

Membrane energy equations [4], [5], [6]

The rate of membrane energy is defined as

$$\dot{E}_m = t\int \sigma_{\alpha\beta}\dot{\varepsilon}_{\alpha\beta}dS \tag{15}$$

Where t is the thickness, and the stresses $\sigma_{\alpha\beta}$ and strain rate tensors $\dot{\varepsilon}_{\alpha\beta}$ are described based on the assumption below.

Assumption:

No compression in front of crack tip $\dot{\varepsilon}_{xx} = 0$.

No shearing process between two neighbor petals $\dot{\varepsilon}_{xy} = 0$.

$$\dot{E}_m = 2t\int_0^{l_p}\int_0^{\xi(x)} \frac{2}{\sqrt{3}}\sigma_0\dot{\varepsilon}_{yy}dydx \tag{16}$$

$$\dot{E}_m = \frac{2}{3}\sigma_0 t x_p \dot{l}(\sin\theta)^{-1} \tag{17}$$

From geometry relations, length of near-tip plastic zone x_p is defined as

$$x_p = 1{,}44\delta_t{}^{1/3}\rho^{\,2/3}(\sin\theta)^{-1/3}(\cos\theta)^{-1} \tag{18}$$

Where δ_t is CTOD parameter, see Figure 9,

The rate of membrane energy become

$$\dot{E}_m = 3.84M_0t^{-1}\delta_t{}^{1/3}\rho^{\,2/3}\dot{l}(\sin\theta)^{-4/3}(\cos\theta)^{-1} \tag{19}$$

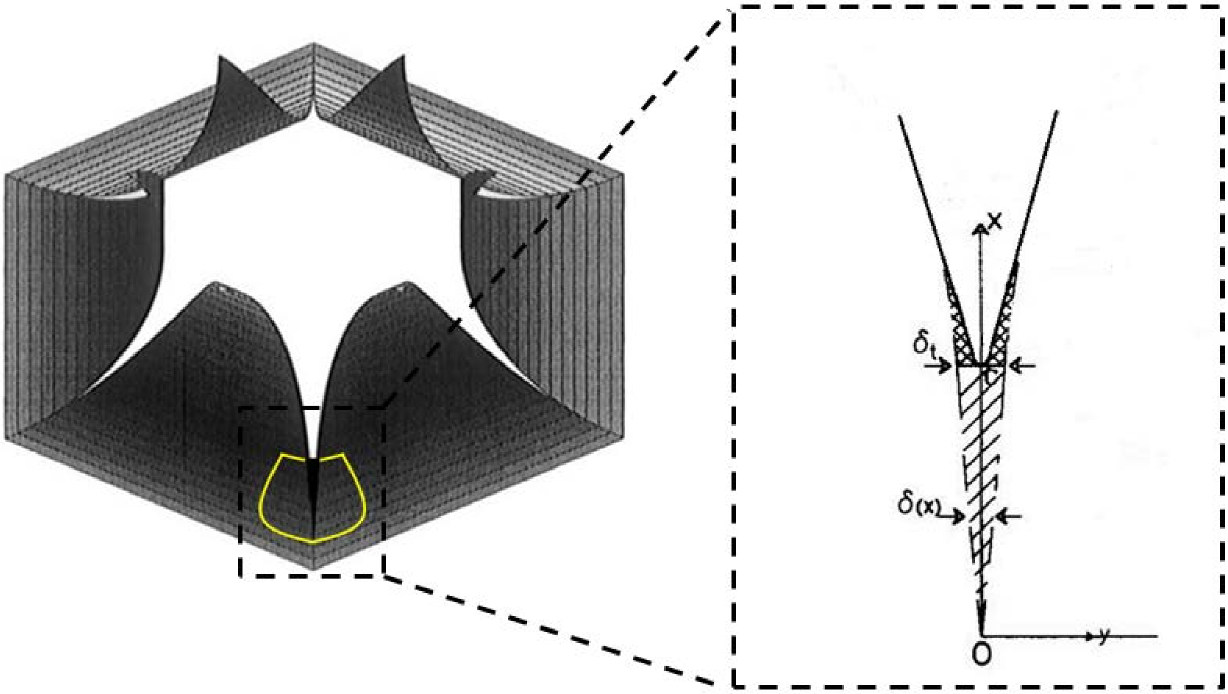

Figure 9. COD parameter of near tip plastic zone [4]

Total rate energy equations [4], [6]

Total rate energy, normalized with respect to$M_0\dot{l}$.

$$\frac{\dot{E}}{M_0\dot{l}} = 4\eta\frac{l}{\rho}tan\,\theta + 3{,}84\bar{\delta}^{1/3}\left(\frac{\rho}{t}\right)^{2/3}(sin\,\theta)^{-4/3}(cos\,\theta)^{-1} \tag{20}$$

The bending radius could be found by minimizing of the total rate of energy.

$$\frac{d\left(\frac{\dot{E}}{\dot{l}}\right)}{d\rho} = 0 \tag{21}$$

$$\rho_{min} = 1{,}3\eta^{0,6}l^{0,6}t^{0,4}\bar{\delta}^{-0,2}(sin\,\theta)^{1,4} \tag{22}$$

The normalized rate of energy per petal becomes.

$$\frac{\dot{E}}{M_0\dot{l}} = 7{,}65\left(\frac{l\eta}{t}\right)^{0,4}\bar{\delta}^{0,2}(sin\,\theta)^{-0,4}(cos\,\theta)^{-1} \tag{23}$$

The rate of energy per *n* petals is

$$\left(\frac{\dot{E}}{M_0\dot{l}}\right)_n = 7{,}65\pi\left(\frac{l\eta}{t}\right)^{0,4}\bar{\delta}^{0,2}f(\theta) \tag{24}$$

Where,

$$f(\theta) = [\theta(sin\,\theta)^{0,4}\,cos\,\theta]^{-1} \tag{25}$$

Function $f(\theta)$ attains a minimum at $\theta{\sim}50^o$giving approximately number of petals $n = 4$, see Figure 10. However, because the minimum of the rate of energy is rather weak, a large number, i.e. five or six petals, can be produced as well.

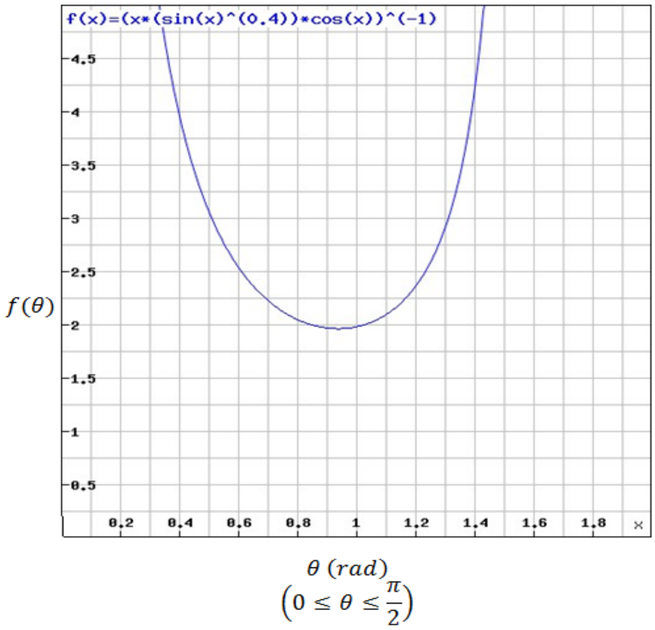

Figure 10. Minimum petal semi angle θ calculated [4]

In these research of Wierzbicki [4][5] and Lee, Wierzbicki [6], there are some places which possible to be improved such as studying of contribution of shear energy in membrane energy and modification of existing tearing model. Besides that, numerical simulation work will be conducted to compare with the new theory.

Conclusions

Understanding about petalling process is very important in design of plate against highly localized load. From the above review, some future works can be proposed to improve the existing theoretical analysis of petalling mechanics process. One proposed work will focus on new analytical method to modify more precisely COD criteria and to calculate the contribution of all energy dissipation mechanism in the petalling process, i.e. through bending, tearing, shearing, and stretching deformation. Besides that, numerical simulation work can be conducted to compare with the new theory.

Acknowledgement

This research was supported by AUN/SEED-Net Scholarship and Light Weight Structure Research Group, Institute Technology Bandung.

References

[1] G.N. Nurick, and A.M. Radford, "Deformation and tearing of clamped circular plates subjected to localised central blast loads," In *Recent developments in computational and applied mechanics: A volume in honour of John B. Martin*, Reddy BD ed.: International Center for Numerical methods in Engineering (CIMNE), Barcelona, pp. 276-301, 1997.

[2] M. Zaid, and B. Paul, "Mechanics of high speed projectile perforation," *Journal of the Franklin Institute*, Vol. 264, No. 2, pp. 117-126, 1957.

[3] B. Landkof, and W. Goldsmith, "Petalling of thin metallic plates during penetration by cylindro-conical projectiles," *International Journal of Solids Structure*, Vol. 21, No. 3, pp. 245-266, 1985.

[4] T. Wierzbicki, "Petalling of plates under explosive and impact loading," *International Journal of Impact Engineering*, Vol. 22, No. 9-10, pp. 935-954, 1999.

[5] T. Wierzbicki, and P. Thomas, "Closed-form solution for wedge cutting force through thin metal sheets," *International Journal of Mechanical Sciences*, Vol. 18, No. 6, pp. 209-229, 1993.
[6] Y-W Lee, and T. Wierzbicki, "Fracture prediction of thin plates under localized impulsive loading. Part II: Discing and petalling," *International Journal of Impact Engineering*, Vol. 31, No. 10, pp. 1277-1308, 2004.
[7] Y-W Lee, and T. Wierzbicki, "Fracture prediction of thin plates under localized impulsive loading. Part I: Dishing," *International Journal of Impact Engineering*, Vol. 31, No. 10, pp. 1253-1276, 2004.
[8] T. Wierzbicki, and G.N. Nurick, "Large deformation of thin plates under localised impulsive loading," *International Journal of Impact Engineering*, Vol. 18, No. 6, pp. 899-918, 1996.
[9] M. Mihailescu-Suliciu, and T. Wierzbicki, "Wave Solution For An Impulsively Loaded Rigid-Plastic Circular Membrane," *The Quarterly Journal of Mechanics and Applied Mathematics*, Vol. 54, No. 5-6, pp. 737-759, 2002.
[10] S. Kazemahvazi, D. Radford, S.V. Deshpande, and A.N. Fleck, "Dynamic failure of clamped circular plates subjected to an underwater shock," *Journal of Mechanics of Materials and Structures,* Vol. 2, No. 10, 2007.
[11] Y. Bao, and T. Wierzbicki, "A comparative study on various ductile crack formation," *Journal of Material Technology*, Vol. 126, pp. 314–24, 2004.
[12] Y. Bao, and T. Wierzbicki, "On fracture locus in the equivalent strain and stress triaxiality space," *International Journal of Mechanical Science*, Vol. 46, pp. 81–98, 2004.
[13] S. Glasstone, and P. Dolan, *The Effects of Nuclear Weapons*, 3rd Edition, U.S. Government Printing Office: 1977. 0-213-794, The United States Department of Defense & The United States Department of Energy, 1977.